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Alaska Power Authority
Susitna Hydroelectric Project

Subtasks 4.01 through 4.08

INTERIM REPORT ON SEISMIC STUDIES FOR SUSITNA HYDROELECTRIC PROJECT

December 1980

Prepared by

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for

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PREFACE

This interim report presents the results of the seismic studies conducted during 1980 for the Preliminary Feasibility Study of the proposed Susitna Hydroelectric Project site. These studies include geologic evaluation of faults and lineaments, an historical and microearthquake seismicity study, and preliminary estimation of ground motions. The results of this interim report are being used as the basis for seismic geology and ground motion studies which are scheduled for 1981.

The report includes 14 sections which summarize the results of the studies to date. The eight appendices present support data for the interpretations and conclusions presented in Sections 1 through 14. Tables and figures appear at the end of each section and appendix.

Measurements reported in this volume typically were made in the metric system and then converted to the English system. For these conversions, the measurements reported in the English system are rounded off to the nearest single unit (e. g., 70 km converts to 43 miles) even when in the context of the sentence the conversion should be rounded off to the nearest ten units (e. g., 70 km converted to 40 miles). This was done to retain the original number used to make the conversion. Conversely, some measurements were made using the English system; in this case, the conversion to the metric system also has been rounded off to the nearest single unit. Both sets of numbers have been presented for the convenience of the reader.

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DEFINITION OF KEY TERMS

Site Region:	The area within a 62-mile (100-km) radius about either site.
Project Area:	This generally includes the Devil Canyon and Watana areas and the region in between.
Devil Canyon Area:	The area within a 6-mile (10-km) radius about the Devil Canyon site.
Devil Canyon Site:	The presently proposed location of the Devil Canyon Dam and related facilities.
Devil Canyon Reservoir:	The area of the Susitna River upstream from the proposed Devil Canyon site which will be inundated by impoundment by the dam.
Watana Area:	The area within a 6-mile (10-km) radius about the Watana site.
Watana Site:	The presently proposed location of the Watana Dam and related facilities.
Watana Reservoir:	The area of the Susitna River upstream from the proposed Watana site which will be inundated by impoundment by the dam.

DEFINITION OF KEY TERMS (CONTINUED)

Microearthquake Study Area: The area in which microearthquake monitoring was conducted in 1980. The boundaries are 62.3° to 63.3° north latitude and 147.5° to 150.4° west longitude.

ACKNOWLEDGMENTS

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The Woodward-Clyde Consultants personnel who participated in the seismological portion of the seismic geology investigation were: Jim Agnew, Jean Briggs, Jim Cullen, John Hobgood, and William Savage. Jason McBride and Richard Thompson of Woodward-Clyde Consultants, and Milton Mayr, Dianne Marshall, Cole Sonafrank, and Rodney Viereck of the University of Alaska Geophysical Institute assisted with the microearthquake operation. The earthquake engineering portion of the investigation was conducted by John Egan and Maurice Power of Woodward-Clyde Consultants..

Discussions were held with members of the Alaska Geological Observatory, the Alaska Geophysical Institute, the Lamont-Doherty Geological Survey, the University of Alaska, and the U. S. Geological Survey.

Dr. Ulrich Luscher was the prinicipal-in-charge of the investigation; George Brogan assisted by Jon Lovegreen was Project manager. Dr. William Savage directed the seismology study and Maurice Power directed the earthquake engineering study.

Project peer review was provided by Dr. Robert Forbes, Professor Emeritus of Geology of the University of Alaska (geology); and Dr. I. M. Idriss, (earthquake engineering), Dr. Duane Packer (geology), Dr. William Savage (reservoir-induced seismicity); and Tom Turcotte (seismology) of Woodward-Clyde Consultants.

Aircraft support was provided by Akland Helicopter Inc. and ERA Helicopters Inc. and was arranged by Acres American Inc. Lodging and logistical support in the field was arranged by Acres American Inc.

This report was prepared by Woodward-Clyde Consultants. Technical support and typing was provided by Carole Wilson assisted by Barbara Beldon, Esther Martin, and Hazel Whittaker. Illustrations were prepared by Arlene Padamada, assisted by Dennis Fisher, Robyn Sherrill, and Chairoach Siripatanapaibul. Technical editing was done by Karen Lundegaard. Printing and binding of the report was done by Continental Graphics.

1 - SUMMARY

1.1 - Project Description

The Susitna Hydroelectric Project as currently proposed involves two dams and reservoirs on the Susitna River in the Talkeetna Mountains of southcentral Alaska. The Project is approximately 50 miles (80 km) northeast of Talkeetna, Alaska and 118 miles (190 km) north-northeast of Anchorage, Alaska (Figures 1-1 and 1-2). The downstream dam at Devil Canyon (62.8° north latitude, 149.3° west longitude) is currently being considered as an arch dam approximately 635 feet (194 m) high. It would impound a 28-mile- (45-km-) long reservoir with a capacity of approximately 1,050,000 acre feet (1,296 x $10^6 m^3$). The upstream dam, Watana (62.8° north latitude, 148.6° west longitude), is currently being considered as an earthfill or rockfill dam, approximately 810 feet (247 m) high. It would impound a 54-mile- (87-km-) long reservoir with a capacity of approximately 9,624,000 acre feet (11,876 x $10^6 m^3$). These dimensions are approximate and subject to revision during design of the project. Collectively, the proposed dams and related structures will be referred to as the Project.

This report is part of a feasibility study being managed and conducted by Acres American Inc. for the Alaska Power Authority. The investigation conducted to date has involved the first year of a planned two-year study (1980 and 1981). The purpose of this report is to summarize the results of the seismic geology, seismology, and earthquake ground motion investigation conducted during the 1980 study.

The primary objectives of this investigation have been to identify faults which have the potential for surface rupture through the Project and to make a preliminary estimate of earthquake ground motions which would be applicable to preliminary feasibility level decisions for the project. Using the results of the investigation to date, a study plan for the 1981 investigation has also been developed.

The 1980 investigation has included: review of available geologic and seismologic literature and data; monitoring of microearthquake activity for three months within approximately 30 miles (48 km) of either proposed dam site with a 10-station microearthquake network; a preliminary review of the potential for reservoir-induced seismicity; interpretation of existing remotely sensed data; a 10 person-month geologic field reconnaissance of mapped faults and lineaments within 62 miles (100 km) of the Project; analysis and interpretation of these data; and a preliminary estimate of potential earthquake ground motions for the project.

The review of geologic and seismologic data and the interpretation of remotely sensed data were conducted in the winter and spring of 1980. The microearthquake monitoring and geologic field reconnaissance were conducted in the summer and early fall, 1980. In the winter of late 1980, the ground motion studies were conducted and analysis of the data, including the preliminary assessment of the potential for reservoir-induced seismicity, was completed. Approximately 25 geologists, seismologists, and earthquake engineers have had a direct involvement with the study to date.

This section summarizes the results presented in this report; thus, full development of concepts, data, and bases for interpretations have been abstracted or deleted in the interest of brevity. Consequently, concepts, interpretations, and conclusions are intended to be read and understood within the context of corresponding sections in the text.

1.2 - Conceptual Approach

According to present understanding of plate tectonics, the earth's lithosphere, which contains the brittle 12 to 19 miles (20 to 30 km) or so of more rigid crust, overlies the denser and more viscous mantle. Observed major horizontal movements of the crustal plates are considered to be related to, or caused by, thermal convective processes within the mantle.

Within this plate-tectonic framework, faults that have the potential for generating earthquakes have had recent displacement and may be subject to repeated displacements as long as they are in the same tectonic stress regime. In regions of plate collision such as Alaska, the tectonic stress regime is the result of one plate being subducted, or underthrust, beneath the adjacent plate. Within this environment, primary rupture along fault planes can occur: within the downgoing plate where it is decoupled from the upper plate; along the interface between the upper and lower plates where they move past each other; and within the overriding plate. In the site region, faults with recent displacement are present in the overriding (upper) plate and at depth in the downgoing plate where it is decoupled from the upper plate.

Faults with recent displacement in the downgoing plate and in the upper plate can generate earthquakes which result in ground motions at the surface. These earthquakes are considered for seismic design purposes. The faults in the downgoing plate are considered not to have the potential for surface rupture. In the upper plate, if the rupture that occurs on these faults is relatively small and relatively deep, then rupture at the ground surface is likely not to occur. If the rupture along the fault plane is at sufficiently shallow depth and is sufficiently large, then surface rupture can occur.

Criteria for establishing guidelines to define what is considered "recent displacement" have been developed by Acres American Inc. and are presented in Section 3. According to these criteria. faults that have been subject to surface displacement within approximately the past 100,000 years are classified as having recent displacement.

Inherent with this concept of "fault with recent displacement" is the basic premise that faults without recent displacement will not have surface rupture nor be a source of earthquakes. Faults without recent displacement (as determined during this investigation) are considered to be of no additional importance to Project feasibility and dam design.

1.3 - Method of Study

The application of the "fault with recent displacement" concept for this investigation involved:

(a) Identification of all faults and lineaments in the site region that had been reported in the literature and/or were observable on remotely sensed data.

(b) Selection of faults and lineaments of potential significance in developing design considerations for the Project, from the standpoint of seismic source potential and/or potential surface rupture through a site. These faults and lineaments were selected using the length-distance criteria described in Section 3. These 216 faults and lineaments were designated as candidate features.

(c) Evaluation of the 216 candidate features during the geologic field reconnaissance studies. On the basis of this field work, the microearthquake data, and application of the preliminary significance criteria described in Section 8, 48 faults and lineaments were designated as candidate significant features. These features were subjected to additional evaluation using refined analyses, as described in (d) below, to select those features of potential significance to Project design considerations.

(d) Refinement of the evaluation process, using the significance criteria which are summarized in Section 1.6. On the basis of this evaluation, 13 significant features were selected for continued studies in 1981.

1.4 - Tectonic Model

An understanding of the regional geologic and tectonic framework is essential for: the assessment of fault activity; estimation of preliminary maximum credible earthquakes; evaluation of the potential for surface fault rupture; and evaluation of the potential for reservoir-induced seismicity.

The site region is located within a tectonic unit defined here as the Talkeetna Terrain. The Terrain boundaries are the Denali-Totschunda fault to the north and east, the Castle Mountain fault to the south, a broad zone of deformation with volcanoes to the west, and the Benioff zone at depth. All of the boundaries are (or contain) faults with recent displacement except for the western boundary which is primarily a zone of uplift marked by Cenozoic age volcanoes. The Terrain is part of the North American plate (as discussed in Section 5 and shown in Figure 5-1).

Preliminary results of this study suggest that the Talkeetna Terrain is a relatively stable tectonic unit with major strain release occurring along its boundaries. This conclusion is based on: the evidence for recent displacement along the Denali-Totschunda and Castle Mountain faults and the Benioff zone; the absence of major historical earthquakes within the Terrain; and the absence of faults within the Terrain that clearly have evidence of recent displacement. As discussed below, none of the faults and lineaments observed within the Talkeetna Terrain were observed to have strong evidence of recent displacement.

Strain accumulation and resultant release appears to be occurring primarily along the margins of the Terrain. Some compression-related crustal adjustment within the Terrain is probably occurring as a result of the proposed plate movement and the stresses related to the subduction zone.

This tectonic model is preliminary. It is intended to serve as a guide to understanding tectonic and seismologic conditions in the site region. As additional data are obtained, the model may be refined; however, these refinements are not expected to result in major changes in the model or its interpretations.

1.5 - Candidate Significant Features

As discussed in Section 1.3, a total of 48 candidate significant features were identified in the site region on the basis of the initial length-distance screening criteria, their proximity to the site, their classification in the field, and application of preliminary significance screening criteria. These features and their characteristics are summarized in Table 8-2.

Candidate significant features are those faults and lineaments which on the basis of available data at the end of the field reconnaissance, were considered to have a potential effect on Project design. Subsequent evaluation, using a refined, systematic ranking methodology, resulted in the identification of the significant features discussed below in Section 1.6.

1.6 - Significant Features

The 48 candidate significant features were subsequently evaluated by making detailed analyses regarding their seismic source potential and surface rupture potential at either site. For the evaluation of seismic source potential, the analyses included: an assessment of the likelihood that a feature is a fault with recent displacement; an estimation of the preliminary maximum credible earthquake that could be associated with the feature; and an evaluation of the peak bedrock accelerations that would be generated by the preliminary maximum credible earthquake at either site.

To evaluate the potential for surface rupture at either dam site, the analyses included: an assessment of the likelihood that a feature is a fault with recent displacement; an assessment of the likelihood that a feature passes through either site; and an evaluation of the maximum amount of displacement that could occur along the feature during a single event (e. g., the preliminary maximum credible earthquake).

Our evaluation of the 48 candidate significant faults, applying the judgments described above, resulted in the selection of 13 features, designated significant features, that should have additional studies to understand and more fully evaluate their significance to the Project.

Of these 13 features, four are in the vicinity of the Watana site including the Talkeetna thrust fault (KC4-1), Susitna feature (KD3-3), Fins feature (KD4-27), and lineament KD3-7 Nine of the features are in the vicinity of the Devil Canyon site including an unnamed fault (designated KD5-2), and lineaments KC5-5, KD5-3, KD5-9, KD5-12, KD5-42, KD5-43, KD5-44, and KD-45 (the alpha-numeric symbol (e. g., KC4-1) has been assigned to each fault and lineament using procedures discussed in Appendix A). The characteristics of these features are described in Section 8.5 and their locations are shown in Figures 8.2 through 8.5.

None of these signficant features are known to be faults with recent displacement; rather, the significant features are those for which additional data are required to preclude recent displacement along a fault. The significant features are not known to be accepted seismic sources with recent displacement; however, additional data are needed to confirm this judgment.

1.7 - Seismicity

Historical earthquake activity within 200 miles (322 km) of the Project is associated with displacement along crustal faults in the upper plate (as discussed in Section 1.2 above) and with the subducting (downgoing) plate. The largest earthquake within 200 miles (322 km) of the Project is the 1964 Prince William Sound earthquake of magnitude (M_S) 8.4. This earthquake occurred outside the Talkeetna Terrain on the interface between the Wrangell Block in the North American Plate and the Pacific Plate (Figure 4-1); the associated rupture and deformation extended to within approximately 88 miles (140 km) of the Project.

Within the site region (62 miles (100 km) from the Project), the level of seismicity on the Benioff zone is at least several times greater than that of the crustal region. The larger historical earthquakes (M_S > 5) that have occurred in the crust are apparently associated with known major faults with recent displacement, such as the Denali fault and the Castle Mountain fault. Most of these earthquakes, however, occurred prior to the operation of the regional seismographic network that began in 1964, so the accuracy of locations and focal depths is low, with uncertainties as large as 31 to 62 miles (50 to 100 km). The two largest, possibly crustal earthquakes that may have had epicenters in the site region, occurred in 1904 (M_S 7-3/4) and 1912 (M_S 7.4). If these events occurred in the crust, they are both likely to have occurred on the Denali fault which is at a closest distance of 40 miles (64 km) to the Project.

Within the site region, the largest reported earthquake (magnitude (M_S) 6-1/4) occurred on 3 July 1929. The epicenter and focal depth uncertainty of this event ($\pm$ 31 miles (50 km)) are great enough to suggest that it may have occurred on the Benioff zone at a depth of 31 to 43 miles (50 to 70 km).

During three months of mid-1980, a ten-station microearthquake array was operated to study the area within 30 miles (48 km) of the Project. More than 260 earthquakes in the magnitude (M_L) range 0.0 to 3.7 were analyzed. The discussion below summarizes the results.

Earthquake activity clearly delineates two seismic zones. The upper zone of crustal activity occurs predominantly in the depth range 5 to 12 miles (8 to 20 km). The lower zone of activity defines a northwestward dipping zone (the Benioff zone) at a depth of 25 miles (40 km) in the southeast to 50 miles (80 km) in the northwest portion of the micro-earthquake study area. The Benioff zone is approximately 6 to 9 miles (10 to 15 km) thick and is characterized by widely distributed seismicity. Within the Benioff zone, no lineations or other prominent features were observed. The seismicity appears to occur throughout the zone and does not define a single interplate interface. Focal mechanism interpretations for the Benioff zone suggest that the primary mode of deformation is due to high-angle normal faulting produced by down-dip extensional faulting within the plate.

During the three-month period of monitoring, 13 earthquakes of magnitude (M_L) 3.0 and larger were located in the Benioff zone. This level of activity is about ten times greater than that recorded for the shallow (crustal) zone. The slope of the magnitude-frequency graph for the Benioff zone is 0.68, similar to that for many areas worldwide. This curve suggests a relatively low number of larger earthquakes compared to smaller earthquakes. These results are consistent with the historical seismicity record.

The crustal earthquake activity was found to be generally confined to the geographic area of the Talkeetna Mountains. There were relatively few events occurring at depths shallower than 5 miles (8 km) or deeper than 12 miles (20 km). No seismic activity that appeared to be associated with the crust was deeper than 19 miles (30 km). The level of seismicity within the crustal zone within 30 miles (48 km) of the Project is very low, about one-tenth of the Benioff zone activity. The slope of the associated magnitude frequency curve is 1.48.

Map views and cross-sections of the shallow earthquakes were examined for possible spatial associations with mapped faults and lineaments. No associations were identified. Two clusters of small microearthquakes were located 16 to 22 miles (25 to 35 km) south of the Project at a depth of 9 to 12 miles (15 to 20 km). These clusters occurred within 12 miles (20 km) of the surface trace of the Talkeetna thrust fault; however, on the basis of results obtained to date, they do not appear to be associated with the Talkeetna thrust fault or any other surface feature. These clusters are related to extremely small-scale rupture on faults at depth in the crust. The rupture plane is too small and too deep to cause surface rupture.

Focal mechanism studies of crustal earthquakes within approximately 30 miles (48 km) of the Project indicate the occurrence of a regionally uniform west-northwest to east-southeast oriented horizontal compressional stress field. This stress field is producing thrust or strike-slip movement on small, features distributed in the lower crust.

1.8 - Reservoir-Induced Seismicity

The reservoirs which will be impounded behind the proposed dams will be very deep (greater than 492 feet (150m)). In the case of Devil Canyon, the reservoir will be large, with a volume greater than 1 x 10^6 acre feet (1,234 x $10^6 m^3$); in the case of Watana, it will be very large, with a volume greater than 8.1 x 10^6 acre feet (10,000 x $10^6 m^3$). Because of the proximity of the two reservoirs to each other, they will constitute one hydrologic unit which will be very deep and very large.

Given that the proposed combined hydrologic unit will be very deep and very large, the potential for reservoir-induced seismicity (RIS) has been estimated by evaluating reservoir-induced seismicity at other deep, very deep, and very large reservoirs. The results of this comparison show that the likelihood that a reservoir-induced event of any size (including microearthquakes) will occur at the proposed reservoir is 0.9 (on a scale of 0 to 1).

Since the likelihood of a reservoir-induced event is high, it is important to understand what the maximum earthquake is likely to be for the site region, and how the reservoir will affect the likelihood that a moderate-to-large (magnitude (M_s) > 5) event will occur. Previous studies (Packer, Lovegreen and Born, 1977; Packer and others, 1979) have presented data which support the concept that reservoirs can trigger earthquakes by means of pore pressure increases or incremental increase in stress. Because reservoirs act as triggering mechanisms, they are not expected to cause an earthquake larger than that which could occur in a given region "naturally." Rather, the reservoirs are expected to have a potential affect on the length of time between events and possibly on the location of the event. Thus, if the tectonic and seismologic setting of a region is known and if the maximum earthquake has been adequately defined, the maximum size of a reservoir-induced event can be identified.

Data reviewed for this investigation suggest that reservoir-induced earthquakes of magnitude (M_s) larger than 5 occur where faults with recent displacement lie within the hydrologic regime of the reservoir. No faults with recent displacement are known to be present within the hydrologic regime of the proposed reservoirs. Consequently, the likelihood of a reservoir-induced earthquake of magnitude (M_S) greater than 5 is considered to be low. However, if studies conducted during 1981 demonstrate that faults with recent displacement are present within the hydrologic regime of the reservoir, then the likelihood of a RIS event of magnitude (M_S) greater than 5 will need to be re-evaluated.

1.9 - Preliminary Maximum Credible Earthquakes (PMCEs)

Preliminary maximum credible earthquakes (PMCEs) have been estimated for crustal faults with unequivocal evidence of recent displacement and for the Benioff zone. The PMCEs for the crustal faults have been estimated using the fault rupture length relationships of Slemmons (1977) and the rupture area relationship of Wyss (1979). The higher (more conservative) of the two values has been used where the two relationships provided different values. The PMCE for the Benioff zone was estimated using historical activity. The PMCE estimated for the Denali fault and Benioff zone is magnitude (M_S) 8.5. For the Castle Mountain fault, it is magnitude (M_S) 7.4.

1.10 - Preliminary Ground Motion Studies

A preliminary assessment was made of earthquake ground motion at the sites. The characteristics of ground motions addressed in these studies included peak horizontal ground acceleration, response spectra, and the duration of strong shaking. The assessment was made for preliminary maximum credible earthquakes on the known faults with recent displacement in the site region. The results of this assessment are presented in Section 12.

1.11 - Conclusions

Two sets of conclusions have been drawn from the results of the investigation conducted to date. One set, designated feasibility conclusions, are those considered important to evaluate the preliminary feasibility of the Project. The second set, designated technical conclusions, are those related to the scientific data collected. Both sets of conclusions are discussed in Section 13 and form the basis for the proposed 1981 study plan (summarized below in Section 1.12). The feasibility conclusions are summarized in this section; they include:

(a) No faults with known recent displacement (displacement in the last 100,000 years) pass through or adjacent to the Project sites.

(b) The faults with known recent displacement closest to the Project sites are the Denali and Castle Mountain faults. These faults, and the Benioff zone associated with the subducting Pacific Plate (at depth below the Project site), are considered to be accepted seismic sources.

(c) Preliminary maximum credible earthquakes for the Denali and Castle Mountain faults and the Benioff zone have been estimated as a: magnitude (M_S) 8.5 earthquake on the Denali fault occurring 40 miles (64 km) from the Devil Canyon site and 43 miles (70 km) from the Watana site; magnitude (M_S) 7.4 earthquake on the Castle Mountain fault occurring 65 miles (105 km) from the Devil Canyon site and 71 miles (115 km) from the Watana site; and magnitude (M_S) 8.5 earthquake on the Benioff zone occurring 37 miles (60 km) from the Devil Canyon site and 31 miles (50 km) from the Watana site.

(d) Within the site region, 13 faults and lineaments have been judged to need additional investigation to better define their potential affect on Project design considerations. These 13 faults and lineaments (designated significant features) were selected on the basis of their seismic source potential and potential for surface rupture through either site. Four of these features are in the vicinity of the Watana site and nine are in the vicinity of the Devil Canyon site.

(e) At present, the 13 significant features are not known to be faults with recent displacement. If additional seismic geology studies show that any of these features is a fault with recent displacement, then the potential for surface rupture through either site and the ground motions associated with earthquakes on such a fault will need to be evaluated.

(f) Preliminary estimates of ground motions at the sites were made for the Denali and Castle Mountain faults and the Benioff zone. Of these sources, the Benioff zone is expected to govern the levels of peak horizontal ground acceleration, response spectra, and duration of strong shaking. The ground-motion estimates are preliminary in nature and do not constitute criteria for design of project facilities. The site ground-motion estimates will be made final and the design criteria will be developed as part of the next phase of study.

1.12 Proposed 1981 Study Plan

The proposed study plan is designed to provide additional data on the seismologic setting of the Project, on the geologic characteristics of the 13 significant features, and for earthquake ground motion studies. These data are needed: to evaluate faults with crustal sources of seismicity; to refine the evaluation of reservoir-induced seismicity; to obtain additional data on recent geologic units and morphologic surfaces that can be used for assessing the recency of fault displacement; and to evaluate whether or not the significant features are faults with recent displacement (and, if they are, to provide as much information as possible on the recurrence intervals, amount of displacement, and maximum credible earthquake). In addition, the study plan will incorporate the results of the geologic investigation in a refined analysis of ground motions at the sites and will develop ground motion design criteria.

The proposed study plan is expected to be evolutionary in nature. Therefore, the details of the plan, presented in Section 14 and summarized below, may change during the course of the 1981 studies. The plan is to:

(a) Conduct a detailed Quaternary geology investigation.

(b) Conduct field geologic studies of the 13 significant features. These studies will include additional air photo analysis and field mapping in appropriate locations. These studies may also include test pits, trenches, geophysical traverses, borings, and age dating.

(c) Obtain and analyze low-sun angle aerial photography around both sites and along portions of the Talkeetna thrust fault and Susitna feature.

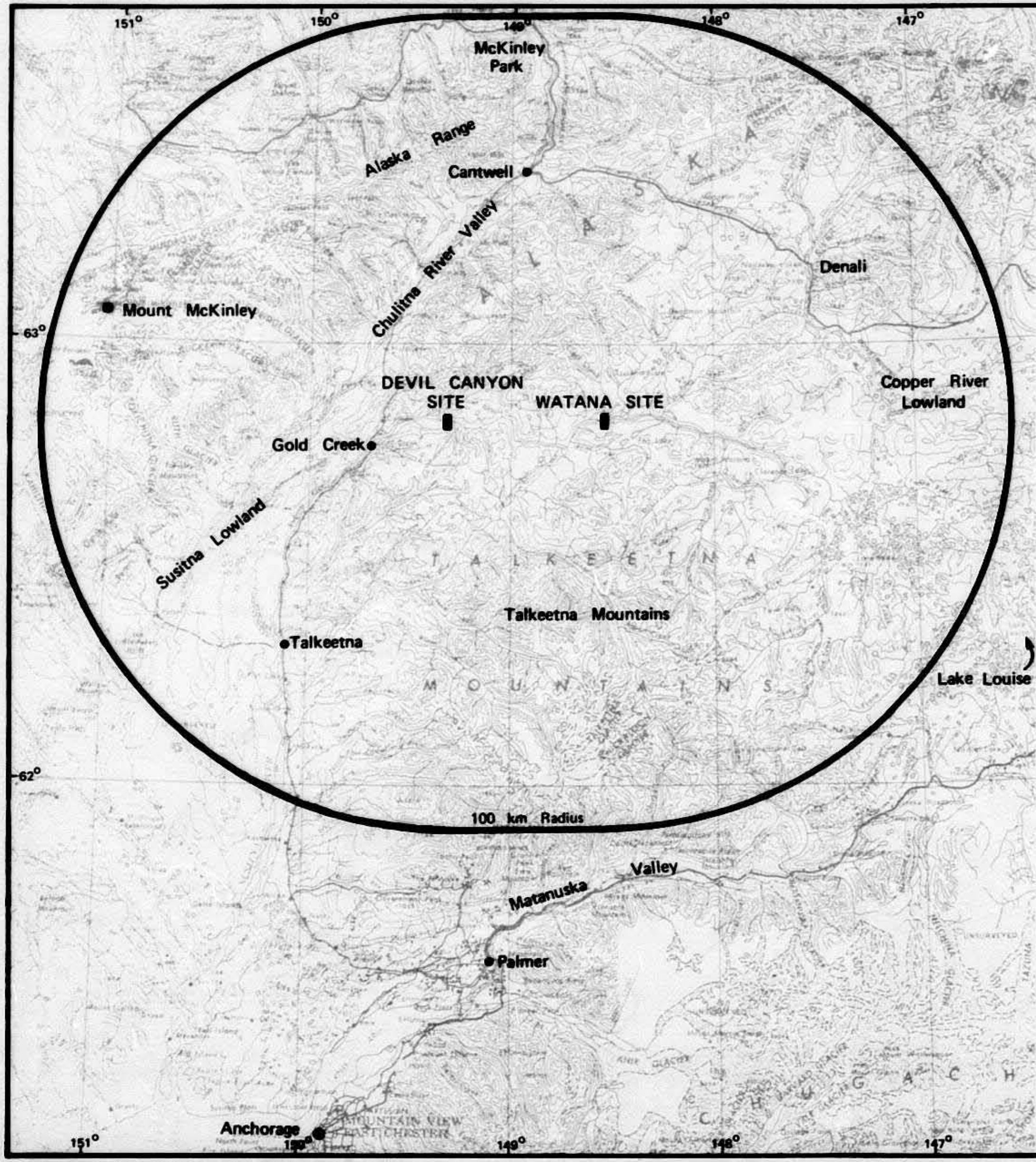
(d) Conduct calibration studies along faults with recent displacement (e. g., either the Denali or Castle Mountain faults). The calibration can include field mapping, air photo analysis, and trenching.

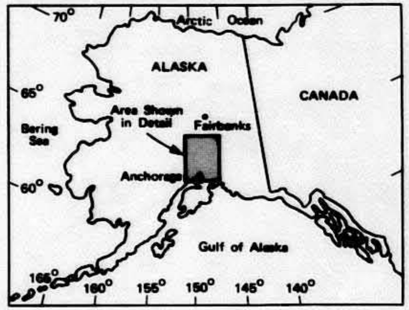
(e) Design a program manual for future seismologic network monitoring.

(f) Re-evaluate the estimated potential for reservoir-induced seismicity using the data obtained from the other portions of the 1981 study plan.

(g) Finalize the ground-motion estimates for the Project (after the seismic geology field studies are performed to assess the seismic activity of the significant features).

(h) Develop project earthquake ground-motion design criteria based on the results of the ground-motion evaluations.





NOTE

1. Physiographic areas after Wahrhaftig (1965).

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LOCATION MAP

0 10 20 30 40 Miles

0 10 20 30 40 50 Kilometers

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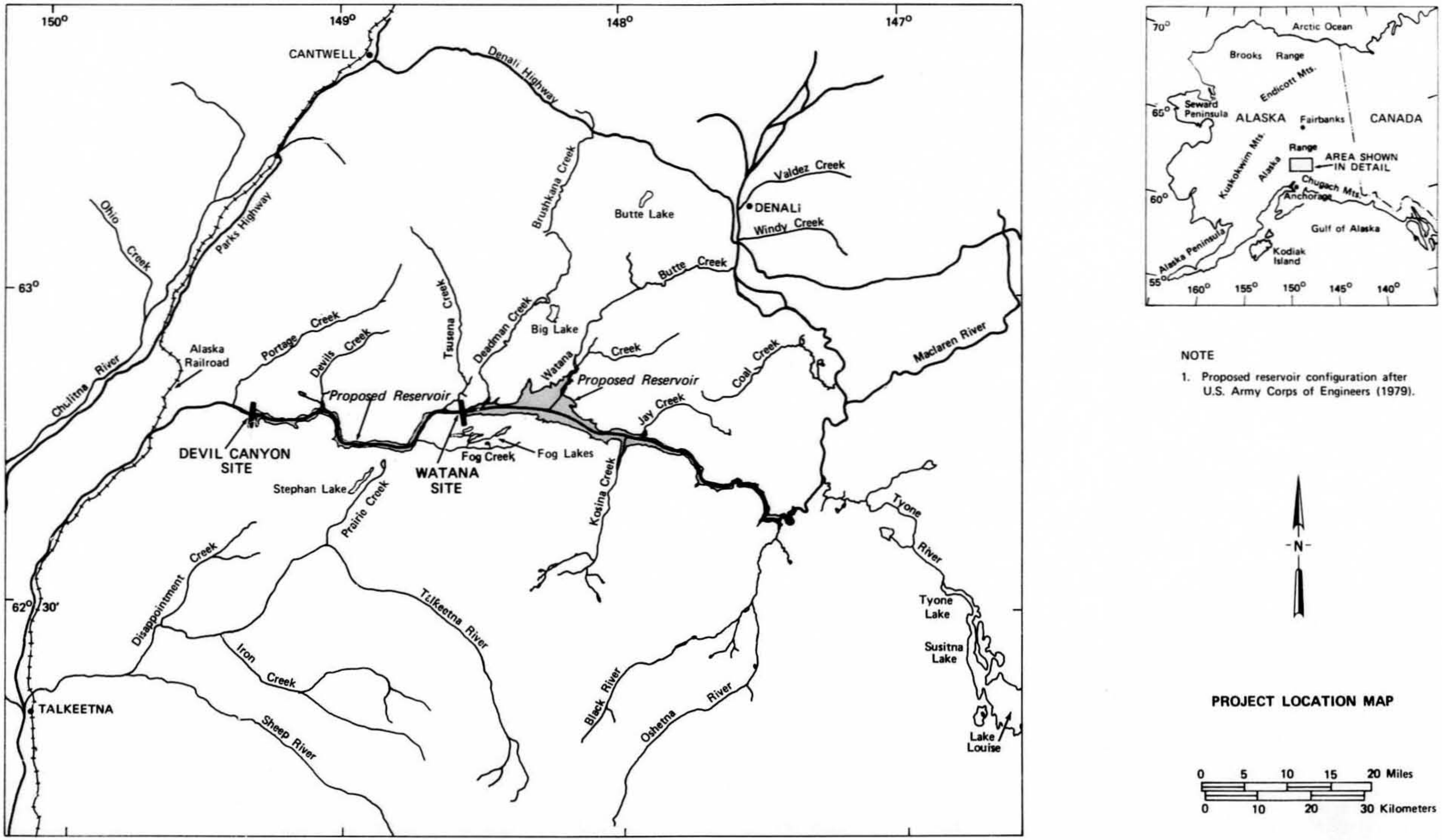
FIGURE 1-1



NOTE

1. Proposed reservoir configuration after U.S. Army Corps of Engineers (1979).

PROJECT LOCATION MAP

2 - INTRODUCTION

2.1 - Project Description and Location

According to present conceptual plans the Susitna Hydroelectric Project (referred to hereafter as the Project) includes two dams and reservoirs in the Talkeetna Mountains of south-central Alaska (Figure 1-1). The present study to evaluate the feasibility of the Project was authorized by the Board of Directors of the Alaska Power Authority (APA) on 2 November 1979. Acres American Inc. (AAI) was selected by the Alaska Power Authority to conduct the feasibility study. A Plan of Study (POS) was developed by AAI which identified the scope of services to be conducted for the feasibility study (Acres American Inc., 1980). The overall objectives of the feasibility study are to:

(1) Establish technical, economic, and financial feasibility of the Project to meet future power needs of the Railbelt Region of the State of Alaska;

(2) Evaluate the environmental sequences of designing and constructing the Susitna Project; and

(3) File a complete license application with the Federal Energy Regulatory Commission.

Woodward-Clyde Consultants is one of a six-member team of consultants assembled by AAI to meet the objectives of the study. The objectives and scope of participation in the feasibility study by Woodward-Clyde Consultants are described below in Sections 2.2 and 2.3.

The Project is located on the Susitna River, 50 miles (80 km) northeast of Talkeetna, Alaska, in the Talkeetna Mountains (Figures 1-1 and 1-2). The Devil Canyon site will be located at river mile 133 (62.8° north latitude, 149.3° west longitude); the Watana site will be located at river mile 165 (62.8° north latitude, 148.6° west longitude). This report encompasses the region within 62 miles (100 km) of either site. Thus, the Project site region includes the Talkeetna Mountains, the north-central portion of the Alaska Range, and portions of the Susitna and Copper River lowlands (Figure 1-1).

The Project, as presently planned, involves two dams on the Susitna River (Figures 1-1 and 1-2). Downstream will be the Devil Canyon site which is presently planned to include a concrete arch dam having a structural height of approximately 635 feet (194 meters) with an estimated maximum water depth of 545 feet (166 meters). The impounded reservoir will be approximately 28-miles long (45 km) with a storage capacity of approximately 1,050,000 acre feet (1,296 x 10^6 m^3). Upstream will be the Watana site which is presently planned to include an earthfill or rockfill dam having a structural height of approximately 810 feet (247 meters) with an estimated maximum water depth of 725 feet (449 m). Its impounded reservoir will be approximately 54 miles (87 km) long with a storage capacity of 9,624,000 acre feet (11,876 x 10^6 m^3) (U. S. Army Corps of Engineers, 1978).

A transmission line, approximately 365 miles long (588 km), is planned to connect the power plants at the dam sites with existing transmission lines. Several tunnel alignments from the Watana site to the vicinity of the Devil Canyon site are being considered on a preliminary basis. However, no conceptual details are available on the tunnel alternative at the time of this report.

2.2 - Objectives

The responsibility of Woodward-Clyde Consultants for the Project feasibility study is defined in the Plan of Study (POS) prepared by AAI and issued by the Alaska Power Authority in February, 1980. The objectives of the POS are to:

(a) Determine the earthquake ground motions which will provide the seismic design criteria for major structures associated with the Project;

(b) Undertake preliminary evaluations of the seismic stability of proposed earth-rockfill and concrete dams;

(c) Assess the potential for reservoir-induced seismicity and landslides; and

(d) Identify soils which are susceptible to seismically induced failure along the proposed transmission line and access routes.

A series of subtasks were identified to meet these overall task objectives. The subtasks were established to provide the geologic, seismologic, and earthquake engineering data needed to assess the feasibility of the Project. The subtasks and their corresponding objectives are:

Subtask No.	Subtask Title	Objective
4.01	Review of Available Data	To acquire, compile, and review existing data and to identify the earthquake setting of the Susitna River.
4.02	Short Term Seismology	To establish an initial monitoring system, obtain and analyze basic seismologic data on potential earthquake sources within the Susitna River area, and to supply information required to implement a more thorough long-term monitoring program.

4.03	Preliminary Reservoir-Induced Seismicity	To evaluate the potential for the possible future occurrence of reservoir-induced seismicity (RIS) in the Project area.
4.04	Remote Sensing Image Analysis	To select and interpret available remote sensing imagery to identify topographic features that may be associated with active faulting.
4.05	Seismic Geology Reconnaissance	To perform a reconnaissance investigation of known faults in the Susitna River area and of lineaments that may be faults, to identify active faults, and to establish priorities for more detailed field investigations.
4.06	Evaluation and Reporting	To complete a preliminary evaluation of the seismic environment of the project, to define the earthquake source parameters for earthquake engineering input in design, and to document studies in reports suitable for use in design studies.
4.07	Preliminary Ground Motion Studies	To undertake a preliminary estimate of the ground motions (ground shaking) to which proposed Project facilities may be subjected during earthquakes.
4.08	Preliminary Analysis of Dam Stability	To make preliminary evaluations of the seismic stability of proposed earth, rockfill, and/or concrete dams during maximum credible earthquakes.

The results of subtasks 4.01 through 4.05 are presented in this report (as part of subtask 4.06) and have been used to provide input to subtask 4.07. This latter subtask addresses objective (a) and is discussed in Section 12. Limited consultation has been provided by Woodward-Clyde Consultnats to Acres for Objective (b) and is not included as a part of this report. Objective (c) is addressed by subtask 4.03, with results presented in Section 10. Objective (d) is scheduled to be evaluated in 1981; consequently, it has not been addressed during this investigation.

It should be emphasized that the results presented in this report have been developed solely for the purpose of evaluating Project feasibility. These results are subject to revision after completion of 1981 studies and therefore are not intended for use in final dam design considerations.

The data provided by this report are expected to be used in the application for the Federal Energy Regulatory Commission (FERC) license and in documentations submitted to the U. S. Army Corps of Engineers and the State of Alaska. This application will be made by Acres American Inc. on behalf of the Alaska Power Authority.

2.3 - Scope

The 1980 study, as part of a planned two-year investigation and as summarized in this report, was designed and conducted to provide data for seismic design feasibility considerations. After project feasibility has been satisfactorily established, the 1981 study will evaluate specific features and seismic conditions pertinent to seismic design. In this report, the work conducted during the first year will be referred to by the term "study." The term "investigation" will be used for the two-year program.

The multidisciplinary approach being utilized for this investigation involves an interactive team of structural geologists, Quaternary geologists, seismologists, and earthquake engineers. Their task is the analysis of potential seismic sources, recency of fault displacement, and surface rupture potential. The subtask objectives (Section 2.2) incorporate this approach into a detailed scope and work plan. The following discussion summarizes the implementation of that detailed scope for subtasks 4.01 through 4.08.

The scope of those subtasks included:

(a) the compilation of information for all faults and lineaments reported in the literature within 62 miles (100 km) of either dam site, for major faults with recent displacement in or adjacent to the site region, and for all lineaments interpreted by Woodward-Clyde Consultants which have morphologic relationships that may be fault related;

(b) the compilation of historic earthquake data which could then be used to understand the seismic setting of the Project and to better define differences in the seismic characteristics between crustal earthquakes and the Benioff zone;

(c) a geological field study to ascertain, on a reconnaissance level, which features in the site region are, or potentially are, faults with recent displacement;

(d) the installation and operation of a 10-station microearthquake network within a 30-mile (48-km) radius about each proposed site to monitor seismicity in the vicinity of the sites, to provide information on crustal sources of seismicity and the depth to the Benioff zone, and to provide information on attenuation characteristics associated with crustal and Benioff zone sources;

(e) a preliminary comparison of the depth, volume, and geologic characteristics of the proposed reservoirs with those of other reservoirs that are deep, very deep, and/or very large (including those with accepted cases of reservoir-induced seismicity) in order to make a preliminary estimate of the likelihood of reservoir-induced seismicity and of the likelihood that an earthquake of a given magnitude can occur;

(f) a preliminary assessment of the potential for reservoir-induced landslides;

(g) development of preliminary estiamtes of ground motions at the Project sites from preliminary maximum credible earthquakes in the site region;

(h) development of a proposed 1981 study plan to improve understanding of the structural and seismic setting of the site region and to refine the judgments needed for seismic design; and

(i) preparation of this interim report to summarize the results of the 1980 study.

Completion of the scope of the 1980 study involved approximately a 60 person-month level of effort. This included: approximately 15 person-months for the data compilation, items (a) and (b) above; 25 person-months for the field studies, items (c) and (d) above; and 20 person-months for data analysis and report preparation, items (e) through (i) above.

2.4 - Fault Study Rationale

2.4.1 - Conceptual Approach

The earth's crust is comprised of a series of plates that are moving relative to one another. Although the mechanism responsible for this movement is not completely understood, a variety of interactions between plates can occur as a result of this movement. These interactions can include: collision, with resultant subduction (underthrusting) of one plate beneath another; extension, where adjacent plates move away from each other; or shearing, where adjacent plates pass each other at different relative rates. Examples of these types of interactions are discussed by a number of investigators including Wilson (1963), Dewey (1972), Cowan and Silling (1978) and Scholl and others (1980).

The type of plate interaction depends on a number of factors, such as the relative rate of movement of adjacent plates, the relative direction of these plates, and the type of crust involved (i. e., oceanic or continental). In the case of collision between two crustal plates (one of continental and the other of oceanic crust), the plate with the heavier oceanic crust typically is subducted (underthrust) beneath the continental crust. Eventually, this subducting plate falls or is thrust downward into the upper mantle and becomes detached (or disengaged) from the overriding plate.

Where subduction is occurring, the subduction process generates tectonic stress (a) within the downgoing plate, (b) within the overriding crustal plate, and (c) along the interface between the two plates where they are in contact with one another. The stress is stored as accumulated strain energy. When the elastic limit of crustal material within or between the plates is reached, failure (fault rupture) occurs, releasing the accumulated energy along planes of weakness (faults) in an earthquake. Thus, earthquakes occur as the result of rapid displacement along fault planes. The instantaneous release of energy (the earthquake) occurs in part in the form of seismic waves which are propagated through the earth's crust and mantle and which result in ground motion, commonly referred to as earthquake shaking.

Faults are typically subject to repeated displacements as long as the tectonic stress environment remains unchanged. Therefore, faults which show evidence of recent displacement are assumed to have the potential for future displacement. These faults are subject to surface rupture when the energy released is at a sufficiently shallow depth that the fault rupture plane intersects the ground surface. When the energy release occurs at depth, and when the energy release is small relative to the depth of occurrence, the fault rupture plane exists at depth and does not rupture the surface of the crust. Further, for displacement slippage along fault planes in the subducting plate and along small fault planes at depth in the overriding crustal plate, the fault rupture plane does not reach the ground surface. Therefore, movement along these faults does not affect consideration of surface fault rupture potential at a given location. However, movement along these faults may affect seismic design considerations. This effect can be evaluated from the historical seismicity records and from theoretical considerations. From this evaluation, the size earthquake that can be expected to occur can be estimated and the size of the fault rupture plane can be inferred.

For faults in the overriding crustal plate, along which energy release is sufficiently large and shallow to rupture the ground surface, the following factors affect consideration of these faults.

During geologic time, the movements between plates may change, resulting in a changed tectonic stress environment. When exposed to a new tectonic stress environment, some of these pre-existing faults may serve as planes of weakness along which slippage may continue to occur; other pre-existing faults will no longer be the location of slip, although they continue to be zones of weakness in the crust. Thus, at a given location during a specific period of geologic time, displacement along faults, resulting in earthquakes, is controlled by the stress environment influencing that part of the crust at that time.

The type of displacement that can occur along a fault is a function of the orientation of the prevailing stress regime relative to the orientation of the faults and the plane in which strain release can be most readily accommodated. Figure 2-1 shows the various components of displacement or slip which can occur along a fault together with applicable terminology. The three primary types of faults are thrust or reverse, normal, and strike-slip or shear faults (Figures 2-2 through 2-4).

Faults with recent displacement can occur as relatively simple, individual traces along which displacement occurs (primarily strike-slip faults) or as a complex pattern of fault traces within a fault zone (primarily reverse and normal faults). Within fault zones, some traces or planes can be undergoing recent displacement while the rest of the zone is quiescent with no recent displacement (as shown in Figure 2-5).

The frequency of the cyclic elastic strain buildup and release by fault rupture varies greatly from one part of the earth's crust to another. The interval between earthquakes on the same fault or fault system is potentially long. However, the available worldwide historical records, which may encompass several hundred years of surface rupture and earthquakes, typically do not cover a long enough period to forecast reliably the location or frequency of future surface rupture and associated earthquakes. Often, the most informative record of historical surface rupture and associated earthquakes is best preserved in surficial materials cut by the faults. If the stratigraphic record is complete and observable and if the ages of surficial materials, especially of the Quaternary period, are known, then the most recent geologic information on past tectonic stress environments and past earthquake activity can be deduced. Therefore, the most reliable approach to evaluating potential surface rupture and earthquake potential is one that relies substantially on understanding the geologic record of the past tens of thousands to millions of years.

Surface rupture and the related earthquake potential at a given location in the earth's crust or lithosphere can be evaluated by using the concept of faults with recent displacement. This concept, as it is most commonly applied, relies on the history of the surface fault rupture (or displacement); if displacement has occurred on a fault within a specified time, the fault is classified as having recent displacement. Faults with recent displacement (as defined for a particular project), are then inferred to have a potential for surface rupture and earthquakes. This potential is then considered in the design of that project. Guidelines defining what is considered "recent displacement" for this project are described in Section 3.1.2.

A fault which has been subject to frequently occurring and large recent displacement appreciably affects the surface geology and topography. In such an area, it is improbable that all evidence of young faulting would be completely obliterated by weathering, erosion, and deposition. A fault that has been subject to relatively infrequent and small displacement may not greatly affect the landscape, and the evidence of geologically young faulting may be difficult to detect and to evaluate. However, experience during the past decade or so has indicated that the exceptional case is the one for which no evidence of fault activity can be found, provided detailed studies are completed by geologists experienced in assessment of fault activity (Sherard and others, 1974).

Incomplete preservation of diagnostic geomorphic features and of stratigraphic evidence along a given length of fault requires that investigations designed for identifying and evaluating faults with recent displacement be regional in scope. Individual faults should be traced for considerable distances in order to evaluate adequately the tectonic setting and the amount, style, age, and frequency of past displacements.

Incomplete evidence for conclusive evaluation of fault activity along short portions of faults is a common problem in Alaska. Critical stratigraphic evidence may often be destroyed or buried where a fault trends along or crosses a river valley; this is because of intense erosion or rapid deposition that can occur near rivers or in a fluvial basin. Another common problem in Alaska is that geomorphic evidence of faulting may be covered or masked by glacial or periglacial processes. In addition, the surficial materials deposited in river valleys, such as in the Susitna River valley, often are not old enough to be evaluated effectively for recent fault displacement.

Sometimes adequate evaluation of recent fault displacement can only be made with confidence at locations remote from Project sites; in these areas, which are away from the area of active erosion and deposition, the stratigraphic and geomorphic evidence necessary for a confident assessment of fault activity is preserved. When no conclusive evidence of recent displacement is observed along faults in the vicinity of the sites, it is reasonable to apply (to these faults) an understanding of the characteristics of geologically similar faults that are remote from the site. In this way, the recency of displacement on faults that are present in the vicinity of Project sites can be evaluated. The degree of confidence in such evaluations depends upon the quality, quantity, and strength of the evidence; this evidence may vary from fault to fault and from location to location.

Procedures generally used for the regional evaluation of recent fault displacement include a multidisciplinary review of literature, interpretation of regional remotely sensed data (i.e., U-2 near-infrared color photography, satellite imagery, and geophysical data), and review of historical seismicity data. Features that are potentially of interest to the Project are then reviewed in detail on the aerial photographs.

Surface faults that have had displacement in recent geologic time are expressed in youthful units by characteristic geomorphic features such as scarps, linear vegetational patterns, groundwater barriers, and lithologic contrasts. These features which are visible on aerial photographs, are usually expressed in linear or semilinear configurations (referred to as lineaments), and are visible during aerial reconnaissance. However, lineaments are also produced by other erosional, depositional, structural, or cultural processes.

After preliminary results are obtained from the above procedures, additional investigations can be conducted for selected features as appropriate. These investigations can include reconnaissance and/or detailed field mapping, aerial reconnaissance, Quaternary geology studies, age-dating of selected units, trenching, drilling, or the installation of microearthquake networks.

The interpretation of the results of these investigative procedures forms the basis for: delineating faults with recent displacement; estimating the amount and type of displacement; and estimating the size of the maximum credible earthquake that might be expected during displacement along an individual fault.

There are major constraints limiting the observation of faults with recent displacement in the Talkeetna Mountains. These constraints include: (a) youthful geologic processes, primarily glaciation; (b) a lack of information on the glacial deposits in the Talkeetna Mountains; and (c) the lack of detailed bedrock and surficial mapping within the Talkeetna Mountains.

The youthful geologic processes involve primarily recent widespread glacial events that tend to obliterate or remove older Pleistocene units, soil horizons, and morphologic features. The result is widespread youthful deposits and surfaces that provide information on fault activity only in the most recent geologic time (i. e., the last 10,000 years). The absence of detailed glacial and bedrock data in the Talkeetna Mountains makes the evaluation of faults and faults with recent displacement difficult, because the information necessary to understand the faults is lacking.

2.4.2 - Surface Rupture and Earthquake Magnitudes

Several authors have investigated the relationship between earthquake size and length of fault rupture (Tocher, 1958; Bonilla and Buchanan, 1970; Patwardhan and others, 1975; Slemmons, 1977). On the basis of their work, it appears that surface rupture is typically associated with shallow earthquakes of magnitude (M_S) 5.5 or greater, although earthquakes of smaller magnitude have been associated with surface rupture (e. g., the Imperial, California, (M_S) 3.6 earthquake of March, 1966, which was associated with 0.6 inches (1.5 cm) of displacement (Slemmons, 1977). On the basis of the available data, and to be reasonably conservative, a magnitude of (M_S) 5 was selected as the lower magnitude value for earthquakes having the potential for associated surface rupture.

Albee and Smith (1966) have plotted length of observed surface faulting (or long axis of aftershock area) versus magnitude. Their best fit curve suggests that at least a 5-mile (8-km) long rupture length would be necessary for an earthquake greater than magnitude (M_S) 5 to occur. However, events of higher magnitude are shown to have occurred on faults with as little as 0.6 miles

(1 km) of rupture length. Slemmons (1977) in his evaluation of earthquakes, faults, surface rupture, and displacement shows 3 miles (5 km) as generally being the shortest rupture length on which events of magntiude (M_S) 5 or larger have occurred (although one event, the 1951 Superstition Hills, California, event of magnitude (M_S) 5.6 had 2 miles (3 km) of surface rupture length). Considering the Slemmons (1977) and Albee and Smith (1966) data, we assume that approximately a 3-mile (5-km) long surface rupture length is necessary to generate a magnitude (M_S) 5 or larger earthquake.

For the purposes of this study, it is assumed that the observed length of a lineament or fault represents half the potential length of a fault and the observed length represents the maximum probable rupture length should the fault have recent displacement (the rationale for this concept is presented in Section 3.2). The observed lineament or fault length, (i. e., the potential rupture length) has been used to evaluate seismic source potential and to infer the maximum amount of displacement that could occur during a single earthquake. This approach introduces a relatively large degree of conservatism to the study. Typically, the maximum potential rupture length of a fault during a single event is assumed to be one-half of the observed fault length (as discussed in Wentworth and others (1969)).

2.5 - Method of Study

The methodology employed for the seismic geology study is summarized in Figure 2-6 and is described below. Information of a geologic (including geomorphic) and seismologic nature was evaluated to identify previously reported faults and lineaments that may be fault-related in the area within 62 miles (100 km) of the Project (Figure 1-1). The methodology associated with both the geological and seismological portions of the investigation are described below.

The geological portion of the investigation included: a comprehensive review of the literature (approximately 350 references were reviewed); discussions with other geologists familiar with the study area; interpretation of selected remotely sensed data (approximately 250 images and aerial photographs were reviewed); aerial reconnaissance; and limited field studies of the identified lineaments and faults that are within 62 miles (100 km) of the Project. The locations of lineaments, faults, and inferred faults derived from the literature review and from discussions with other geologists were plotted on a 1:250,000-scale topographic base for the study area. Lineaments considered to be possibly fault-related were interpreted on high-altitude color-near-infrared photographs (scale 1:125,000) and on LANDSAT imagery (scale 1:1,000,000 and 1:500,000). The coverage of imagery and photography used for this study is shown in Appendix A. These data were plotted on the photograph or image on which they were observed.

For the identification of potential seismic sources, length-distance screening criteria were developed to select only those faults and lineaments for further evaluation which potentially could be of concern for seismic design. These criteria were based on available worldwide data on faults with recent displacement, associated maximum magnitude earthquakes, and an attenuation relationship applicable to the western United States (the latter is discussed in Section 12). The length-distance screening criteria and the rationale behind their development are discussed in detail in Section 3.2.

Features which were long enough and close enough to the site to meet the length-distance screening criteria were plotted on 1:250,000 scale field maps. In addition, to evaluate potential surface rupture in the vicinity or through the sites, all faults and lineaments that passed within 6 miles (10 km) of either site were plotted on a 1:63,360 scale topographic base map and on U-2 color near-infrared photographs at a scale of 1:125,000. These features were then evaluated during the field reconnaissance.

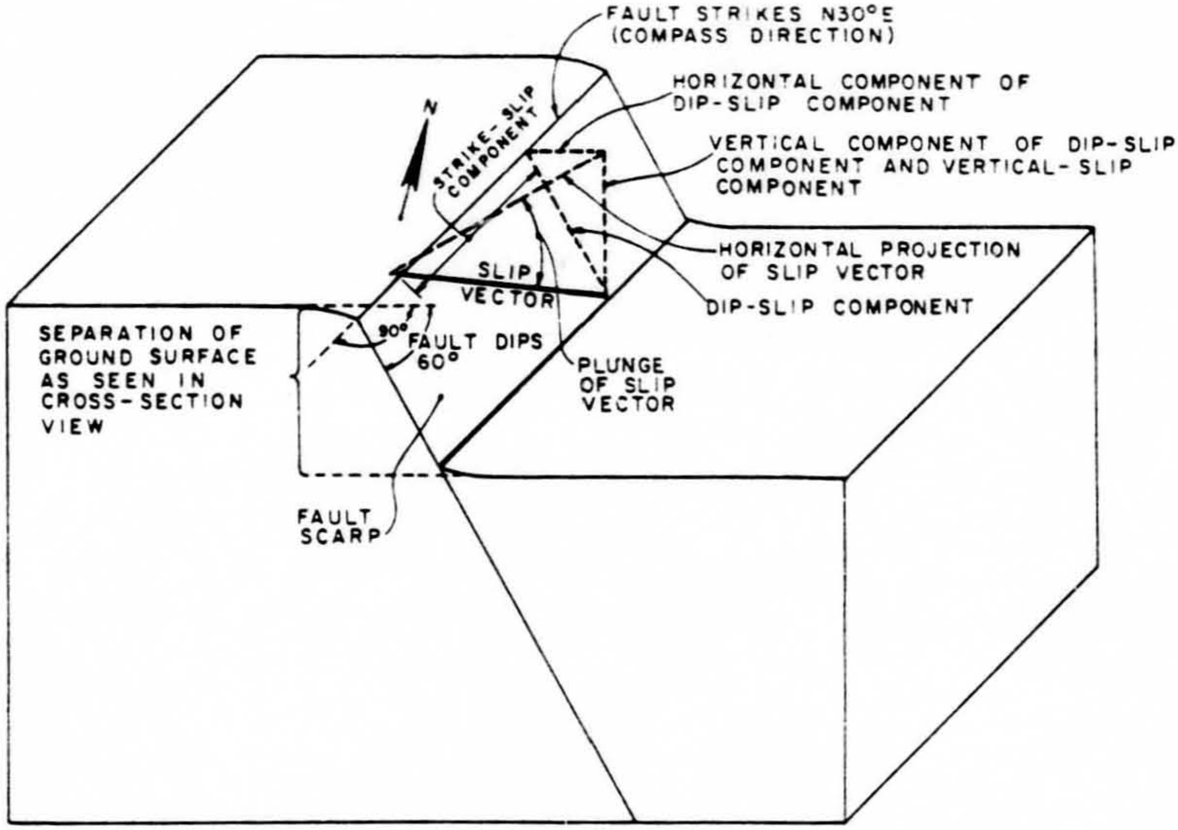
During the field reconnaissance, each fault and lineament was examined for characteristics indicative of faulting and recent displacement. The field reconnaissance involved helicopter and fixed-wing aerial reconnaissance of all faults and lineaments within the site region which were considered to be potentially significant to the sites. The aerial reconnaissance included systematic review of all quadrangles within the site region to locate faults or lineaments which were not identified previously. Ground reconnaissance studies were conducted at selected locations along specific lineaments to augment observations made during the aerial reconnaissance. Observations were documented in writing and in photographs as described in Appendix A. The purpose of this part of the investigation was to ascertain, on a reconnaissance level, which features in the site region are, or potentially are faults with recent displacement. This field effort was conducted from 1 July 1980 through 21 August 1980. The faults and lineaments were classified during the field reconnaissance: as having been subject to recent displacement; as being indeterminate features with a moderate, low to moderate, or low likelihood of recent displacement; or as being nonsignificant, i. e., clearly not a fault. Section 8.2 describes the basis on which the classifications were made.

The seismological input into the lineament and fault evaluation process included a review of available historical and recent earthquake activity and a review of unpublished data obtained from the National Oceanic and Atmospheric Administration (NOAA), the Geophysical Institute at the University of Alaska, and the U. S. Geological Survey. The data were reviewed to assess accuracy and completeness before computer processing and cataloguing. From these data, a catalog was compiled of historical earthquake and microearthquake data which includes all available records. Computer plots of epicenters, at a scale of 1:250,000, were used as overlays to geologic maps and were compared with the 1:250,000-scale compilation of faults and lineaments. The computer plots were checked for clusters or alignments of epicenters that would suggest the presence of a fault. Seismologic data were further analyzed to estimate maximum earthquake magnitudes for seismic clusters and alignments and for recurrence intervals of earthquakes of varying magnitudes. Available earthquake data were also reviewed to assess both the adequacy of the data and the effect of this factor on the seismologic analyses.

A 10-station microearthquake network was installed within a 30-mile (48-km) radius about each proposed site. The network was in operation for three months, from 28 June 1980 through 28 September 1980. Seismograms of earthquakes recorded by the network were used to calculate the size (magnitude), location (epicenter), focal depth, and focal plane mechanism of the earthquakes.

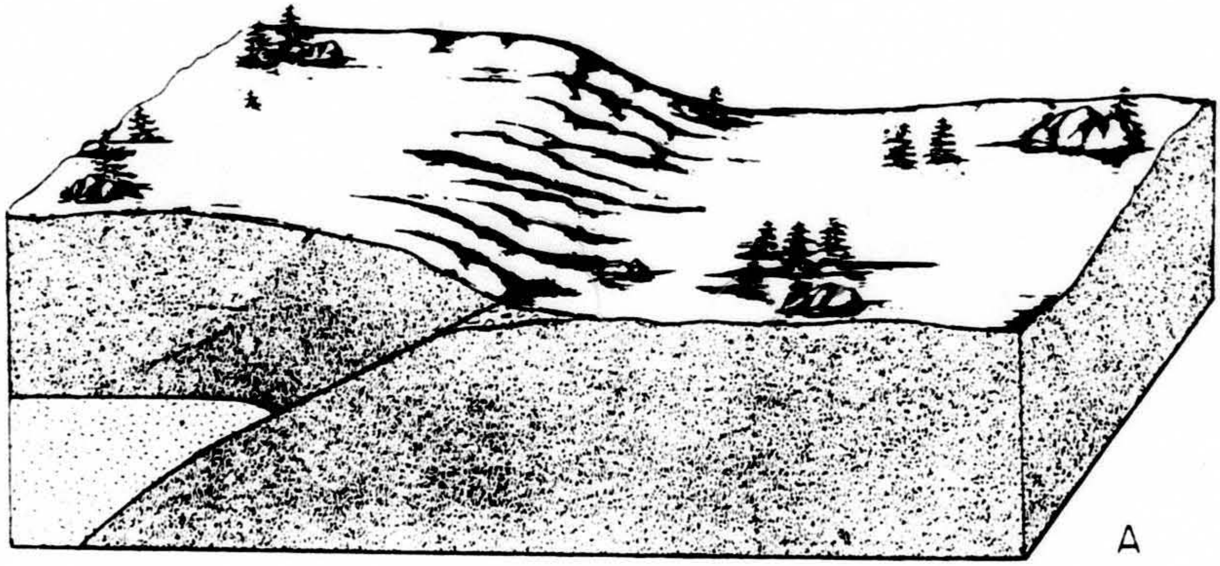
Preliminary analysis of events recorded by the network were made in the field using a portable minicomputer. These preliminary analyses were compiled concurrently with the fault and lineament field studies. This multi-disciplinary approach permitted field evaluation of areas with apparent concentrations of seismic activity to assess whether or not correlations should be made.

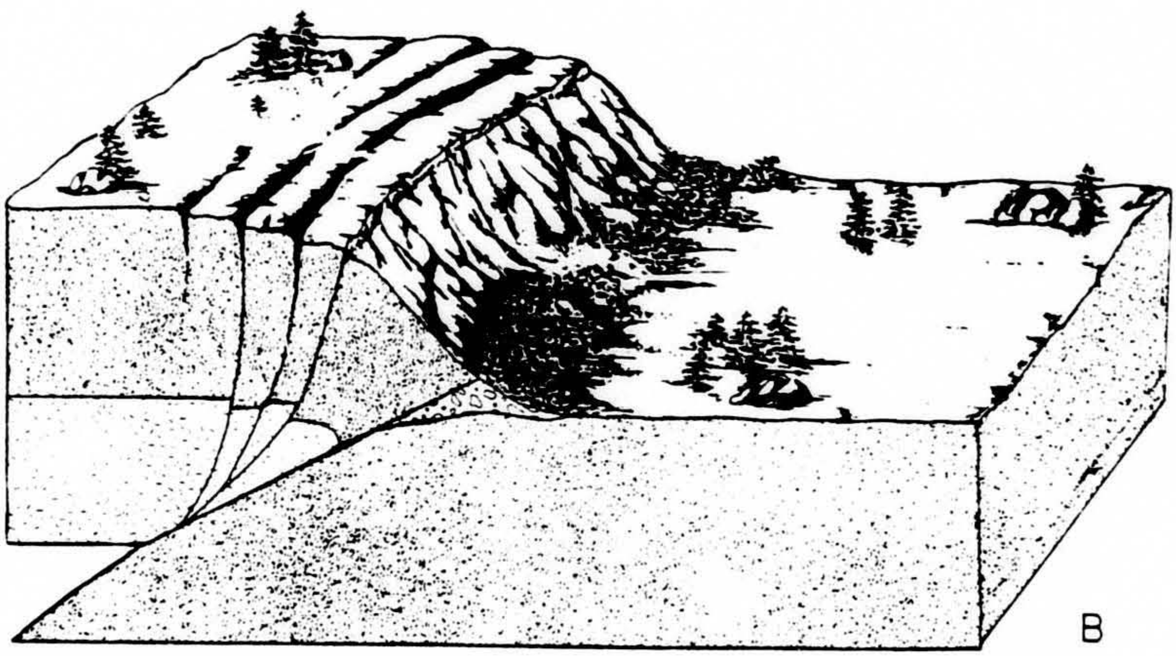
Subsequent to completion of the field studies, the geologic and seismologic data were reviewed and checked for accuracy. The faults and lineaments which were judged to have a potential effect on consideration of seismic design and surface rupture through the sites were selected by use of the criteria described in Section 8.3. The preliminary evaluation of reservoir-induced seismicity was completed using procedures described in Section 10. The results of the data compilation, field studies, and data analyses were then compiled and are presented in this report.



Block diagram illustrating the various components of fault slip. The fault illustrated here is an oblique-slip fault with a left-slip component combined with a normal-slip component. The dip and strike together comprise the attitude of the fault. The slip vector, a line, lies in the fault surface and has a true length that can be designated in terms of a vertical component and a horizontal component. It can also be depicted in terms of its horizontal projection and its angle of plunge.

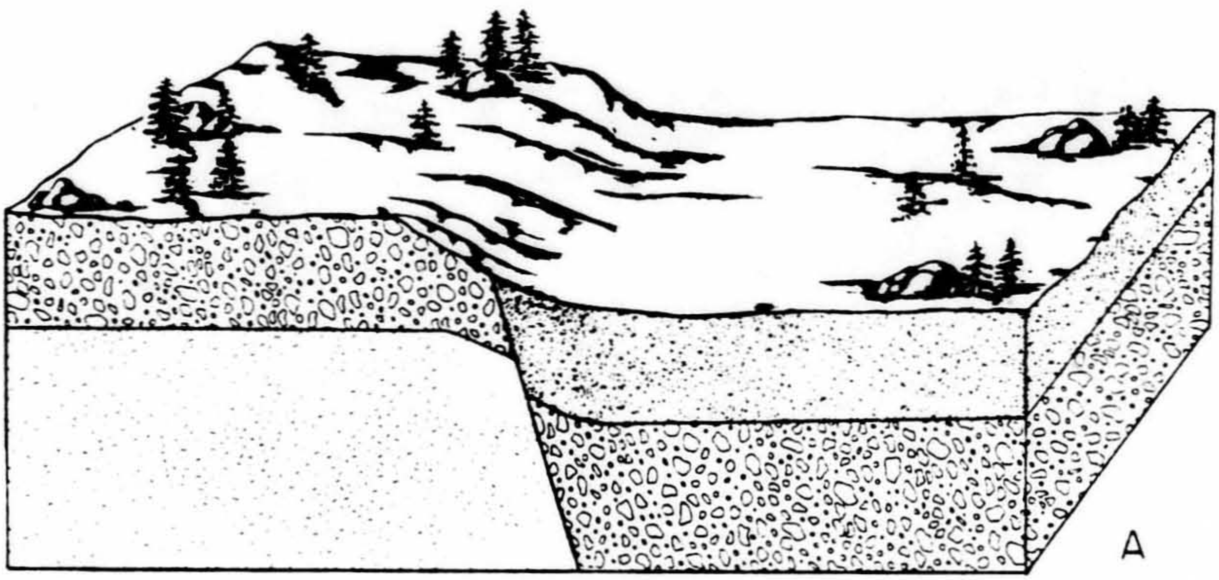
BLOCK DIAGRAM OF VARIOUS FAULT SLIP COMPONENTS

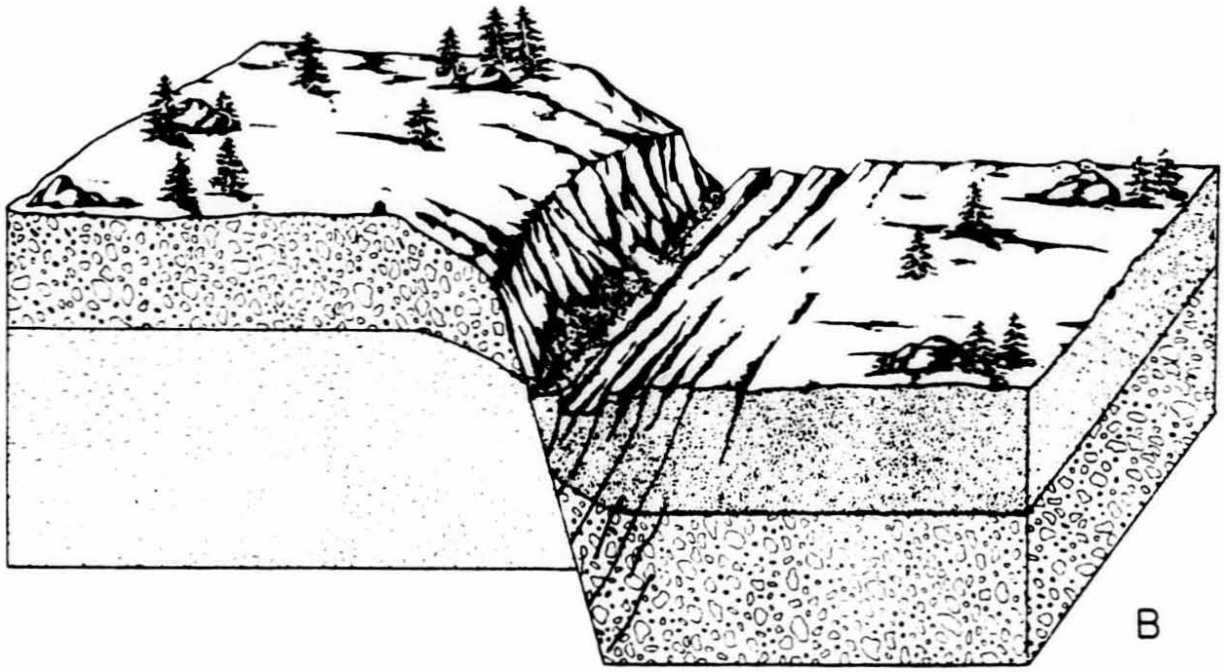




Block diagrams showing schematic effects of shift along a reverse-slip fault: (A) before the most recent shift, (B) after the most recent shift.

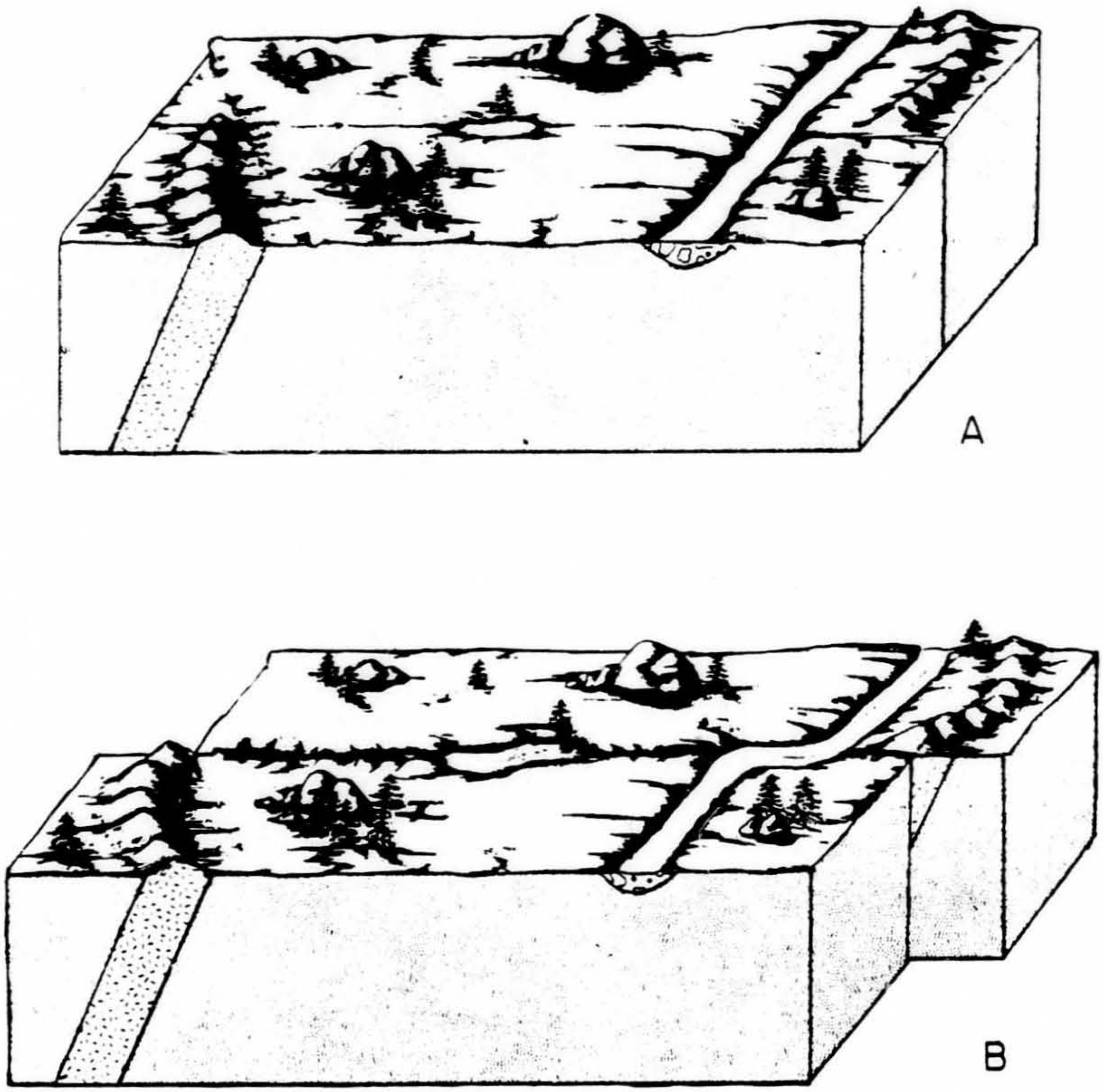
BLOCK DIAGRAMS OF SCHEMATIC EFFECTS OF SHIFT ALONG A REVERSE-SLIP FAULT





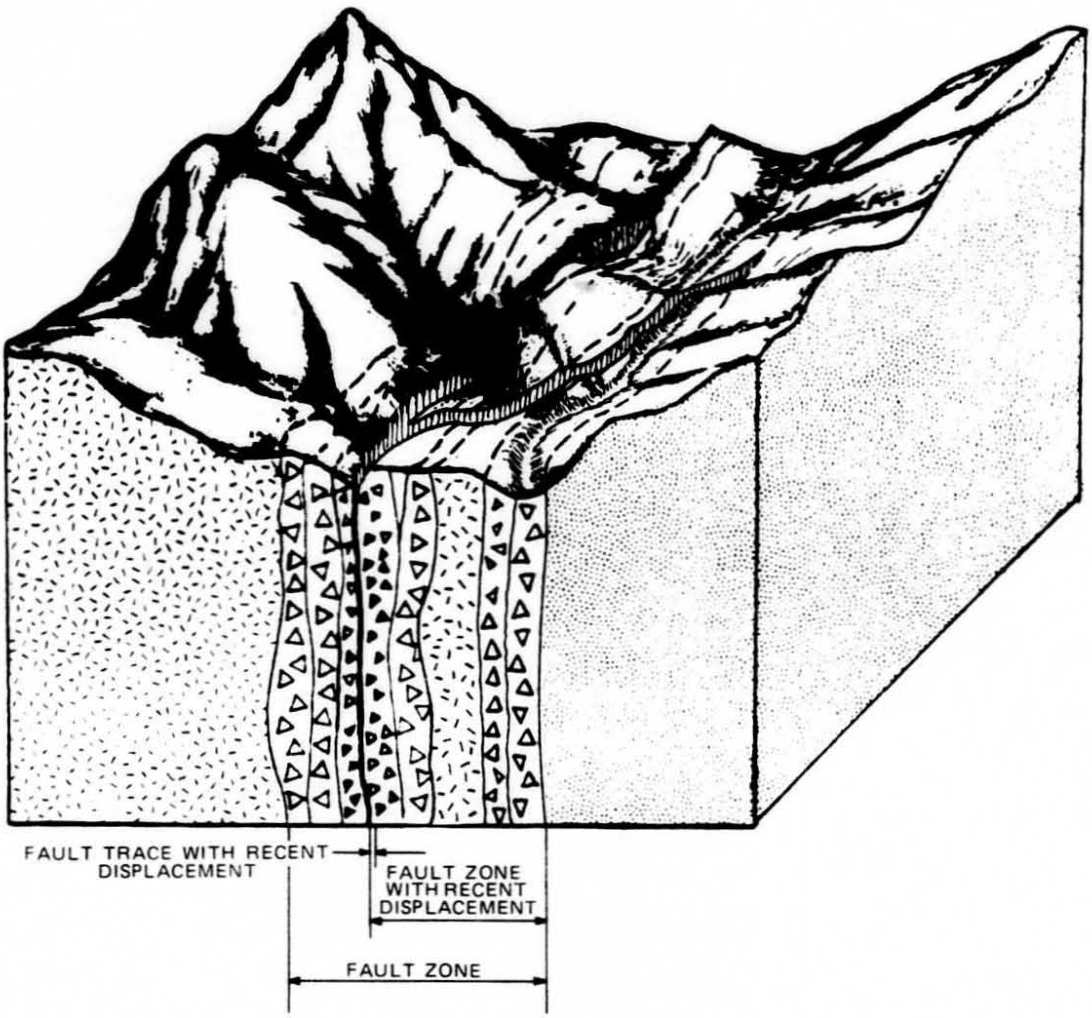
Block diagrams showing schematic effects of shift along a normal-slip fault: (A) before the most recent shift, (B) after the most recent shift.

BLOCK DIAGRAMS OF SCHEMATIC EFFECTS OF SHIFT ALONG A NORMAL-SLIP FAULT



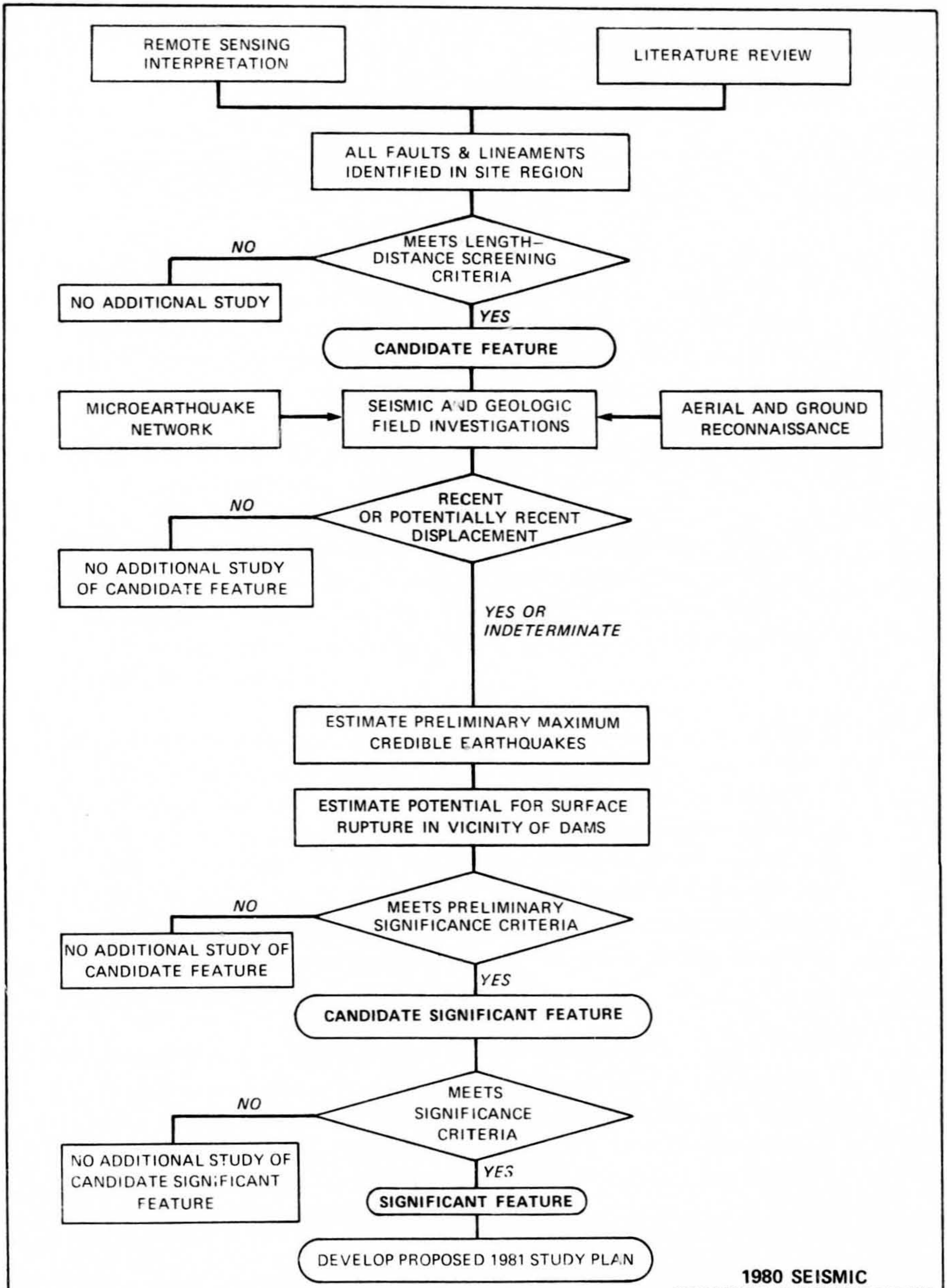
Block diagrams showing schematic effects of shift along a strike-slip fault: (A) before the most recent shift, (B) after the most recent shift.

BLOCK DIAGRAMS OF SCHEMATIC EFFECTS OF SHIFT ALONG A STRIKE-SLIP FAULT



Block diagram illustrating the relationship of a fault zone with recent displacement to a fault zone. This example is a left slip fault. Although the fault zone is composed of several fault planes or traces, the geomorphic features within the fault zone indicate that the most recent surface faulting has occurred along the planes labeled as fault trace with recent displacement. On the basis of geomorphic evidence, the location of potential future surface faulting within this fault zone is judged to be along the planar features labeled as fault trace with recent displacement. The width of the area that potentially could be affected by future surface faulting, is judged to be that of the fault zone with recent displacement.

BLOCK DIAGRAM OF RELATIONSHIP OF A FAULT ZONE WITH RECENT DISPLACEMENT TO A FAULT ZONE



1980 SEISMIC GEOLOGY FLOW DIAGRAM

FIGURE 2-6

3.0 - FAULT EVALUATION CRITERIA AND GUIDELINES

Several sets of criteria and guidelines are typically developed and used during the course of a seismic geology investigation. They provide a systematic method of identifying faults and lineaments which are important to design considerations. For this investigation, four sets of criteria and guidelines have been developed. These sets are:

(1) Guidelines to clarify, for purposes of the Project, the definition of a fault with recent displacement.

(2) Length-distance screening criteria. These were developed prior to the field reconnaissance studies to identify only those faults and lineaments that could potentially be significant to consideration of seismic source potential and/or potential surface rupture through the dam sites.

(3) Preliminary significance criteria, incorporating the results of the field reconnaissance studies. These identify candidate significant features that could potentially be significant to consideration of seismic source potential and/or potential surface rupture through the sites. These criteria represent a refinement of the screening process conducted in (2) above. The refinement is based on the observations made during the field reconnaissance studies and takes into account initial judgments regarding ground motions and preliminary maximum credible earthquakes.

(4) Significance criteria, which are refinements of the preliminary significance criteria. These identify significant features which are of potential importance to consideration of seismic source potential and/or potential surface rupture through the sites. These significant features are to be further evaluated and studied during the field studies planned for 1981.

Recent fault displacement and length-distance screening criteria are discussed below in Sections 3.1.1 and 3.1.2, respectively. The preliminary significance, and significance criteria are discussed in Section 8.3 as an introduction to the discussion of the significant features.

3.1 - Guidelines for Defining Recent Fault Displacement Criteria

3.1.1 - Regulatory Criteria

The criteria described in this section are those regulatory guidelines which have been used for other projects of similar magnitude to this Project. The agencies for which criteria were reviewed include: the Water and Power Resources Service, formerly called the U. S. Bureau of Reclamation (USBR); the U. S. Army Corps of Engineers; the Nuclear Regulatory Commission; the Federal Energy Regulatory Commission (FERC); the State of Alaska; and the State of California.

Agencies responsible for critical structures such as dams and power plants have developed criteria which are used to evaluate the importance of faults to these structures. These criteria typically deal with one aspect of faulting, the recency of movement or displacement along a fault. Faults which have had displacement within a specified time period have been assigned descriptive terms such as active fault or capable fault.

The review below provides a summary of regulatory criteria used previously on other projects (including dams and power plants) to define active faults, or capable faults. These criteria have been considered in defining, for the Project, the term fault with recent displacement.

Water and Power Resources Service (WPRS)

Criteria for defining an active fault were adopted by the WPRS (formerly the USBR) for evaluation of faults at the proposed Auburn Dam site in California (Cluff, Packer, and Moorhouse, 1977). An active fault was defined as a fault which had been subject to relative displacement during the last 100,000 years. A fault is considered active if it (a) exhibits direct evidence of displacement in deposits less than 100,000 years old (e. g., surface rupture); (b) has indirect evidence of displacement on the fault, on or in deposits less than 100,000 years old (e. g., offset streams, scarps, etc.); or (c) has earthquake epicenters which have been accurately defined instrumentally or well-documented historically and which produce a geometrical arrangement that demonstrates a direct relationship to the fault.

An inactive fault is one for which there is direct evidence that there has not been relative displacement during the past 100,000 years.

U. S. Army Corps of Engineers (USACE)

The U. S. Army Corps of Engineers defines a capable fault as one which has had: (a) displacement in the past 35,000 years; (b) a demonstrated relationship with macroseismicity (magnitude greater than or equal to 3.5) based on instrumental data; or (c) a structural relationship with a known active fault where movement on one would cause movement on the other (U. S. Army Corps of Engineers, 1977).

U. S. Nuclear Regulatory Commission (USNRC)

The U. S. Nuclear Regulatory Commission (formerly the U. S. Atomic Energy Commission), defined a capable fault as one which exhibits one or more of the following characteristics:

(1) Movement at or near the ground surface at least once within the past 35,000 years, or movement of a recurring nature within the past 500,000 years.

(2) Instrumentally determined macroseismicity with records of sufficient precision to demonstrate a direct relationship with the fault.

(3) A structural relationship to a capable fault according to characteristics (1) and (2) above such that movement on one could be reasonably expected to be accompanied by movement on the other (U. S. Nuclear Regulatory Commission, 1975).

Federal Energy Regulatory Commission (FERC)

Federal Energy Regulatory Commission regulations and guidelines, as they apply to dam projects, do not discuss or define faults (Federal Energy Regulatory Commission, undated; Acres American Inc., 1980).

State of Alaska

State of Alaska regulations and guidelines, as they apply to dam projects, do not discuss or define faults or faults with recent displacement. The only reference encountered to date which pertains to faults is contained in Standards of the Alaska Coastal Management Program. Included under the subject of "geophysical hazards" is the term "severe faults." No definition of this term is provided.

State of California Division of Mines and Geology (CDMG)

The Alquist-Priolo Special Studies Zone Act of 1976 defines a "sufficiently active" fault as one along which the most recent movement along one or more of its segments or branches can be dated, by evidence or inference, within Holocene time (the last 11,000 years) (Californa Division of Mines and Geology, 1976).

Evidence for activity on a fault in historic time (the last 700 years) can include one or more of the following: (a) observed fault rupture or creep; (b) evidence of seismicity clearly associated with the fault; and (c) strain measurable across the fault.

These regulatory definitions of a fault with recent displacement, while useful, can lead to a somewhat simplistic and possibly misleading concept of the significance of a particular fault. If a fault has been subject to displacement within a specified period of time, whether it is 11,000 years, 35,000 years, or 100,000 years, it is important to understand how much displacement has occurred, how often it has occurred, and the sense of displacement. For example, a fault that has been subject to 0.2 inches (5 mm) of displacement every 75,000 years and a fault that has been displaced 3.3 feet (1 m) every 10,000 years both can be considered to have recent displacement (if displacement within 100,000 years is used as the definition of a fault with recent displacement). But for purposes of dam design, the effect of displacement on these two faults can be significantly different. In addition, the sense of relative displacement is also important. As discussed by Sherard and others (1974), the effect on dam design of displacements on thrust faults, normal faults, and strike-slip faults is different for each type of fault.

Dams have been designed to accommodate ground motions from relatively large earthquakes which have occurred relatively close to the dam. For example, the San Pablo Dam in California is designed to accommodate the ground motions of a magnitude (M_S) 8-1/2 event on the San Andreas fault and a magnitude (M_S) 7-1/2 event on the Hayward fault, approximately 12 miles (20 km) and 10 miles (16 km) from the dam, respectively. Dams have also been designed to accommodate surface rupture. For example, the Coyote Springs Dam, built in California in 1936, was designed as an earth dam to accommodate 20 feet (6 meters) of horizontal displacement and 3.3 feet (1 meter) of vertical displacement in the foundation. No displacement along the fault has been reported, and the dam continues in service without problems.

Consequently, any consideration of faults with recent displacement ultimately needs to address not only how recently the fault has had displacement, but also how much displacement has occurred, how often it has occurred, and what the sense of displacement has been. From these data, an assessment can be made of the likelihood that the fault will have these characteristics in the future. From this assessment, the seismic source potential and potential for surface rupture for a particular fault can be considered in an appropriate fashion during dam design.

3.1.2 - Guidelines for Identifying and Studying Faults with Recent Displacement

The guidelines presented below are based on the current state-of-the-knowledge for identifying faults with recent displacement. As developments and improvements evolve, they should be incorporated into future studies and into these guidelines. It is recognized that data allowing straight-forward determination of the recency of displacement along a fault are often lacking and that the judgment of the investigator is required in the final determination. These guidelines have been prepared by Acres American Inc. after review of regulatory and dam building agency guidelines (discussed in Section 3.1.1) and after discussions with project team members.

(1) All lineaments or faults that have been defined by the geology and seismology community as having been subject to recent displacement should be included in assessing the seismic design criteria for the Project.

(2) If a lineament exists within 6 miles (10 km) of a structure site, or if a branch of a more distant lineament is suspected of passing through a structure site, then a more detailed investigation should be made to establish whether the feature is a fault, whether or not it can be considered to have recent displacement, and whether the potential for displacement in the structure foundation exists (structures, as used here, refers to dam structures).

(3) Investigation of features identified in Item 2 should determine whether these features have experienced displacement in the last approximately 100,000 years.

(4) Lineaments more distant than 6 miles (10 km) from a structure site, and for which deterministic impact on the site may control the design of a structure, should be investigated to determine if the lineament is a fault and if it has moved within the last approximately 100,000 years.

(5) All features identified as faults which have experienced movement in the last approximately 100,000 years should be considered to have had recent displacement. All faults with recent displacement warrant consideration when assigning design criteria for ground motions or for surface displacement at the structure sites.

3.2 - Length-Distance Screening Criteria

Review of regulatory criteria combined with the state-of-the-knowledge for faults, earthquakes, and surface rupture (discussed in Section 2.4.2) led to the development of length-distance screening criteria to identify potentially significant faults and lineaments (called candidate featues in this study). These screening criteria were applied to all faults and lineaments identified in the literature and on remotely sensed data as discussed in Section 2.5. The screening criteria were developed to identify candidate features on the basis of (a) seismic source potential and (b) potential for surface rupture through the dam.

Potential Seismic Sources

Screening criteria for potential seismic sources were developed using (a) empirical length of rupture and earthquake magnitude relationships and (b) distance of the fault or lineament from either site. Length of rupture and earthquake magnitude relationships typically have been considered in two ways. One method is to measure surface rupture length which occurs on faults during earthquakes. Slemmons (1977) has presented the most recent published compilation of rupture lengths on different types of faults during earthquakes of various magnitudes. A second method is to define the rupture length as the length of the aftershock zone associated with earthquakes. Cluff, Tocher, and Patwardhan (1977) have summarized this approach and have developed a numerical relationship between the two parameters.

Figure 3-1 shows the relationship between earthquake magnitudes and the length of the aftershock zone associated with earthquakes of specific magnitudes. The length of the aftershock zone is generally greater than the length of ground rupture during an earthquake, because the aftershocks represent continual strain release after the main shock and may migrate laterally along the fault plane. Therefore, by referring to the values derived from Figure 3-1 as surface rupture lengths, one of several degrees of conservatism is added to the criteria developed for assessing faults and lineaments for this study. The data derived from Figure 3-1 are presented in Table 3-1 as the mean relationship between fault rupture length and earthquake magnitude.

The distance of the surface trace of the fault or lineament from either site is considered along with the postulated maximum fault rupture length (a) to screen out potential seismic sources for which associated ground motions would be too small to be significant to the project and (b) to retain those that are of potential significance. These length-distance criteria accommodate the fact that at greater distances from the sites only the longer faults and lineaments have the potential to generate ground motions of potential significance to the site.

The length-distance criteria presented in Table 3-2 were used for this study. They were derived from the rupture lengths presented in Table 3-1. The criteria use the observed length of the fault or lineament as the maximum length that could rupture during a given earthquake. This is a conservative approach because fault rupture length is typically assumed to be half the observed fault length (Wentworth and others, 1969). The values given in Table 3-2 include a degree of conservatism in that the maximum hypothetical earthquake is assumed to occur at the closest approach of the observed portion of the fault or lineament to either dam site.

The length-distance criteria set up concentric zones around the sites in which faults or lineaments of a set minimum length would be further evaluated. Thus, at distances of less than 6 miles (10 km) from either dam, all faults or lineaments with a length of 3 miles (5 km) or more were selected for further evaluation during the field reconnaissance. These represent potential faults that may generate a magnitude 5 or greater earthquake. At distances of 6 to 31 miles (10 to 50 km) from either dam, all faults or lineaments that are at least 6 miles (10 km) long were further assessed. Faults and lineaments with a minimum length of 31 miles (50 km) at a distance of 31 to 93 miles (50 to 150 km) from either dam were also examined during the field reconnaissance.

These length-distance criteria represent the experience from worldwide case histories of earthquakes and their associated rupture lengths along faults. They are also in accordance with previous regulatory guidelines.

This approach was used to select faults and lineaments, from those which had earlier been identified from the literature and interpretation of remotely sensed data, for additional assessment during the field reconnaissance; they were chosen because of their seismic source potential. In addition to features meeting the above criteria, screening was conducted to select features with a potential for surface rupture through either site, as discussed below.

Potential for Surface Rupture Through the Dam

A screening criterion for potential surface rupture was developed from experience with faults with recent displacement. The criterion incorporates variations in the type and extent of displacement associated with different types of faults.

Faults with historic rupture vary greatly in the pattern of rupture that has occurred. Some faults have single, relatively narrow surface traces, while others have branching patterns that include displacement on secondary or splay faults at some distance from the main fault, as shown by Ambrasseys (1968) and Bonilla (1970).

The width of the zone of rupture is related to a large extent to the type of fault and the type of displacement along a fault. As discussed by Sherard and others (1974) and Bonilla (1970), displacement on branch and subsidiary faults occurs more commonly on normal and thrust (reverse) faults than on strike-slip faults. Figure 3-2 shows this relationship where the maximum width of the zone within which displacement has occurred on strike-slip faults is 10 feet (3 m) to 1.8 miles (3 km). The maximum width for normal and thrust (reverse) faults varies from less than 0.1 to 8.5 miles (0.06 to 13 km). A corollary to this is the observation that the zone of deformation in thrust (reverse) faults typically is in the upthrown side, whereas for normal faults the displacement typically is in the downthrown side (Sherard and others, 1974).

Using these empirical relationships for width of zone along which displacement occurs during a single event, a screening criterion for features with potential surface rupture through either dam has been developed. The criterion is that those faults and lineaments (identified in the literature and on remotely sensed data) whose observed length passes within 6 miles (10 km) of either site will be retained for additional assessment during the field reconnaissance study. This criterion is consistent with the degree of conservatism used for other projects of similar magnitude (e. g., criteria adopted by the Water and Power Resources Service as described in Section 3.1.1).

In summary, the length-distance screening criteria, developed prior to the field reconnaissance study, were developed to select all features that potentially could be of significance to Project design either because they represent potential seismic sources or because they have the potential to cause surface rupture through either site. The screening criteria listed in Table 3-2 were used for the selection of potential seismic sources. For the selection of features with surface rupture potential through either site, the criterion of all faults and lineaments within a 6-mile (10-km) radius of either site was used. The faults and lineaments selected through application of these screening criteria have been designated candidate features and were evaluated during the field reconnaissance portion of the study.

TABLE 3-1

MEAN RELATIONSHIP BETWEEN FAULT RUPTURE LENGTH AND EARTHQUAKE MAGNITUDE

Magnitude (M_S)	Rupture Length (km)	Rupture Length (miles)
5	5	(3)
6	12	(7)
6.5	18	(11)
7	45	(28)
7.5	130	(81)

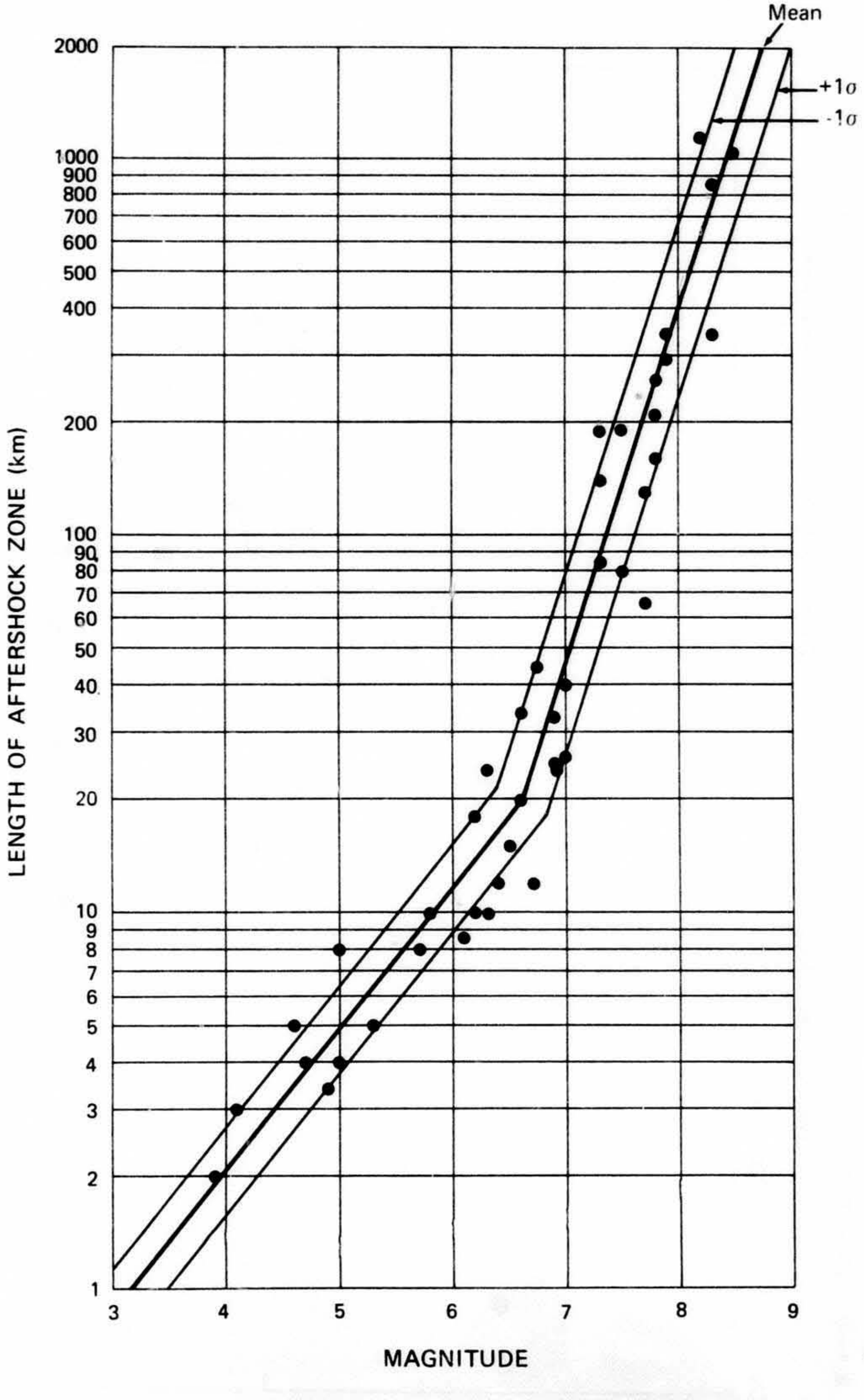
Notes: 1. Data were obtained from Cluff, Tocher, and Patwardhan (1977).
2. Data are shown in Figure 3-1.

TABLE 3-2

LENGTH-DISTANCE CRITERIA FOR IDENTIFICATION OF FAULTS AND LINEAMENTS FOR PRELIMINARY FIELD RECONNAISSANCE

Distance from Dam Site Alignment (km)	(miles)	Minimum Length of Fault or Lineament (km)	(miles)
0 to 10	(0 to 6)	5	(3)
10 to 50	(6 to 31)	10	(6)
50 to 150	(31 to 93)	50	(31)

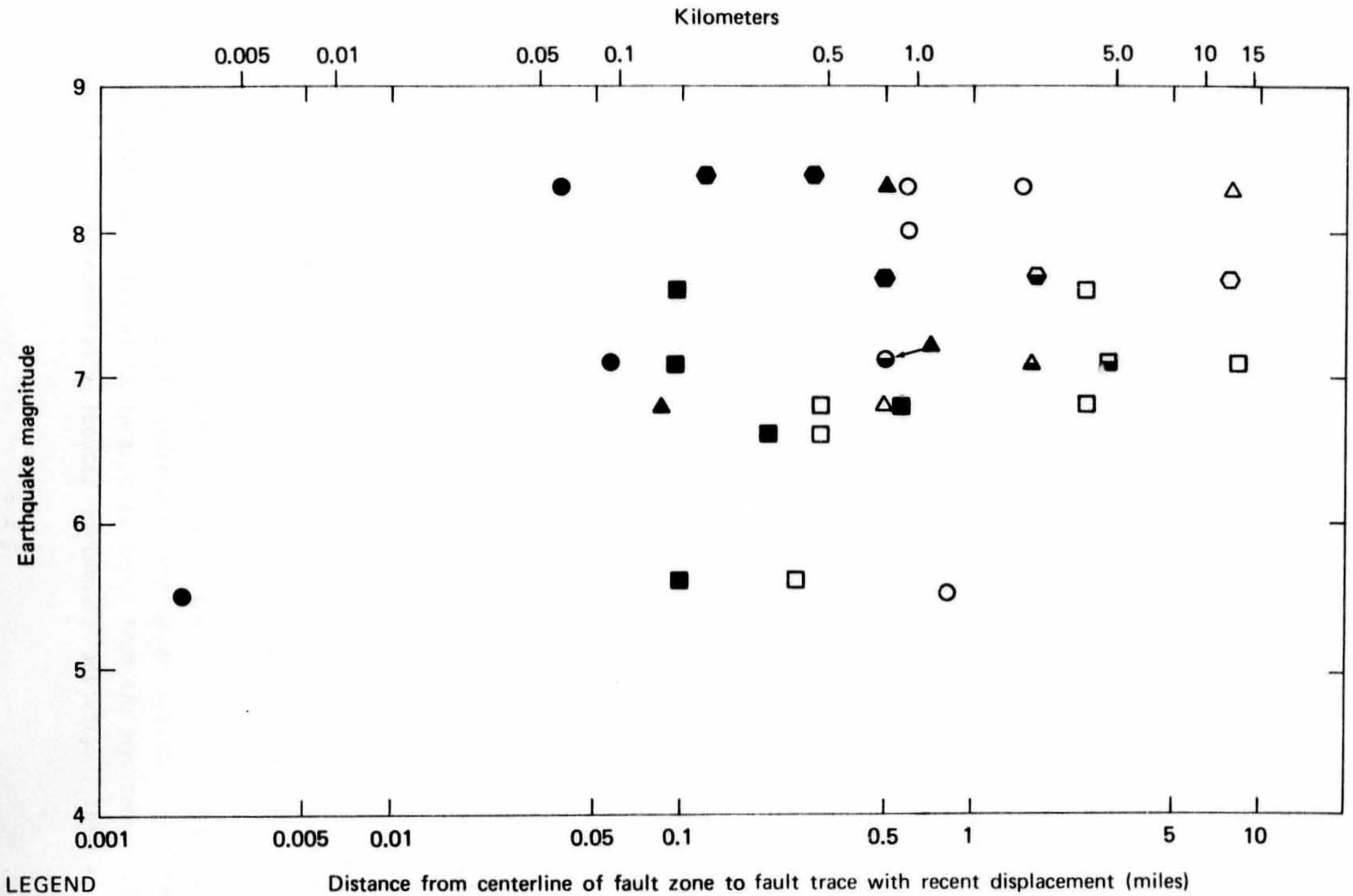
Note: The basis for selection of these criteria is described in Section 3.2



NOTE

1. After Cluff, Tocher, and Patwardhan (1977).

GRAPH SHOWING THE RELATIONSHIP BETWEEN EARTHQUAKE MAGNITUDE AND THE LENGTH OF AFTERSHOCK ZONES



LEGEND

Main	Branch	Secondary	
●	◓	○	Strike–slip faults
■	⬓	□	Normal faults
▲	▲	△	Right–normal faults
⬢	⬣	⬡	Reverse faults

NOTE

1. After Bonilla (1970).

SURFACE RUPTURE ZONE WIDTH RELATIONSHIPS

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FIGURE 3-2

4.0 - REGIONAL HISTORICAL SEISMICITY

4.1 - Plate Tectonic Setting

Recent concepts of plate tectonics have been a major influence in interpreting of the current tectonics of Alaska. Plate tectonics explains the underlying cause of the geologic and seismic activity in central and southern Alaska as the product of the subduction of the Pacific Plate at the Aleutian Trench as the plate spreads northward from the east Pacific Rise (Isacks and others, 1968; Tobin and Sykes, 1968). This northward movement occurs at a rate of approximately 2.4 inches/yr (6 cm/yr) relative to the North American Plate and is illustrated in Figure 4.1. As the Pacific Plate reaches the Aleutian Trench, it is thrust under the portion of the North American Plate that includes Alaska and the Aleutian Islands.

In the Gulf of Alaska area, the interplate movement is expressed as three styles of deformation: right-lateral slip along the Queen Charlotte and Fairweather faults; underthrusting of the oceanic Pacific Plate beneath the continental block of Alaska; and a complex transition zone of oblique thrust faulting near the eastern end of the Aleutian Trench (Figure 4-1). The Trench represents the ground surface expression of the initial bending of the oceanic plate as it moves downward beneath the North American Plate.

The regional earthquake activity is closely related to the plate tectonics of Alaska. Figure 5-2 (presented in Section 5) shows an oblique schematic view of the major geologic and tectonic features of the regional plate tectonics. The subducting plate is shown moving to the northwest away from the Aleutian Trench (off the figure to the south) and dipping gently underneath the upper Susitna River region. The subducted material is located at depth from the hypocenter distribution of instrumentally located earthquake activity. This kind of subcrustal seismic zone is called a Benioff zone. In some areas, such as to the southwest of the site region along the Alaska Peninsula, the presence of subducted oceanic crust is revealed at the ground surface by andesitic volcanic rocks.

The Benioff zone in the site region is characterized by earthquake activity extending to a depth of about 93 miles (150 km) (Agnew, 1980). No autochthonous andesitic volcanic rocks or volcanoes currently are known to be present at the ground surface above the Benioff zone.

Beneath the Prince William Sound area, which is on the North American Plate, the subducted plate moves nearly horizontally. The two plates appear to be closely coupled in this region and have the capacity to accumulate and release very large amounts of elastic strain energy. The most recent example of this process was the 28 March 1964 earthquake of magnitude (M_S) 8.4. The rupture zone of this earthquake, as evidenced by aftershocks, is shown in Figures 4-2 and 5-2.

The overlying North American Plate is also disrupted by compressional and tensional forces caused by the interplate deformation. Evidence for tectonic deformation is found in the Alaska Range more than 279 miles (450 km) northwest of the surface interplate boundary at the Aleutian Trench in the Gulf of Alaska. Much of this deformation is the composite expression of the plate interaction during millions of years and of the seaward migration of the subducting zone, which has periodically accreted additional crust to the continental land mass. Deformation within the upper plate is discussed in Section 5.

4.2 Regional Seismicity and Seismic Gaps

The major earthquakes of Alaska have primarily occurred along the interplate boundary between the Pacific and North American Plates from the

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Alaskan Panhandle to Prince William Sound and then along the Kenai and Alaska Peninsulas to the Aleutian Islands as shown in Figure 4-2. Three great earthquakes were felt in September 1899 near Yakutat Bay, and the magnitudes (M_S) of these are estimated to be 8.5, 8.4, and 8.1 (Thatcher and Plafker, 1977). Ground deformation was extensive and vertical offsets ranged up to 47 feet (14.3m) (Tarr and Martin, 1912); these are among the largest known displacements attributable to earthquakes. Large parts of the plate boundary were ruptured by these three earthquakes and by twelve others that occurred between 1897 and 1907; these included a magnitude (M_S) 8.1 event on 1 October 1900 southwest of Kodiak Island (Tarr & Martin, 1912; McCann and others, 1980) and a nearby magnitude (M_S) 8.3 earthquake on 2 June, 1903, near 57° north latitude , 156°west longitude (Richter, 1958).

A similar series of major earthquakes occurred along the plate boundary between 1938 and 1964. Among these earthquakes were the 1958 Lituya Bay earthquake (magnitude (Mw) 7.7) and the 1972 Sitka earthquake (magnitude (M_S) 7.6), both of which occurred along the Fairweather fault system in southeast Alaska; and the devastating 1964 Prince William Sound earthquake (magnitude (M_S) 8.4) which ruptured the plate boundary over a wide area from Cordova to southwest of Kodiak Island, with up to 39 feet (12m) of displacement (Hastie and Savage, 1970). Figure 4-2 shows the aftershock zones of these and other major earthquakes in southern Alaska and the Aleutian Islands. The main earthquakes and aftershocks are inferred to have ruptured the plate boundary in the encircled areas.

Three zones along the plate boundary which have not ruptured in the last 80 years have been identified as "seismic gaps" (Sykes, 1971). These zones are located near Cape Yakataga in the vicinity of the Shumagin Island, and near the western tip of the Aleutian Chain as shown in Figure 4-2. The Yakataga seismic gap is of particular interest to the Project because of its proximity to the site region. The rupture zone of a major earthquake filling this gap has the potential to extend down the Benioff zone to the north and northwest of the coastal portion of the gap near Yakataga Bay.

The area of the Yakataga seismic gap was probably ruptured extensively in the two great earthquakes of 1899 (Sykes and others, in press). The Yakataga seismic gap extends for approximately 108 miles (175 km) between the rupture zones of the 1964 earthquake and the most recent large event on 28 February 1979 near Icy Bay (magnitude (M_S) 7.2). Using early Russian felt reports and writings, Sykes and others (in press) show that almost all of the plate boundary along the Alaska-Aleutian Arc has been ruptured previously in large or great earthquakes. Consequently, the presently existing seismic gaps are considered to be the probable sites of future large events rather than normally quiescent areas where plate motion is relieved by aseismic slip. In Alaska, the cylcle of large earthquakes with intervening periods of relative quiescence is characteristic of activity on the Aleutian Trench along the boundary between the North American and Pacific Plates.

The last large earthquakes in the Yakataga area occurred in 1899. No information is available for earthquakes before 1899 for the Yakataga area to estimate a recurrence interval, but the amount of displacement during the 1899 events amounted to about 16 feet (5m). Sykes and others (in press) estimate that 16 feet (5 m) $\pm$ 8 feet (2.5 m) of potential displacement could have been built up as strain by the continuing plate motion (2.4 inches/yr (6 cm/yr)) since 1899, if there has been no aseismic slip. Because the 1979 magnitude (M_S) 7.2 earthquake near Icy Bay occurred in the inferred rupture zone of the 1899 events, a large or great earthquake may occur within the next two to three decades in the remaining portion of the Yakataga seismic gap (Perez and Jacob, in press).

4.3 - Historical Seismicity

The historical seismicity within 200 miles (322 km) of the Project is associated with three general source areas: the crustal seismic zone within the North American Plate; the deep (subcrustal) Benioff zone; and the shallow Benioff zone. The seismicity of these three source areas is reviewed in this section following the discussion of seismic networks and their effect on detection levels and location accuracy.

Prior to the installation of a seismograph at College, Alaska (COL) in 1935, only local felt reports or seismograph recordings made at distant stations were available to determine epicenters and focal depths of earthquakes in south-central Alaska. Among these distant stations were: one at Sitka, Alaska, installed in April 1904, consisting of two Bosch-Omori horizontal seismometers; one each at Berkeley and at Lick Observatory in California, installed in 1887 (published readings began in 1910 and 1911, respectively); and some Japanese stations developed in 1879. Davis and Echols (1962), Davis (1964), and Meyers (1976) have published lists of felt earthquakes for Alaska dating from the 18th century, although the very low-population density in Alaska prior to 1900 has precluded historical felt reports of earthquakes in the interior of Alaska earlier than the large event of 1904.

During the early and middle portion of the twentieth century, prior to 1964, epicenters and focal depths of earthquakes in Alaska were computed primarily from teleseismic data. Location uncertainty varied greatly and depended on the specific combination of earthquake size and source region depth. For example, larger earthquakes (magnitude (M_S) greater than 6) occurring within the shallow Benioff zone may have been well-recorded worldwide but may not have had clear pP phases to constrain depth and may have been located using travel time curves that did not account for local tectonic structure. Uncertainties in location and depth could be as large as 62 miles (100 km) or more. Earthquakes of uncertain focal depth are often constrained to 20 miles (33 km) to compute the epicenter location. In addition, recomputations of some earlier earthquakes, such as those published by Sykes (1971), have probably reduced some of the original catalog errors.

The accuracy of epicenter locations improved slightly with the installation of the seismograph at College, Alaska (near Fairbanks) in 1935, but it was not until the mid 1960s, after the devastating 28 March 1964, Prince William Sound earthquake, that earthquake monitoring was significantly improved in central and southern Alaska. After the 1964 earthquake, epicentral and focal depth accuracy improved with the installation of the University of Alaska Geophysical Institute (UAGI), National Oceanographic and Atmospheric Administration (NOAA), and U. S. Geological Survey seismic networks during the period 1964 to 1967, and with the preparation of a velocity model for the area by Biswas (1974).

Since 1974, the focal depths of earthquakes recorded and located by the UAGI are accurate to approximately plus or minus 9 miles (15 km) with epicentral accuracy generally better than depth accuracy. Location accuracy and magnitude detection levels have varied due to the number of stations in operation at a given time and changes in data handling procedures and priorties, so the above values may be too small for some poorly recorded events. From 1967 to 1974, the focal depth error estimates are approximately plus or minus 12 to 19 miles (20 to 30 km), with epicentral uncertainty of plus or minus 12 to 16 miles (20 to 25 km). The accuracy of focal depth estimation within the U. S. Geological Survey seismograph network is very good, probably plus or minus 6 miles (10 km) or less. However, this network is south of the Project and generally ouside of the site region.

The following discussion of historical seismicity is based on the Hypocenter Data File prepared by NOAA (National Oceanic and Atmospheric

Administration, 1980). Data from the U. S. Geological Survey and UAGI stations are routinely reported to NOAA for inclusion in world-wide data analysis. Thus, particularly for earthquakes of magnitude 4 and larger, the NOAA catalog represents a fairly uniform data set in terms of quality and completeness since about 1964 (as explained below). Earthquakes larger than magnitude 4 (using any magnitude scale) or Modified Mercalli Intensity V are plotted in Figures 4-4, 4-5, and 4-6. Earthquakes smaller than magnitude 4 or with no determined magnitude are not included because they are considered to be too small to effect seismic design considerations.

4.3.1 - Shallow Benioff Zone

The shallow Benioff zone is a major source of earthquake activity that could potentially affect seismic design considerations. This zone is the region of primary interplate stress accumulation and release between the Pacific and North America Plates and is indicated in Figures 4-4 and 5-2. The 28 March 1964 Prince William Sound earthquake, discussed in Sections 4.1 and 4.2, is the closest major interplate earthquake to the site region (as shown on Figures 4-2 and 4-4). Focal depths of earthquakes within the area of the 1964 aftershock zone are generally shallow, in the range of 15 to 28 miles (25 to 45 km) as shown in Figures 4-5 and 4-6.

Several additional large earthquakes have occurred during the twentieth century in the same vicinity as the 1964 event. Two of these, the magnitude (M_S) 7-1/4 earthquake of 31 January 1912 and the magnitude (M_S) 6-1/4 earthquake of 14 September 1932, were given focal depths of 50 and 31 miles (80 and 50 km), respectively.

It is likely that these depths are not correct, since the recent and better-located events are shallower and more consistent with the tectonic model. Similar uncertainties in focal depth for earlier earthquakes are discussed in Sections 4.3.2 and 4.3.3.

4.3.2 - Deeper Benioff Zone

The historical seismicity catalog as plotted in Figure 4-4 was sorted during this study to select those earthquakes with depth greater than or equal to 22 miles (35 km). This depth was selected to exclude those events constrained to a depth of 20 miles (33 km). On the basis of the results of the microearthquake study (Section 9), the seismically active portion of the upper plate does not extend deeper than about 19 miles (30 km). The resulting data set of subcrustal, Benioff zone earthquakes is shown in Figure 4-5. Several surface geographic points are shown for reference, but surface fault traces are left off the figure since the Benioff zone lies beneath and is separated from surface geologic faults.

The Benioff zone descends in a northwesterly direction under interior Alaska, through Cook Inlet and the Susitna Lowland to the Alaska Range (Biswas, 1973; Davies and Berg, 1973; Van Wormer and others, 1973). It dips gently across a wide zone, and reaches a depth of approximately 93 miles (150 km) near Mt. McKinley. Although the deeper Benioff zone is discussed separately from the shallow Benioff zone, they appear to be associated with a continuous geologic unit (the subducting plate) with possible differences in associated seismicity, as discussed in Section 9. The Benioff zone increases in horizontal extent (measured in the dip direction) from west to east. It is approximately 124 miles (200 km) wide along the Aleutian Arc and attains a maximum width of approximately 291 miles (470 km) near Mt. McKinley (Figure 4-2). The northeastern limit of subduction is believed to be located at approximately 64.1° north latitude, 148° west longitude (Agnew, 1980), 28 miles (45 km) north of the Hines Creek strand of the Denali fault.

The northwestern portion of the subduction zone has been studied in detail by Agnew (1980). He used a selected high-quality data set to contour the upper edge of the Benioff zone, and these contours are reproduced in Figure 4-5. Additional details on the Benioff zone are discussed as a product of the microearthquake study in Section 9.

As shown in Figure 4-5, moderate-sized earthquakes have occurred on the Beniof zone almost directly beneath the Project sites. A magnitude (M_s) 4.7 event with a focal depth of 47 miles (76 km) which occurred on 1 October 1972 was located 6 miles (10 km) east of the Devil Canyon site and also 17 miles (27 km) west of the Watana site. An event of magnitude (M_s) 4.6 with a focal depth of 50 miles (80 km) occurred 16 miles (25 km) northeast of the Watana site on 28 December 1968. On 5 February 1974, a magnitude (M_s) 5.0 event with a focal depth of 46 miles (75 km) occurred 17 miles (27 km) southeast of the Devil Canyon site and 13 miles (21 km) southwest of the Watana site. A magnitude (M_s) 5.4 event with a focal depth of 66 miles (106 km) was located approximately 38 miles (62 km) northwest of the Devil Canyon site on 18 May 1975. Earthquakes recorded prior to 1964 include several large earthquakes near the sites. A magnitude (M_b) 6.1 event with a focal depth of 49 miles (79 km) occurred on 2 May 1963 17 miles (27 km) northwest of the Devil Canyon site, and an earthquake of magnitude 5.1 with a focal depth of 59 miles (95 km) occurred within 11 miles (17 km) southwest of the Devil Canyon site on 14 December 1963.

An interesting feature of Figure 4-5 is the region of very low seismic activity lying between the edge of the 1964 aftershock zone and the area of seismic activity to the northwest on the Benioff zone. This quiet zone does not appear to be a product of mislocation or error in depth of focus, since Figure 4-4, with all the seismicity data, also shows a low seismicity zone. The location of this zone is refined in Section 9 and is discussed in terms of its potential for future seismic activity.

4.3.3 - Crustal Seismicity

The historical record indicates that the seismicity within the Talkeetna Terrain, which lies between the Denali and Castle Mountain faults, is low. Figure 4-6 shows the data from Figure 4-4 for earthquakes with depths less than or equal to 19 miles (30 km). The shallow seismic activity is discussed in terms of four areas: the shallow Benioff zone, the Castle Mountain fault, the Talkeetna Terrain, and the Denali fault.

Shallow Benioff Zone

As noted above in Section 4.3.1, the events included within the area of the 1964 aftershock zone are most likely associated with the interaction between the North American and Pacific Plates. The seismic potential of this area is best assessed in terms of seismic gap concepts, as discussed in Section 4.2.

Castle Mountain Fault

Five moderate to large earthquakes (magnitude (M_S) greater than 5) have occurred in the general vicinity of the Castle Mountain fault (Figure 4-6). A series of 4 events occurred in 1933 (magnitude (M_S) 5.6 to 7.0) and a large earthquake occurred in 1943 (magnitude (M_S) 7.3), all with assigned focal depth of zero (National Oceanic and Atmospheric Administration, 1980; Sykes, 1971). These earthquakes all took place before good station coverage existed in Alaska, and their locations and focal depths are subject to substantial uncertainty. Because of the occurrence at depth of more recent seismic activity (post 1964), it is more likely that these earlier events actually occurred at depth along the Benioff zone (Figure 4-5 shows substantial recent activity taking place at depths of 31 to 50 miles (50 to 80 km)). However, the association of this activity in 1933 and 1943 with a surface fault, such as the Castle Mountain fault, cannot be precluded. The 1933 activity was accompanied by a large number of smaller felt events (Neumann, 1935), suggesting a shallow source in the upper Cook Inlet area.

Talkeetna Terrain

Four moderate earthquakes have been located at shallow depths in the Talkeetna Terrain; from west to east they are the 18 Janaury 1936 event of magnitude (M_S) 5.6, the 29 May 1931 event of magnitude (M_S) 5.6, the 3 July 1929 event of magnitude (M_S) 6.25, and the 17 July 1923 event of magnitude (M_S) 5.6. As is the case for seismicity in the vicinity of the Castle Mountain fault, these earthquakes all took place prior to the installation of regional instrumentation and are anomalous with respect to the current seismic activity that is concentrated on the Benioff zone. The location uncertainity of these events is such that, even if they occurred in the crustal zone, they cannot be definitively associated with specific faults.

Additional shallow events, in the depth range 19 to 22 miles (30 to 35 km), are included in Figure 4-4. These are small (magnitude (M_S) 4 to 5) and are widely scattered. On the basis of these events and the low-level crustal seismicity discussed in Section 9, the seismic environment of the Talkeetna Terrain appears very low. It should be noted, however, that the occurrence of the 1964 earthquake may have affected the rate of occurrence of earthquakes in the Talkeetna Terrain by releasing stress regionally and lowering the present level of instrumental seismicity.

Denali Fault

Within the study area shown in Figure 4-6, four earthquakes lie along or to the north of the Denali fault. Two of these, the event of 21 January 1929 (magnitude (M_S) 6.5) and the event of 4 July 1929 (magnitude (M_S) 6.5) were recorded and located using worldwide stations. Both the epicenter location and focal depth are uncertain, but the felt reports of the January event (Heck and Bodle, 1931) suggest that it was shallow and occurred south of Fairbanks and north of the Talkeetna Terrain.

The first instrumentally recorded earthquake in south-central Alaska occurred on 27 August 1904 with a magnitude (M_S) of 7-3/4; it was located at 64° north latitude, 151° west longitude. Very few news reports were published for this earthquake, reflecting the sparse population of the state. Figure 4-7 presents the estimated Modified Mercalli felt intensities at locations where the earthquake was reported. The instrumental epicentral location was determined from records made in California and could be in great error. Also, the published hypocentral depth of 16 miles (25 km) is only an estimate. As shown in Figure 4-7, the earthquake appears to have been felt more strongly in western Alaska than elsewhere in the state. Thus, the epicentral location may actually be farther west than originally plotted using the teleseismic records.

The location and geologic association of the 1904 event are very uncertain. The present data do not substantially constrain the location and it could be associated with either the Denali fault or the westernmost portion of the Benioff zone. These two sources are the most likely, since the size of the event requires association with major tectonic features.

The 7 July 1912 earthquake occurred after the population and numbers of newspapers had increased dramatically in the Alaskan interior. Felt reports and assigned intensities are summarized in Figure 4-8. The intensity pattern suggests that the earthquake was shallow and could have occurred on the Denali fault. The Denali fault in this area is covered with glaciers, and the observation of any evidence for recent surface breakage is unlikely.

Sykes (1971) and Tobin and Sykes (1966) have associated smaller ((M_S) 4 to 5) historical earthquake activity with the Denali fault, particularly along the central McKinley strand and the trace of the Denali fault about 62 miles (100 km) east of the site region as shown in Figure 4-6. The seismic character of the Denali fault appears similar to that of the San Andreas fault in California; that is recurrent large earthquakes with major surface faulting separated by intervals of low seismic activity. The possible association of moderate to large historical earthquakes with the Denali fault is consistent with the geologic evidence for recent displacement; thus, the seismic potential for the Denali fault is not strongly dependent on the historical seismicity.

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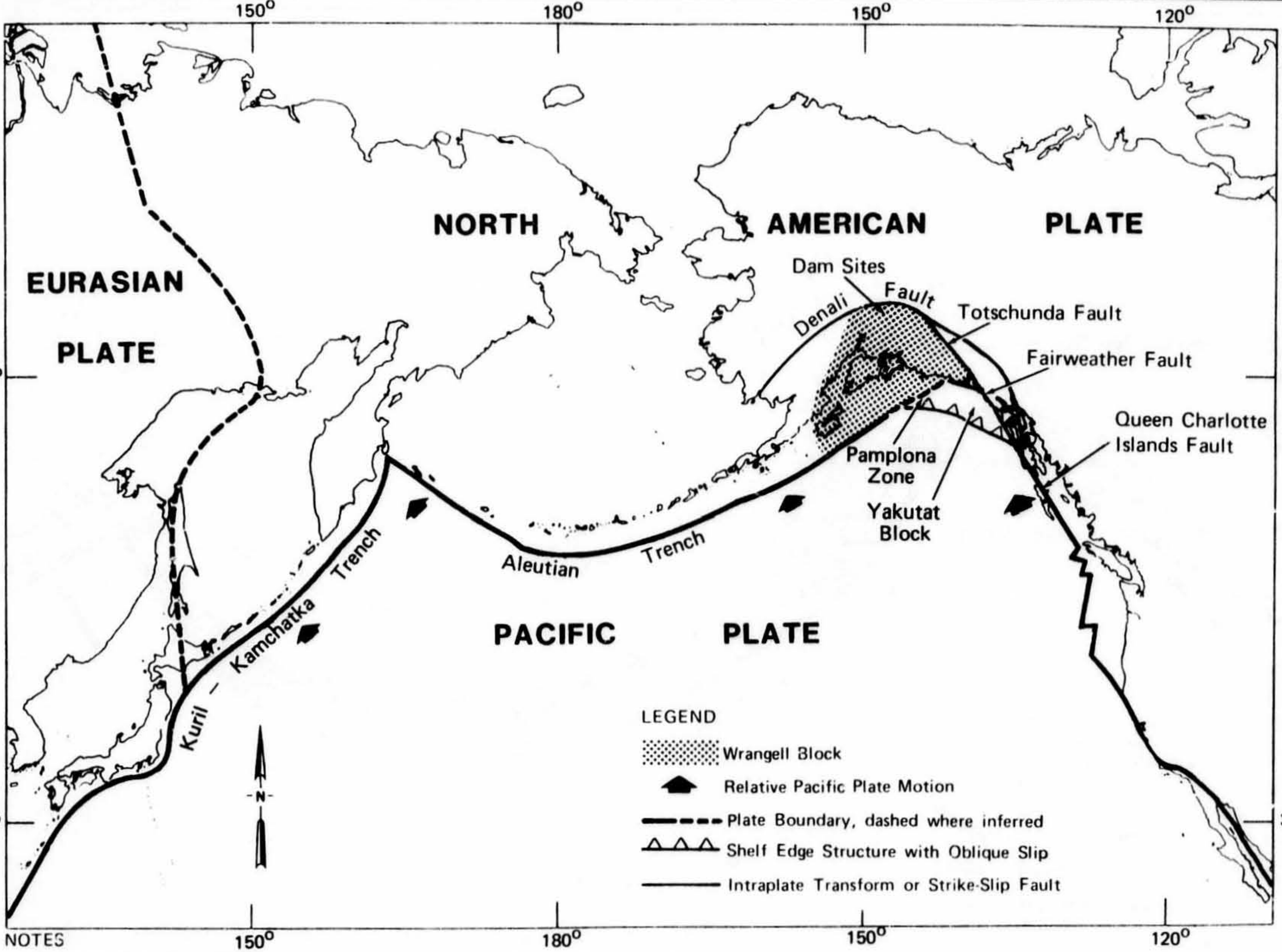
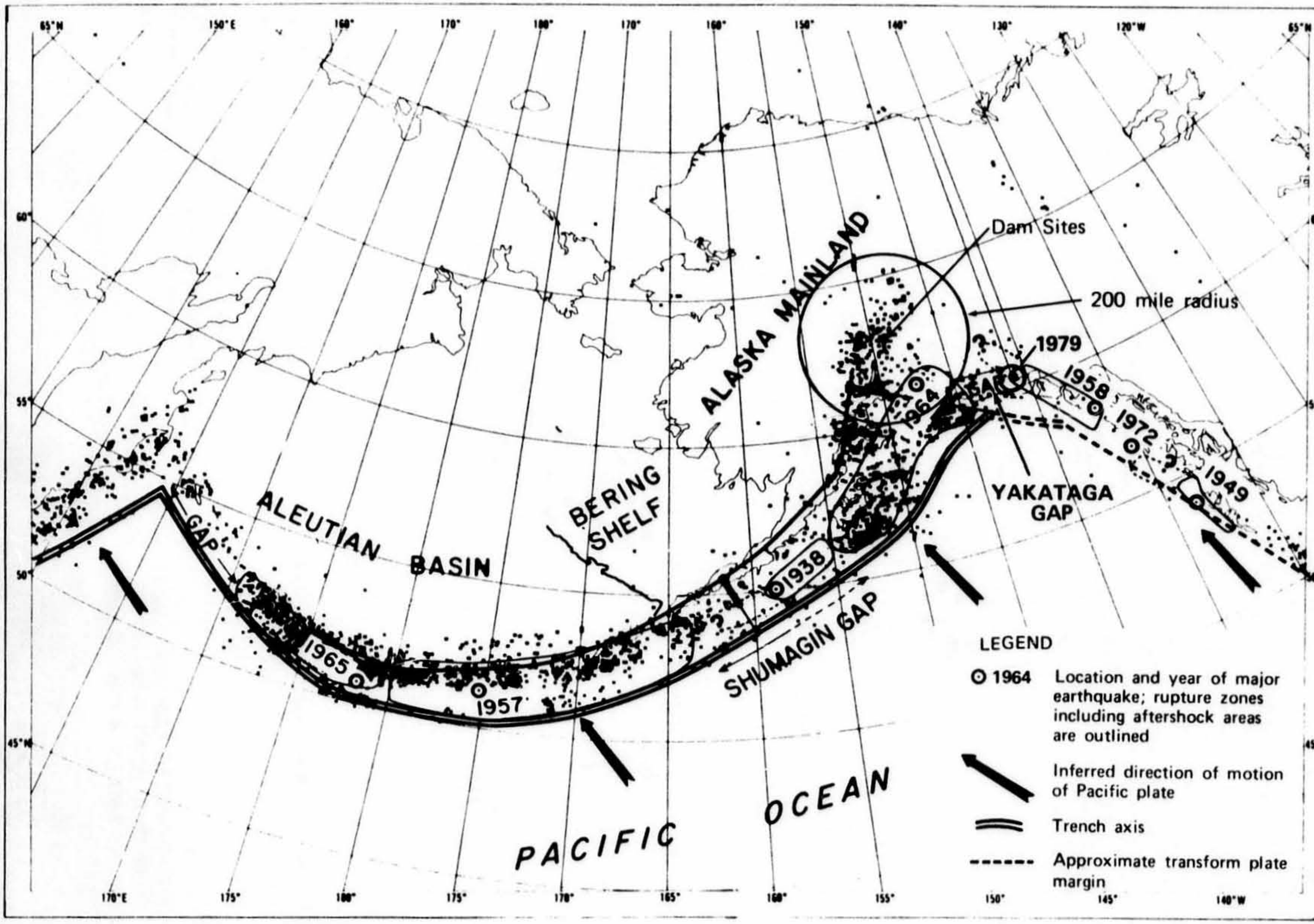


NOTES

1. Base map from Tarr (1974).
2. After Packer and others (1975), Beikman (1978), Cormier (1975), Reed and Lamphere (1974), Plafker, and others (1978).
3. Talkeetna Terrain within the Wrangell Block is shown on Figure 5-1.

PLATE TECTONIC MAP

FIGURE 4-1



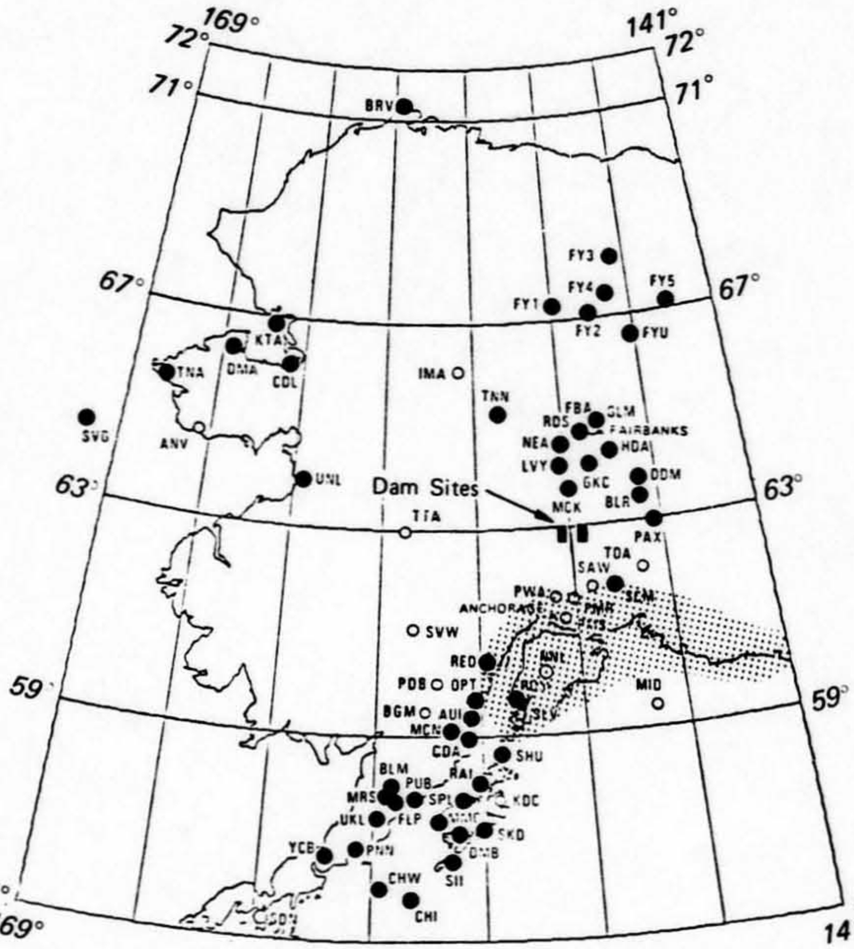
NOTE

1. Modified after Davies and House (1979).

MAJOR EARTHQUAKES AND SEISMIC GAPS IN SOUTHERN ALASKA

WOODWARD-CLYDE CONSULTANTS 14658A December 1980

FIGURE 4.2



LEGEND

▮	Dam Site
●PAX	University of Alaska station location and name
○TTA	NOAA station location and name
(stippled area)	Area of coverage by USGS network (Actual station locations not shown)

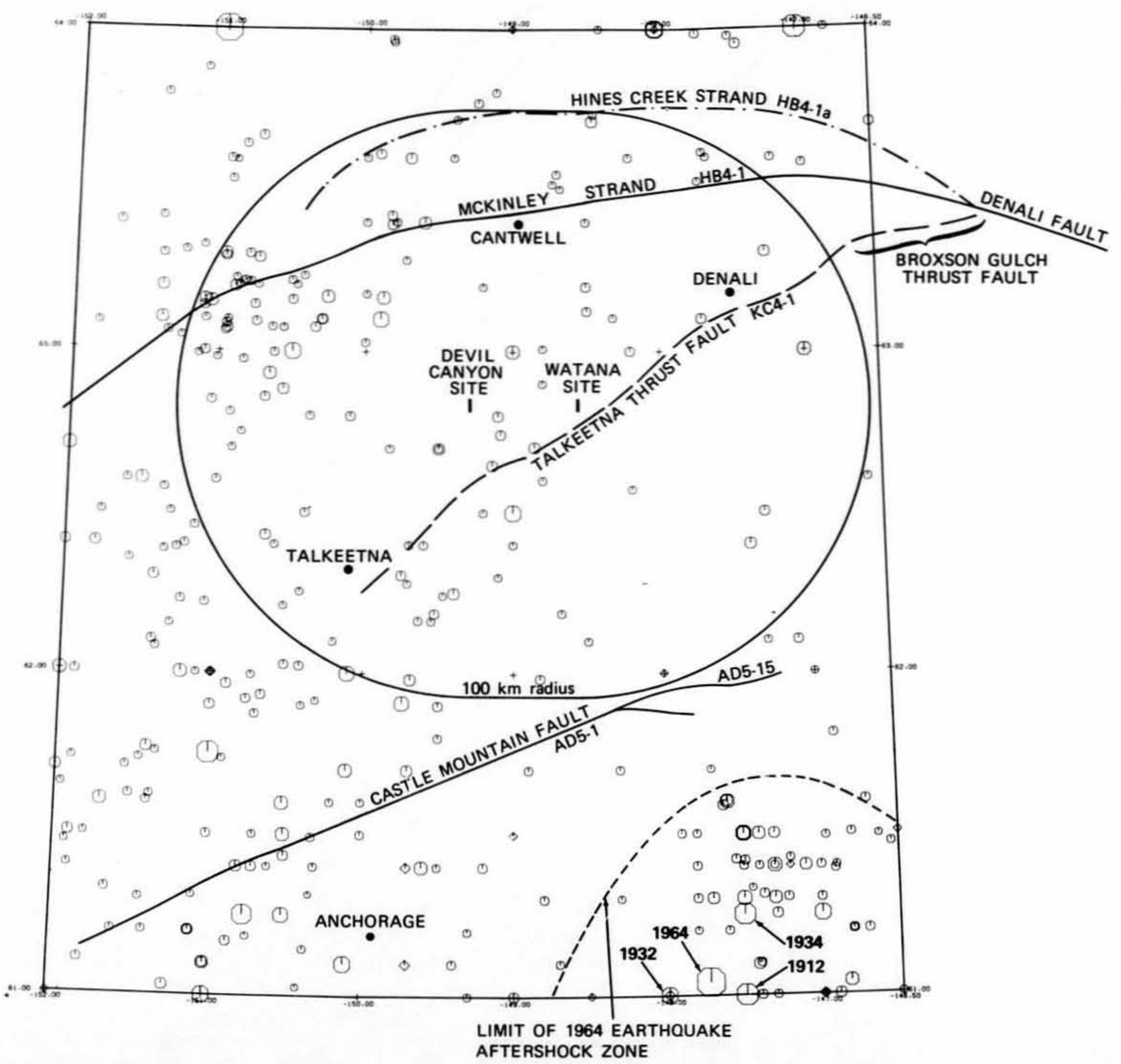
NOTE

1. Modified *after* Agnew (1980) and Lahr (1980).

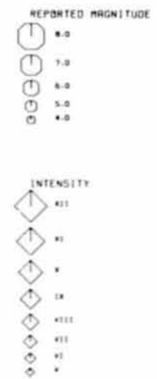
LOCATION MAP OF UNIVERSITY OF ALASKA, USGS, AND NOAA SEISMOGRAPH STATIONS IN ALASKA

0 100 200 300 400 Miles

0 150 300 450 600 Kilometers



LEGEND



BOUNDARY FAULTS

Faults with recent displacement

SIGNIFICANT FEATURES

Indeterminate A feature

Indeterminate B feature

NOTES

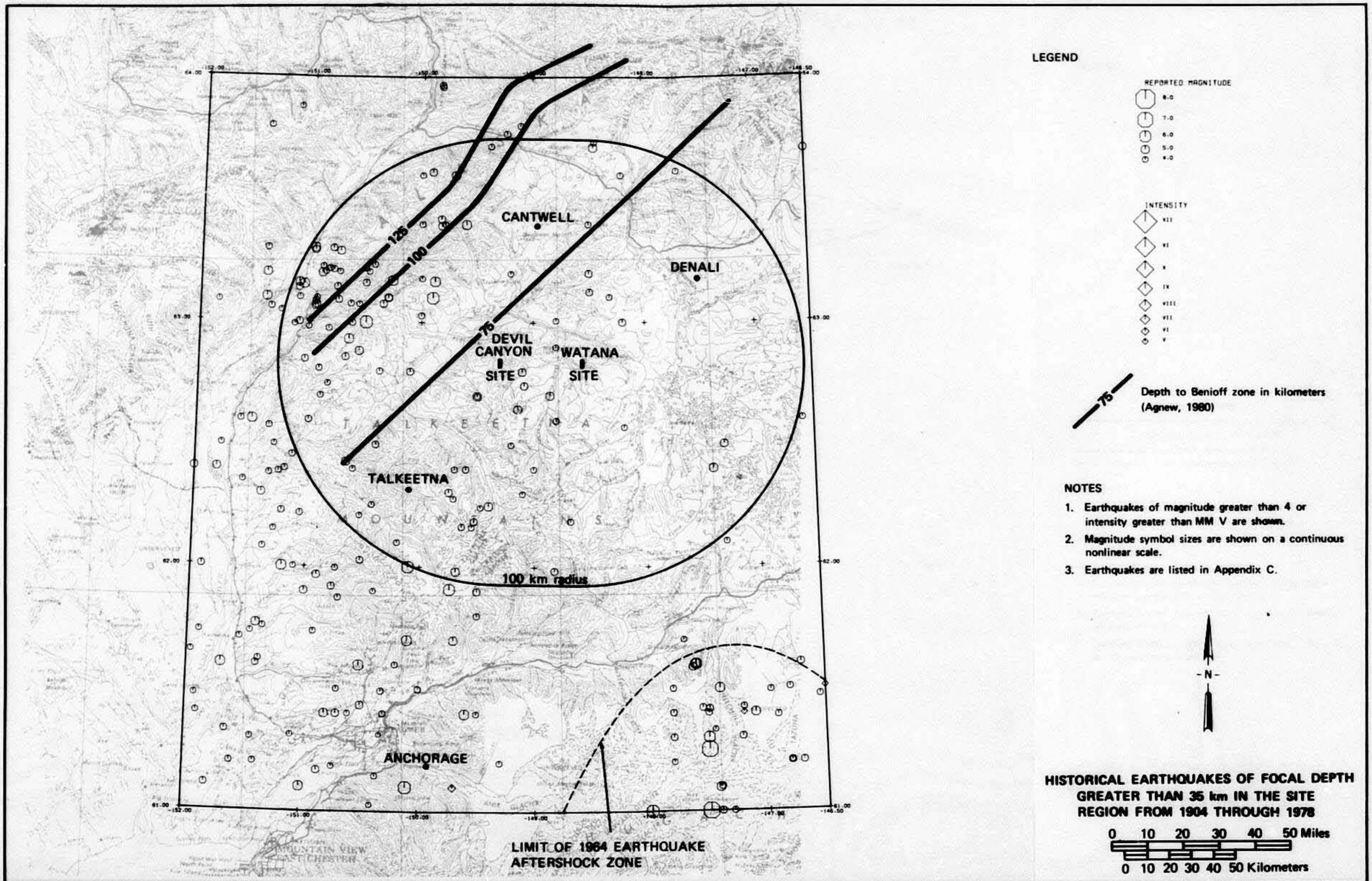
1. Earthquakes of magnitude greater than 4 or intensity greater than MM V are shown.
2. Magnitude symbol sizes are shown on a continuous nonlinear scale.
3. Earthquakes are listed in Appendix C.
4. Explanation of significant feature classification system is presented in Section 8-2.
5. Explanation of alpha-numeric symbols is presented in Appendix A.
6. Number (such as 1964) next to selected epicenters is the year of occurrence.

-N-

HISTORICAL EARTHQUAKES OF ALL FOCAL DEPTHS IN THE SITE REGION FROM 1904 THROUGH 1978

0 10 20 30 40 50 Miles

0 10 20 30 40 50 Kilometers

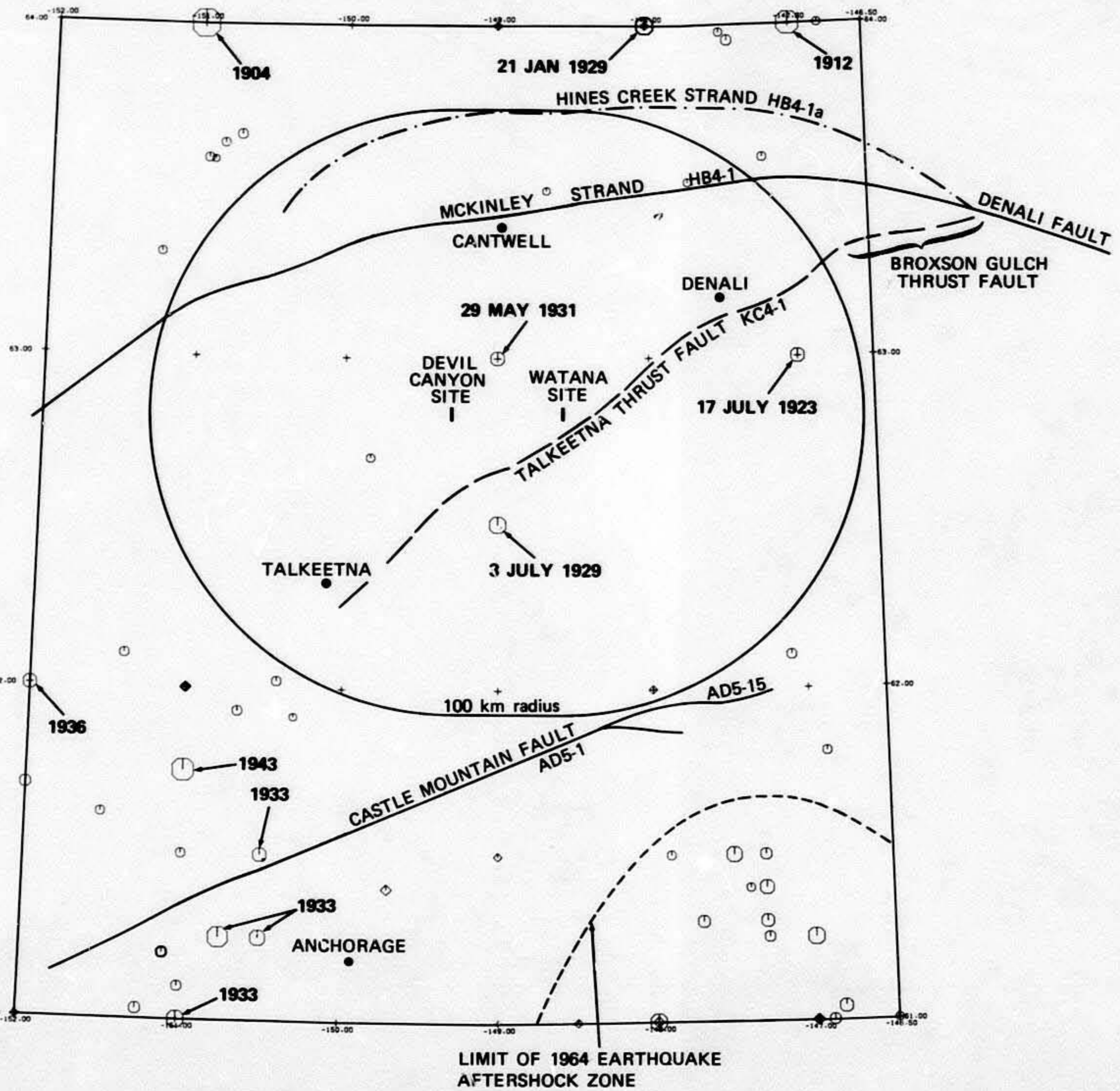


NOTES

1. Earthquakes of magnitude greater than 4 or intensity greater than MM V are shown.
2. Magnitude symbol sizes are shown on a continuous nonlinear scale.
3. Earthquakes are listed in Appendix C.

HISTORICAL EARTHQUAKES OF FOCAL DEPTH GREATER THAN 35 km IN THE SITE REGION FROM 1904 THROUGH 1978

FIGURE 4-5



LEGEND

REPORTED MAGNITUDE
8.0
7.0
6.0
5.0
4.0

INTENSITY
XII
XI
X
IX
VIII
VII
VI
V

BOUNDARY FAULTS
Faults with recent displacement
SIGNIFICANT FEATURES
Indeterminate A feature
Indeterminate B feature

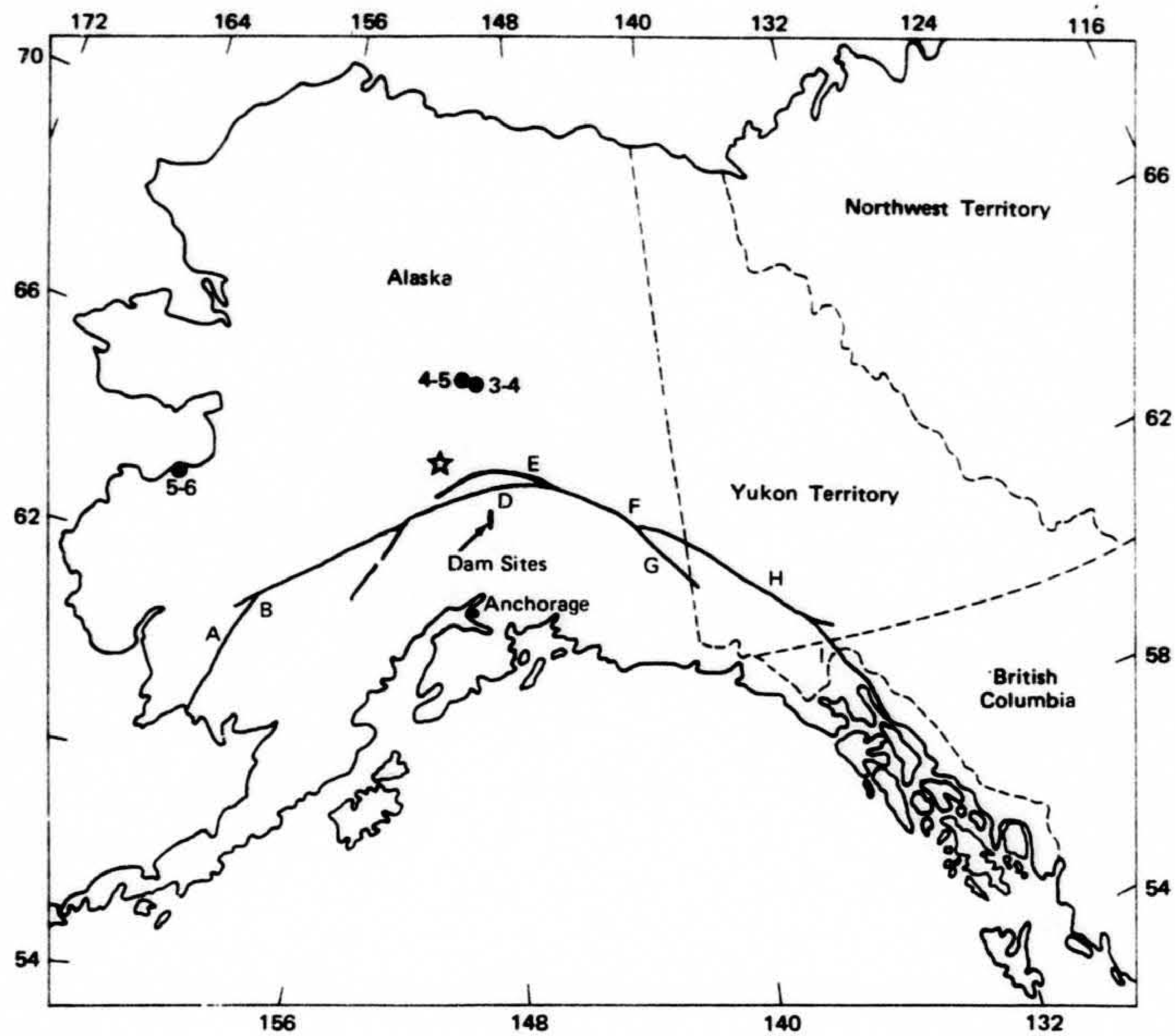
NOTES

1. Earthquakes of magnitude greater than 4 or intensity greater than MM V are shown.
2. Magnitude symbol sizes are shown on a continuous nonlinear scale.
3. Earthquakes are listed in Appendix C.
4. Explanation of significant feature classification system is presented in Section 8-2.
5. Explanation of alpha-numeric symbols is presented in Appendix A.
6. Number (such as 1964) next to selected epicenters is the year of occurrence.

N

HISTORICAL EARTHQUAKES OF FOCAL DEPTH LESS THAN 30 km IN THE SITE REGION FROM 1904 THROUGH 1978

0 10 20 30 40 50 Miles
0 10 20 30 40 50 Kilometers



LEGEND

☆ Epicenter location for the magnitude (M_s) 7¾ earthquake of 1904

●4-5 Estimated felt intensity based on review of historical newspaper reports conducted for this report

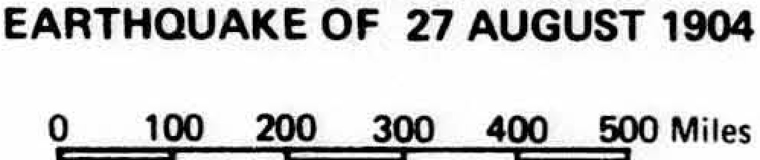
Denali Fault system segments

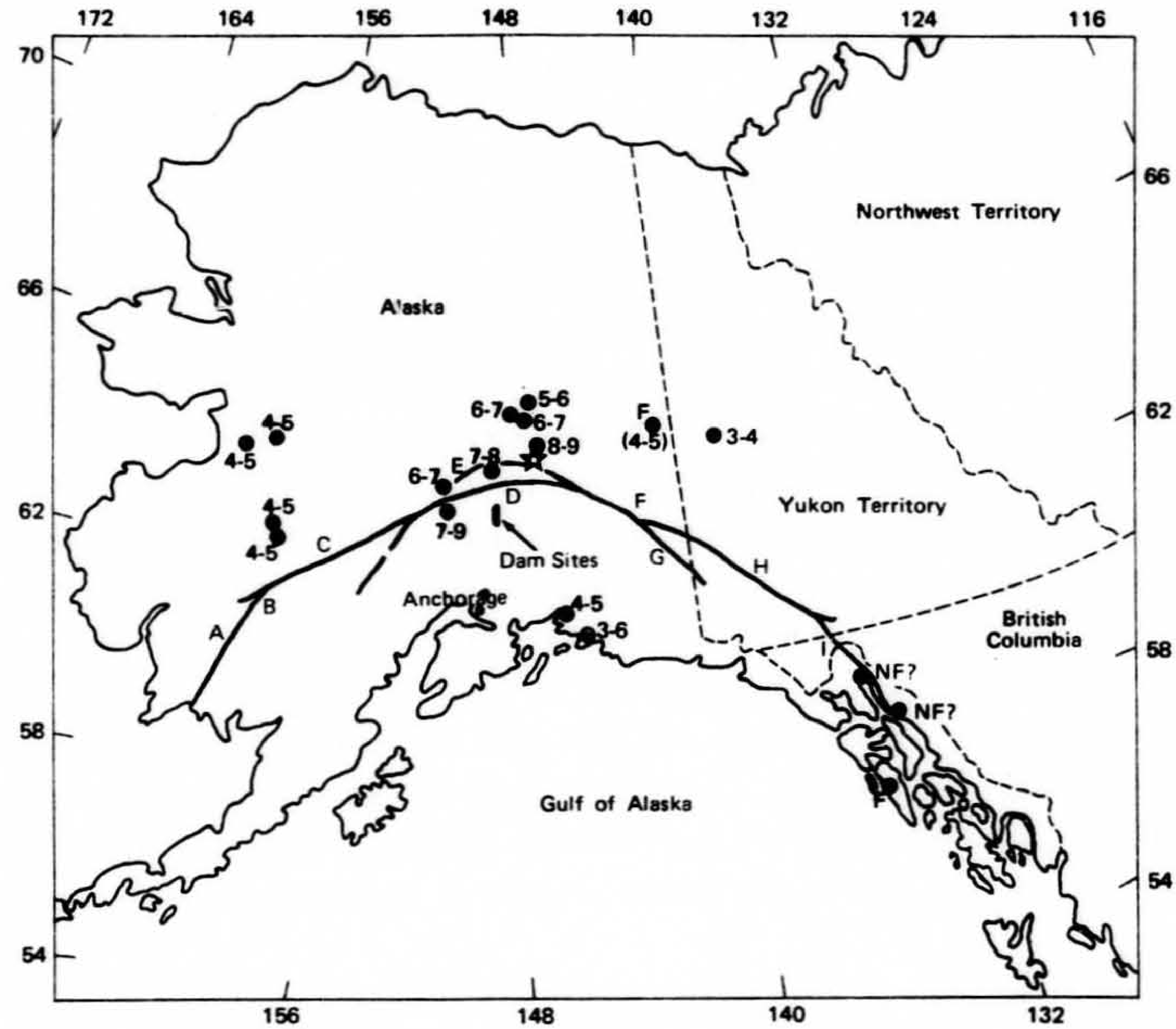
- A Togiak-Tikchik fault
- B Holitna fault
- C Farewell strand
- D McKinley strand
- E Hines Creek strand
- F Denali fault
- G Totschunda Fault system
- H Shakwak fault
- I Chilkat River fault

NOTES

1. Intensity is based on the Modified Mercalli Scale of 1931 (Wood and Neumann, 1931).
2. Magnitude (M_s) is from sources cited in Appendix C.
3. Denali Fault system is from Reed and Lanphere (1974)

ESTIMATED MODIFIED MERCALLI FELT INTENSITIES FOR THE EARTHQUAKE OF 27 AUGUST 1904





LEGEND

- ☆ Epicenter location for the magnitude (M_s) 7.4 earthquake of 1912
- ● 3-4 Estimated felt intensity based on review of historical newspaper reports conducted for this report
- ● F (3-4) Felt intensity very approximate
- ● F Felt information insufficient to estimate felt intensity
- ● NF? No report of the earthquake being felt

Denali Fault system segments

- A Togiak-Tikchik fault
- B Holitna fault
- C Farewell strand
- D McKinley strand
- E Hines Creek strand
- F Denali fault
- G Totschunda Fault system
- H Shakwak fault
- I Chilkat River fault

NOTES

1. Intensity is based on the Modified Mercalli Scale of 1931 (Wood and Neumann, 1931).
2. Magnitude (M_s) is from sources cited in Appendix C.
3. Many aftershocks were felt following this earthquake.
4. Denali Fault system is from Reed and Lanphere (1974).

ESTIMATED MODIFIED MERCALLI FELT INTENSITIES FOR THE EARTHQUAKE OF 7 JULY 1912

0 100 200 300 400 500 Miles

0 200 400 Kilometers

5 - TECTONIC MODEL--TALKEETNA TERRAIN

The site region consists of a tectonic unit designated here as the Talkeetna Terrain, a sub-unit of the Wrangell Block (Figures 4-1 and 5-1). The Talkeetna Terrain is defined as that region of Alaska which is bounded on the north by the McKinley strand of the Denali fault, on the east by the Denali-Totschunda fault system, on the south by the Castle Mountain fault, and on the west by a zone of deformation extending from the Aleutian volcanic chain (which ends at Mt. Spurr) to Mt. McKinley (Figure 5-1). All of these crustal boundaries are faults with recent displacement except for the western boundary which is primarily a zone of uplift marked by Cenozoic age volcanoes. The Aleutian megathrust associated with the subducting Pacific Plate bounds the base of the Talkeetna Terrain (Figures 5-1 and 5-2). A discussion of the plate tectonic framework in which the site region is located is presented in Section 4.1 and is briefly summarized here.

The Pacific Plate is moving north-northwest at a rate of about 2.4 inches/yr (6 cm/yr) with respect to the North American Plate (Lahr and Plafker, 1980). In the region of Prince William Sound where the coastline bends westward, there is a transition zone in which translational motion between the Pacific and North American Plates along the Queen Charlotte Islands-Fairweather fault system is transferred to subduction of the Pacific Plate along thrust faults in the northern Gulf of Alaska and the Aleutian Trench (Figure 5-1). At the southern boundary of the Talkeetna Terrain, the position of the Benioff zone suggests that the Pacific Plate is decoupling from the North American Plate and that they are not directly interacting with one another within the Talkeetna Terrain. Most of the deformation in the Talkeetna Terrain resulting from the convergence of the Pacific and North American Plates appears to be occurring along the boundaries of the Terrain, leaving the interior region relatively free of recent deformation.

A broad area of deformation extending from Montague Island east to the Pamploma Ridge in the Gulf of Alaska is believed to accommodate much of the convergence between the tectonic plates. This area includes the thrust faults in the Chugach-St. Elias Mountains where the 28 February 1979 earthquake (Ms) 7.2 occurred. These structural features largely accommodate the transition from strike-slip faulting along the eastern Gulf to the Aleutian megathrust of the western Gulf.

The Castle Mountain fault is also recognized as a feature actively accommodating a small amount of convergence along the southern margin of the Talkeetna Terrain. In the region approximately corresponding to the trace of the Castle Mountain fault (Figures 5-1 and 5-2), the subducting Pacific Plate is decoupled beneath the Talkeetna Terrain as indicated by seismicity data (Agnew, 1980; Section 9 of this report). The deformation imparted to the Talkeetna Terrain from the Aleutian megathrust is probably expressed largely as ductile deformation, at depth, north of the Castle Mountain fault. However, recent displacement on the Denali fault north of the Terrain indicates a small amount of convergence is transmitted through the Talkeetna Terrain.

The Castle Mountain fault is a right-lateral strike-slip fault with a significant component of north-side-up reverse slip (Page and Lahr, 1971; Detterman and others, 1976). Its surface expression is easily recognized between the Susitna River and the western Matanuska Valley, but its western extension beyond the Susitna River is not well documented. On the eastern end, the Castle Mountain fault apparently dies out in a series of splays, but evidence of faulting exists as far east as the Copper River basin.

The northern and eastern boundaries of the Talkeetna Terrain are the Denali and Totschunda faults (the latter includes an inferred connection with the Fairweather fault), respectively. These faults are right-lateral strike-slip faults that exhibit progressively lower slip rates northward and westward from the Talkeetna Terrain as transform motion between the Pacific and North American Plates is dissipated away from the plate interaction. Motion on the Fairweather fault (southeast of the Totschunda fault) of about 1.9 to 2.3 inches/yr (4.8 to 5.8 cm/yr) (Plafker and others, 1978) is roughly equivalent to the convergence rate between the Pacific and North American Plates. Much of this motion is probably transferred through the Gulf of Alaska to the Aleutian Trench while part is distributed farther north, as only about 0.4 to 1.3 inches/yr (0.9 to 3.3 cm/yr) of displacement is transferred to the Totschunda fault and the section of the Denali fault south of the Delta River (Richter and Matson, 1971; Plafker and others, 1977). A connection between the Fairweather and the Totschunda faults has been inferred as a recently established break less than about 65,000 years old (Lahr and Plafker, 1980). Near the intersection between the Totschunda and Denali faults, the Denali fault has a rate of displacement as high as 1.4 inches/yr (3.5 cm/yr). At the Delta River, the Denali fault bends westward and exhibits only about 0.4 to 1.8 inches/yr (1 to 2 cm/yr) rate of displacement on the McKinley strand (Hickman and others, 1978).

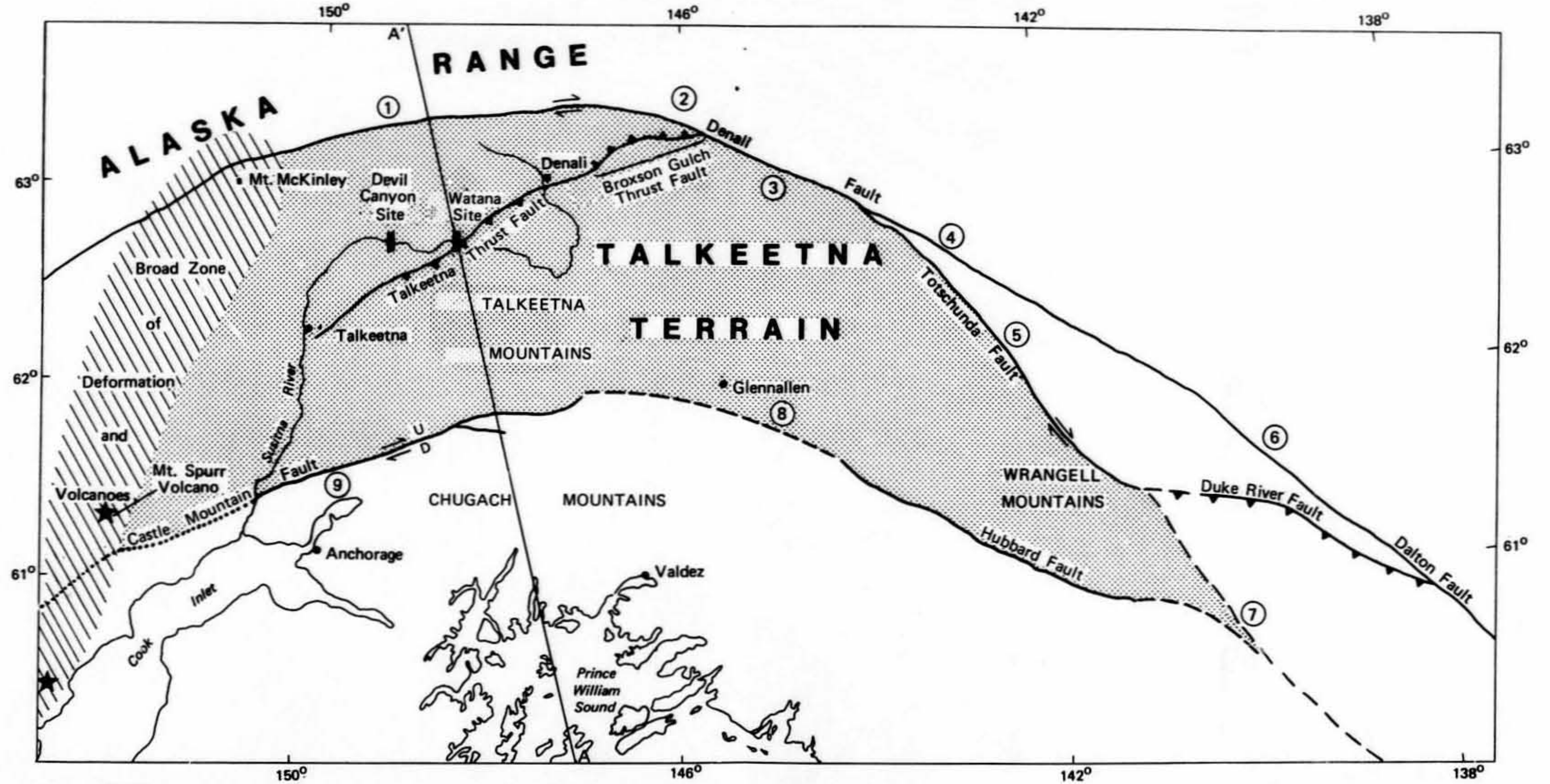
The Broxson Gulch thrust fault, described by Stout (1965, 1972), and Stout and Chase (1980) among others, trends southwestward from the Denali fault (where it intersects the Delta River) through the Talkeetna Terrain. This feature and its southwestward continuation - the Talkeetna thrust fault - is proposed to have been a major fault system in Mesozoic through Tertiary time (Csejtey, 1980) as it accommodated postulated differences in rates of rotation of paleotectonic units along the Denali fault (Stout and Chase, 1980). However, no evidence of post-Tertiary displacement along the Talkeetna thrust fault and Broxson Gulch thrust fault has been observed (Csejtey, 1980; Stout and Chase, 1980).

The sum of the rates of displacement along faults in southern Alaska are less than the rate of convergence of the Pacific Plate relative to the

North American Plate as discussed above. It is suggested here that a significant portion of that unaccounted-for convergence may be transmitted northward, even beyond the Denali fault, and is reflected at the surface in three ways: (1) as broad folds and reverse faults in the Pliocene(?) Nenana Gravels in the Nenana River valley (Wahrhaftig, 1970a, 1970b; 1970c; Hickman and others, 1978); (2) as northward thrusting along the northern front of the Alaska Range; and (3) as the overall uplift of the Alaska Range. The approximately 0.4 inches/yr (1 cm/yr) of right-lateral displacement on the McKinley strand of the Denali fault abruptly diminishes to imperceptible amounts westward from the Mt. McKinley area. The dissipation of this remaining amount of slip along the Mt. McKinley strand may contribute to ductile and brittle deformation in the interior of Alaska and the western boundary of the Talkeetna Terrain.

The western boundary of the Talkeetna Terrain is ambiguous and appears to be represented by a wide zone of uplift, predominantly as ductile deformation in a broad zone, as shown in Figure 5-1. This zone, including the volcanoes from the Aleutian chain, was chosen as the western margin because it is apparently the focal zone of uplift and deformation on the western side of the Talkeetna Terrain. The Aleutian line of volcanoes is believed to result from the down-going Pacific Plate reaching the critical depth for melting the subducted crust, resulting in magma production. This "soft zone" in the overriding plate is an appropriate location for the remaining convergent stresses in the Talkeetna Terrain to be accommodated by uplift, plastic deformation, and imbrication resulting in the broad zone of deformation shown in Figure 5-1.

Although the Talkeetna Terrain is surrounded by margins subject to deformation, the interior is relatively stable and apparently behaves as a coherent unit partly decoupled from the North American Plate. The evidence for this conclusion is the absence of major brittle deformation within the Terrain that appears to be related to current stress conditions, and the absence of major earthquakes tht clearly have occurred within the Terrain as discussed in Section 4. Major faults with recent displacement have not been observed within the Talkeetna Terrain during this investigation as discussed in Section 8. This lack of recent deformation leads to the conclusion that strain release is occurring primarily along the margins of the Terrain, as shown by the major faults (Denali, Totschunda, and Castle Mountain), and that the Talkeetna Terrain is a relatively stable unit.



LEGEND

- Mapped strike-slip fault with dip slip component (U / D)
- Mapped strike-slip fault, arrows show sense of displacement
- Mapped fault, sense of displacement not defined
- Inferred strike-slip fault
- Mapped thrust fault, teeth indicate upthrown side of block, dashed where inferred
- Mapped thrust fault, teeth indicate inferred upthrown side of block

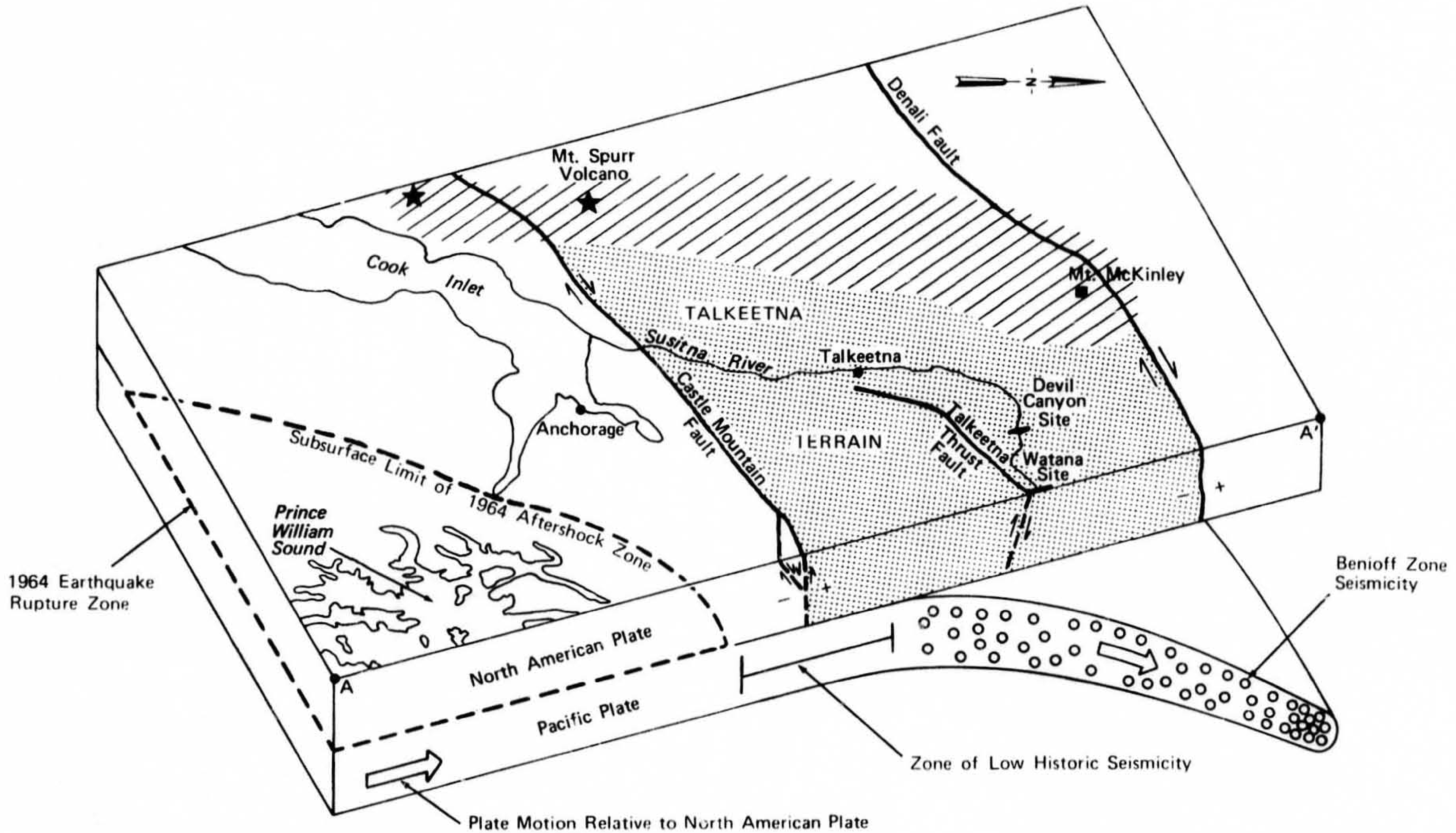
NOTES

① 0.9 - 2.0 cm/yr Hickman and Campbell, (1973); and Page, (1972).
② 0.5 - 0.6 cm/yr Stout and others, (1973).
③ 3.5 cm/yr Richter and Matson, (1971).
④ 1.1 cm/yr, no Holocene activity farther east, Richter and Matson, (1971).
⑤ 0.9 -3.3 cm/yr Richter and Matson, (1971)
⑥ Inferred connection with Dalton fault; Plafker and others, (1978).
⑦ Inferred connection with Fairweather fault; Lahr and Plafker, (1980).
⑧ Connection inferred for this report.
⑨ 0.1 - 1.1 cm/yr Detterman and others (1974); Bruhn, (1979).
10. Slip rates cited in notes ① through ⑨ are Holocene slip rates.
11. All fault locations and sense of movement obtained from Beikman, (1978).
12. Figure 5-2 presents Section A–A'.

TALKEETNA TERRAIN MODEL

0 25 50 100 Miles

0 25 50 100 Kilometers



NOTES

1. Location of Section A–A' is shown in Figure 5-1.
2. Geologic data sources include those cited in Figures 4-1 and 5-1.

SCHEMATIC TALKEETNA TERRAIN SECTION

0 50 100 Miles

0 50 100 Kilometers

FIGURE 5-2

6 - REGIONAL GEOLOGIC SETTING OF THE TALKEETNA TERRAIN

6.1 - Regional Geologic Setting

The geologic setting and geologic history of the project region are directly related to the tectonic setting of south-central Alaska as discussed in Sections 4.1 and 5, and as summarized in Figures 6-1 and 6-2. The Talkeetna Mountains and adjacent areas are continental crust accreted to Alaska as part of the dominantly allochthonous terrain comprising southern Alaska. This terrain has been interpreted to constitute an enormous tectonic mosaic composed of separate structural blocks and fragments of allochthonous continental blocks accreted to the ancient North American Plate during Mesozoic time (Figure 6-1 summarizes geologic time units) and early Cenozoic time (Richter and Jones, 1973; Csejtey, 1974; Jones and others, 1977; Csejtey and others, 1978; Jones and Silberling, 1979). Although the exact number or even the extent of these blocks is still imperfectly known, paleontologic and paleomagnetic studies suggest that the blocks moved northward considerable distances prior to collision with the North American Plate (Hillhouse, 1977; Packer and others, 1975; Stone and Packer, 1977).

Although the Talkeetna Terrain, as defined by the major structural elements bounding it (Section 5), includes the Wrangell Mountains, the area of interest for this discussion includes only the Talkeetna Mountains and adjacent topographic lowland areas. The Talkeetna Mountains are a roughly circular mountain mass separated topographically from the Alaska Range by the broad glaciated Susitna Lowland and Chulitna River valley to the west and northwest, respectively. The Copper River Lowland or Basin forms the eastern boundary (Figure 1-1). The Talkeetna Mountains are bounded on the south by the fault-controlled Matanuska valley.

The central Talkeetna Mountains are extremely rugged, and are dominated by heavily glaciated peaks between 6,000 and 9,000 feet (1,829 to

2,744 m) in elevation. To the northwest, the mountains form a broad rolling, glacially scoured upland which is dissected by deep glaciated valleys.

Stratigraphy

The rocks of the Talkeetna Mountains and adjacent areas can be classified in three distinct bedrock groups on the basis of age and rock type following in part the studies of Csejtey (1974) and Csejtey and others (1978). These bedrock groups lie within a northeast-southwest structural grain and include:

(1) a Mesozoic metasedimentary sequence of marine origin northwest of the Talkeetna thrust fault;

(2) a northeast-southwest trending Jurassic to late Cretaceous or late Tertiary batholithic complex (including Paleozoic volcanic units) southeast of the metasedimentary sequence that forms the backbone of the Talkeetna Mountains; and

(3) a late Mesozoic sedimentary and Tertiary volcanic sequence southeast of the batholithic complex (Figure 6-2).

Bedrock outcrops are often limited locally because of an extensive mantle of Quaternary deposits. Therefore, interpretations of bedrock geology (such as that shown on Figure 6-2) are often inferred locally from their limited exposures. However, aeromagnetic data have been used by various investigators to interpret the bedrock distribution and to identify lithology contrasts across faults as discussed below.

A major bedrock contrast coincides with a distinct difference in the aeromagnetic pattern in the Talkeetna Mountains. The abrupt change coincides with the major northeast-southwest trending Talkeetna thrust fault and Broxson Gulch thrust fault that juxtaposes the Mesozoic batholithic complex (including Paleozoic volcanic units) on the southeast against the Mesozoic metamorphosed sedimentary sequence on the northwest (Csejtey and Griscom, 1978). Aeromagnetic data in the Copper River basin (Andreasen and others, 1964) generally indicate a parallel geologic grain that correlates with the lithology and structure of rocks exposed on the eastern Talkeetna Mountains.

The Mesozoic metasedimentary sequence northwest of the Talkeetna thrust fault, includes allochthonous Triassic and Jurassic flysch deposits and autochthonous Cretaceous flysch deposits which were deposited in marine environments and subsequently metamorphosed. The allochthonous sequence, particularly in the Chulitna area (Figure 6-2), form part of a continental crustal block that was tectonically accreted to rocks of similar age and type (the Cretaceous sequence) along the margin of the North American Plate. Most of these Triassic and Jurassic rocks do not occur elsewhere in Alaska, and fossil faunas and lithologic characteristics of the rocks suggest that they were deposited as sediments in warm water at low paleolatitudes (Jones and others, 1978).

Locally, the Triassic and Jurassic rocks experienced a moderate to high grade of metamorphism (amphibolite facies) as they moved northward on the Pacific Plate prior to their collison with the North American Plate. After collision occurred, the rocks were obducted northwestward onto the continental margin at least several hundred miles (several hundred kilometers (Csejtey and others, 1978)). The southwest trending ophiolitic assemblage of the upper Chulitna district is indicative of the oceanic crust squeezed up at the suture zone of the colliding blocks (Figure 6-2). The autochthonous Cretaceous flysch deposits are described by Csejtey and others (1978) as a monotonous turbidite sequence of argillite and graywacke sandstone which was probably deposited on the margin of the North American Plate.

The Jurassic to early Tertiary batholithic complex includes epizonal and mesozonal plutons that underlie large portions of the central Talkeetna Mountains (Figure 6-2). Compositions range from biotite-hornblende granodiorites to tonalite (Csejtey and others, 1978). Csejtey and others (1978) indicate that the epizonal granitic rocks of Jurassic age are associated with regional metamorphism and deformation during a Jurassic tectonic event. Emplacement of early Tertiary and Cretaceous multiple intrusions is probably a product of the middle Cretaceous alpine style orogeny resulting from crustal block convergence; many of the plutons exhibit well-developed northeast-southwest trending shear foliation (Csejtey and others, 1978). The shearing causing the foliation is as much as 15 miles (25-km) wide and trends across the Talkeetna Mountains parallel to, and southeast of the Talkeetna thrust fault.

The batholith complex is bordered on the northwest within the central Talkeetna Mountains by a Paleozoic volcanic (and metavolcanic) sequence that includes some Triassic volcanic units (Figure 6-2). This volcanic sequence is described by Csejtey and others (1978) as marine sequence of volcanic flows, tuffs, and volcanic clastic deposits which have subsequently been metamorphosed.

The late Mesozoic sedimentary and Tertiary volcanic sequence (southeast of the Jurassic to early Tertiary plutons) consists of Cretaceous, clastic shelf deposits belonging to the Matanuska Formation and a Paleocene to Miocene felsic to mafic subaerial volcanic sequence which in part overlies portions of the plutonic rocks. The volcanic sequence consists of intercalated flows and pyroclastic deposits interpreted to be vent and near-vent deposits of stratovolcanoes.

These rocks are deformed by a complex pattern of normal and high-angle reverse faults which are part of the late Cenozoic Castle Mountain fault.

Structure

In the Talkeetna Mountains rocks have undergone complex and intense thrusting, folding, shearing, and differential uplift with associated regional metamorphism and plutonism. At least three major periods of deformation are recognized by Csejtey and others (1978): (1) a period of metamorphism, plutonism, and uplift in the Jurassic Period; (2) a middle to late Cretaceous alpine-type orogeny; and (3) a period of normal and high-angle reverse faulting and minor folding in the Tertiary Period possibly extending into the Quaternary Period.

Jurassic deformation is characterized by emplacement of epizonal granodiorite plutons and associated regional metamorphism which altered the broad clastic marine sedimentary wedge to the north. Simultaneous crustal uplift caused rapid denudation of the plutons and produced a major nonconformity of the Talkeetna Formation, an interbedded Jurassic sedimentary and volcanic rock sequence located to the southeast of the Talkeetna Mountains (Figure 6-2). The dominant features of the middle Tertiary to Quaternary deformation are the Castle Mountain fault and two normal faults in the Chulitna River valley.

Most of the structural features in the region are a result of the Cretaceous orogeny associated with accretion of northwest drifting continental blocks to the North American Plate (as discussed in Section 4.1). This plate convergence produced a pronounced northeast-southwest trending regional structural grain. The orogeny is typified by complex folding and thrusting as these continental allochthonous rocks were obducted upon the edge of the North American Plate.

The mountains of the Alaska Range are a product of this deformation. Deformation is particularly intense northwest of the Jurassic and Cretaceous plutonic belt. Folds are isoclinal with amplitudes from several hundred to several thousand meters, and the limbs are generally sheared or faulted out (Csejtey and others, 1978). Several episodes of the orogeny are indicated by thrust faults which not only truncate folds but are themselves folded.

The Talkeetna thrust fault (including the Broxson Gulch thrust fault) is the most prominent of the Cretaceous faults within the Talkeetna Mountains. Csejtey and others (1978) indicate that Paleozoic, Triassic, and Jurassic rocks are thrust northwestward over the Cretaceous flysch sequence on a southeast dipping fault--the Talkeetna Thrust fault. However, aeromagnetic data interpretations by Csejtey and Griscom (1978) and Griscom (1978) indicate that the southern extension of the fault south of the Talkeetna Mountain quadrangle dips northwest. Work on the Broxson Gulch thrust fault, the northern extension of the Talkeetna thrust fault, by Stout (1965) and Stout and Chase (1980) indicates that the fault also dips northwest.

The age of the Cretaceous orogeny is well-bracketed by stratigraphic evidence. The youngest rocks involved are Cretaceous argillite and graywacke sandstone units that have large folds and well-developed axial plane slaty cleavage. Late Paleocene granitic plutons intrude the folded and faulted country rock including the Talkeetna thrust fault but are structurally unaffected. A slightly older upper age bracket is provided by the 61 to 75 m.y. old tonalite (or quartz diorite) pluton that cuts and is unaffected by the prominent shearing in the central Talkeetna Mountains (Csejtey and others, 1978). The most important orogenic deformations, therefore, must have taken place during middle to late Cretaceous time.

Tertiary deformations are expressed by a complex system of normal, oblique-slip, and high-angle reverse faults. The Castle Mountain fault, along which the southern Talkeetna Mountains have been uplifted locally as much as 9,184 feet (2,800 m) (Detterman and others, 1976), exhibits evidence of activity continuing to the present (Section 7.2). The Denali fault, a right-lateral strike-slip fault (as discussed in Sections 4.1, 7.2, and 8.4) exhibits evidence of fault displacements in Tertiary and Quaternary time. Deformation is associated with continued northwest convergence of the Pacific Plate with respect to the North American Plate as described in Sections 4.1 and 5.

6.2 - Regional Surface Geology

By the end of the Tertiary Period, most of the area within the Talkeetna Terrain was elevated to approximately its present elevations. Beginning in Quaternary time, slight climatic modifications altered the erosive processes, i.e., the physical weathering. These processes changed from those dominant in temperate climates to those processes characteristic of glacial and periglacial environments--glacial scour, frost action, and solifluction. The intensity of the climatic conditions fluctuated through the Quaternary Period, but active glaciers along the southern flank of the Alaska Range and the high peaks of the Talkeetna Mountains indicate that these geomorphic processes are active today throughout much of the region. Glaciers covered about 50 percent of the present area of Alaska at various times, but the area south of the Alaska Range crest was nearly inundated by ice (Pewe, 1975). Coalescing ice from both the Talkeetna Mountains and the Alaska Range merged to form icecap conditions. As a result, Quaternary to Recent deposits (including colluvium) mantle virtually all of Alaska. These unconsolidated units include fluvial, glacial, lacustrine, and colluvial deposits (Figure 6-3).

The surface geology map (Figure 6-3) modified from Karlstrom and others (1964) indicates that much of the mountainous and hilly regions are veneered with coarse pebbly to fine-grained colluvial deposits. Intense frost shattering and solifluction, results of the rigorous climate, have produced rock and soil debris which mantle all but the steepest slopes. Glacial scouring by alpine glaciers, which followed pre-existing stream valleys, cut deep U-shaped valleys into the upland areas.

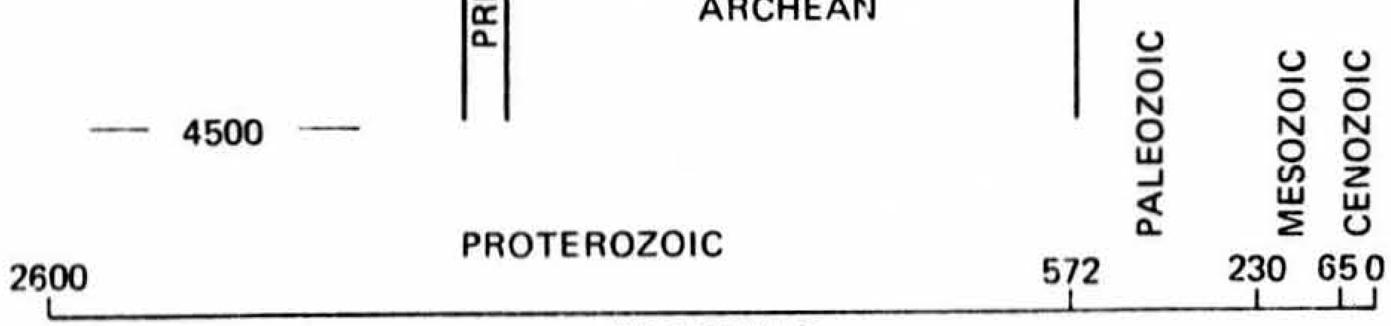
Three different ages of Pleistocene drift units have been identified. Differentiation of drift units is based on position and extent of the deposits and on the degree of morphologic modification of the associated moraines. Age assignments and correlation of glacial deposits by Karlstrom and others (1964) for selected areas indicate that: highly modified moraines are pre-Illinoian; modified moraines are Illinoian; and little modified moraines are Wisconsinan (Figure 6-3). Significant morainal complexes, which define the limits of a particular glaciation or of prominent advances, are also indicated in Figure 6-3.

Extensive deposits reported to be of glacio-lacustrine origin are found in the Susitna Lowland/ Cook Inlet area and in the Copper River Basin area in the southeastern part of the site region (Figure 6-3). Convergence of glacial flow from the surrounding mountains repeatedly blocked drainage, thus producing huge proglacial lakes. The reported lacustrine deposits are finely laminated, rhythmically bedded sand, silt, and clay with ice-rafted pebbles (Pewe, 1975). Although reported as lake clay in the Cook Inlet area by Karlstrom (1964) and Karlstrom and others (1964), detailed studies of fossil forminifera from drill core indicate the clay may be of marine origin (Hansen, 1965).

Alluvial fan deposits are restricted to the north side of the Alaska Range where alpine-style glacial processes are dominant. The terrestrial sands and gravels are confined in the upland areas between major valleys but cover broad areas north of the foothills and the northern limits of glacial deposits.

Fluvial, valley train, and terrace deposits are found along the major river valleys and ncluding those downstream from active glaciers. Most of the major rivers receive glacial meltwater, consequently, most fluvial deposits generally consist of unconsolidated clean sand and gravel. Valley trains are currently being formed by broad anastamosing meltwater streams carrying voluminous amounts of outwash debris. Although terraces are similar in lithology and origin to modern valley trains, rejuvenation of river downcutting has isolated these surfaces from active deposition.

ABSOLUTE AGE (In millions of years Before Present)	ERA	PERIOD		EPOCH	SIGNIFICANT EVENTS IN TALKEETNA TERRAIN
	CENOZOIC	QUATERNARY		HOLOCENE (RECENT)	
0.01				PLEISTOCENE	Glaciation
1.8		TERTIARY	NEOGENE	PLIOCENE	Normal and high angle faults developed. Uplift of southern Talkeetna Mountains along the Castle Mountain fault of approximately 2800m (Pliocene–Oligocene)
				MIOCENE	
22.5			PALEOGENE	OLIGOCENE	
				EOCENE	
				PALEOCENE	Plutonism
65	MESOZOIC	CRETACEOUS			Continental accretion and orogenesis including faulting (reverse and thrust along NE–SW trending faults), folding, low-grade metamorphism and uplift.
141		JURASSIC			Vulcanism, Plutonism, Metamorphism ← Nonconformity
195		TRIASSIC			Vulcanism
230	PALEOZOIC	PERMIAN			Vulcanism and sedimentation in distant terrains prior to accretion.
280		Carboniferous	PENNSYLVANIAN		
			MISSISSIPPIAN		
345		DEVONIAN			
395		SILURIAN			
435		ORDOVICIAN			
502		CAMBRIAN			
572	PRECAMBRIAN – PROTEROZOIC	HADRYNIAN			
1000		HELIKIAN			
1800		APHEBIAN			
2600	PRECAMBRIAN	ARCHEAN			
4500					



BAR SCALE
(In millions of years Before Present)

NOTES

1. Time scale is after Van Eysinga (1978).
2. Geologic events are from data sources identified in the text.

GEOLOGIC TIME SCALE

FIGURE 6-1

7 - GEOLOGIC SETTING OF THE SUSITNA HYDROELECTRIC PROJECT REGION

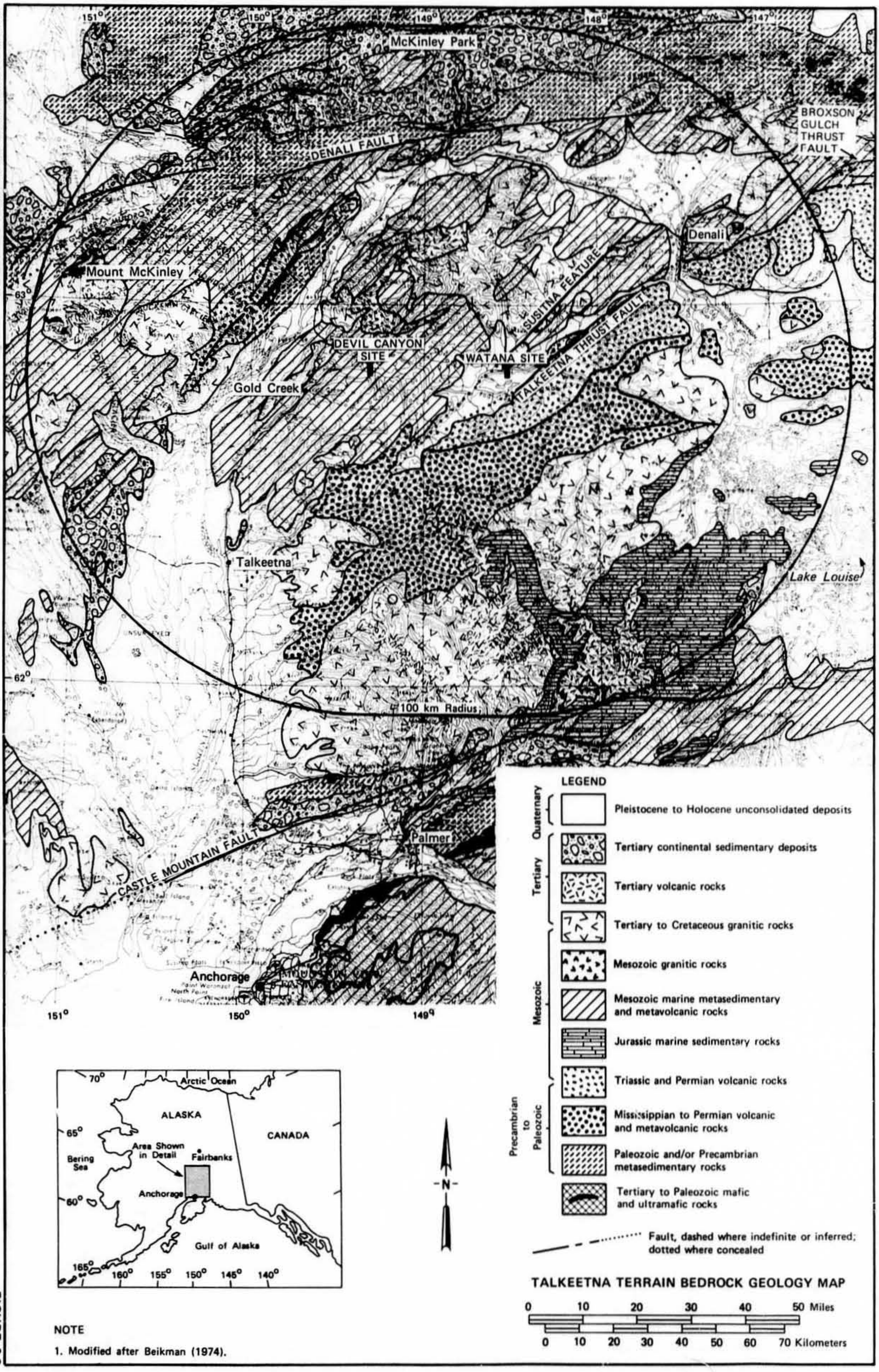
7.1 - Geologic Setting of the Project Area

The geologic setting and structural features characteristic of the Project area, which are shown in Figure 7-1, result from, and are an integral part of the regional geologic conditions as outlined in Section 6.1. The rock types and structural elements are a function of a complex history of deformational episodes associated with plate tectonic interaction. The geologic map, modified after Csejtey and others (1978), covers both the Devil Canyon and Watana sites and associated areas (Figure 7-1). Detailed mapping supplemented by radiometric age dating (Csejtey and others, 1978) has allowed some refinement of the rock types and ages presented by Beikman (1974) (Figure 6-2). The only other detailed geologic study prior to Csejtey and others (1978) was that by Kachadoorian (1974), who investigated the geology of the area about the Devil Canyon site. In addition, this area has been included as part of larger regional geologic and tectonic studies by numerous investigators.

The physiography of the area varies from rugged, steep, glacial-sculptured mountain ridges in the southeast and north to a broad, glacially scoured upland plateau to the west. A broad, structurally controlled intramontane basin trends northeast-southwest through the central portion of the area shown in Figure 7-1. Drainage generally parallels the regional topographic grain--northeast-southwest. The Susitna River valley, except for minor deflections, cuts obliquely across the regional grain.

7.1.1 - Bedrock

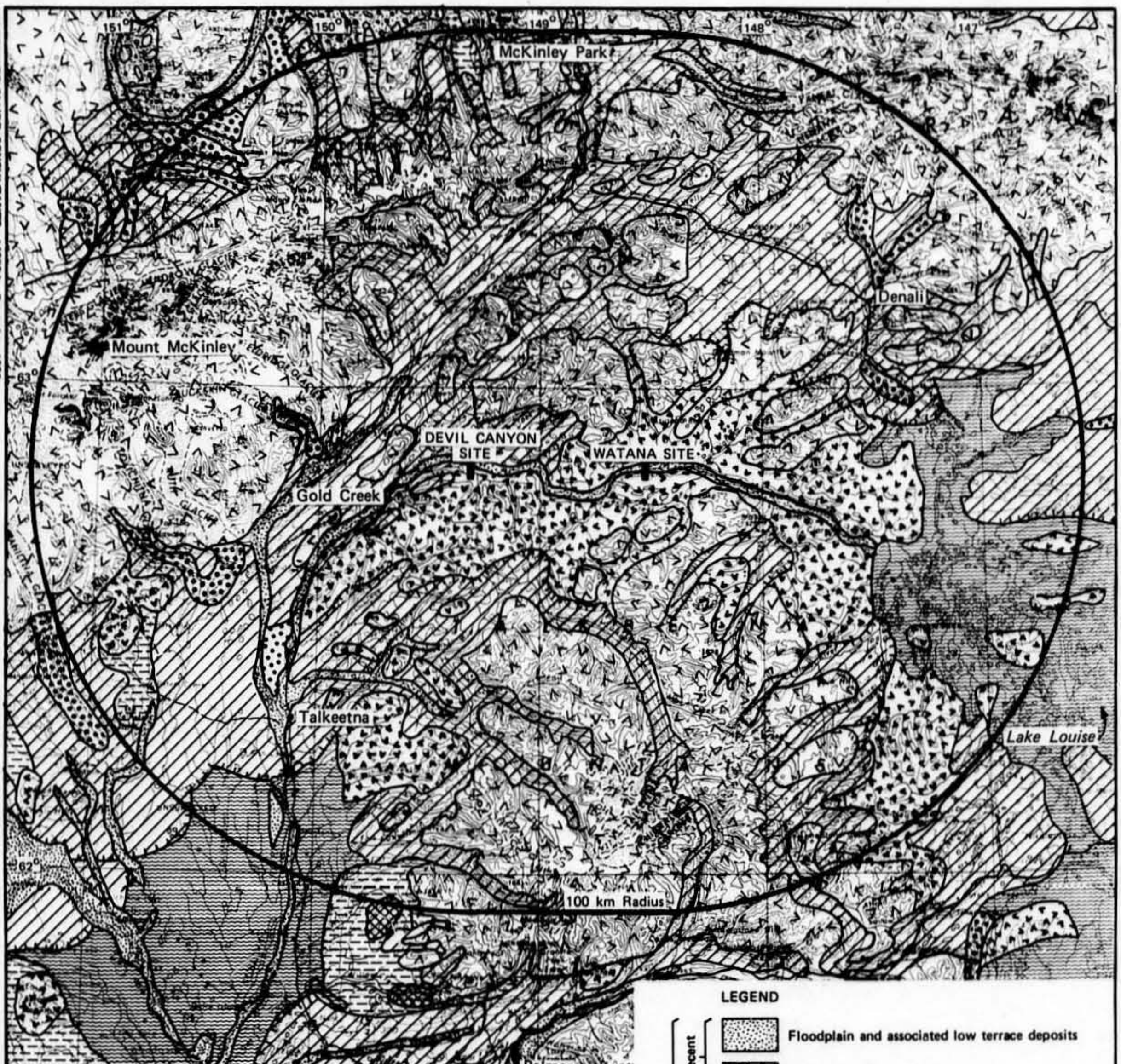
The oldest rocks in the Talkeetna Mountains occur in a northeast-southwest trending belt across the southeast corner of the Project



TALKEETNA TERRAIN BEDROCK GEOLOGY MAP

NOTE

1. Modified after Beikman (1974).



TALKEETNA TERRAIN
SURFACE GEOLOGY MAP

NOTE

1. Modified after Karlstrom and others (1964).

FIGURE 6-3

area (Figure 7-1). This unnamed unit consists of a dominantly Pennsylvanian to Permian marine sequence of interlayered metabasalt to metaandesite flows and tuffs with subordinate fine-grained clastic units and has an aggregate thickness over 16,400 feet (5,000 m) (Csejtey and others, 1978). The composition and lithologic character of the sequence strongly suggests that it represents a remnant of a complex volcanic arc system (Csejtey, 1974; 1976). Regional metamorphism in early to middle Jurassic time produced low-grade metamorphic mineral assemblages. During the later alpine-type orogeny in middle to late Cretaceous time, the whole sequence was tightly folded and complexly faulted. Displacement along the Talkeetna thrust fault has juxtaposed these Paleozoic rocks against Mesozoic rocks to the northwest.

Triassic and Jurassic metasedimentary, and metavolcanic rocks unconformably overlie Paleozoic rocks. Triassic rocks consist of a shallow-water marine sequence of amygdaloidal metabasalt flows and thin interbeds of chert, argillite, and marble in the eastern part of the Project area (Figure 7-1) and a similar sequence of interbedded amygdaloidal metabasalt flows and slate in the northwestern part of the Project area. The lithologies of the metabasalts are virtually identical, and these two rock sequences may have been deposited in different locales and subsequently were brought closer by Cretaceous age thrusting. Mineralogy suggests that both sequences underwent low-grade regional metamorphism associated with early to middle Jurassic plutonism and deformation (as discussed in Section 6.1).

A lower to middle Jurassic amphibolite unit lies in close proximity to middle to upper Jurassic granodiorite plutonic rocks in the southeastern corner of the Project area (Figure 7-1). The amphibolite includes subordinate amounts of greenschist and foliated diorite. The metamorphic rocks were probably derived from both the Paleozoic volcanogenic sequence and the Triassic metabasalt sequence. Adjacent to the amphibolite are dominantly plutonic rocks of granodiorite composition emplaced as multiple intrusions from a common magma source. Isotopic age determinations indicate emplacement took place between 150 and 175 m.y.b.p. (Csejtey and others, 1978). The northwest margin of both the granodiorite and amphibolite have been cataclastically deformed by Cretaceous aged shearing producing a pronounced northeast-southwest trending secondary foliation.

The plutonic and metamorphic rocks associated with Jurassic plutonism and metamorphism were regionally uplifted and experienced subsequent rapid erosion. Material eroded from the uplifted region was deposited as a monotonous flysch sequence of lower Cretaceous shale (subsequently altered to argillite) and lithic graywacke sandstone. These units are present northwest of the Talkeetna thrust fault as shown in Figure 7-1. The lithic graywacke sandstone consists of angular to subrounded grains of fragments from aphanitic volcanic rocks, low-grade metamorphic rocks, and fine-grained sedimentary rocks. Sedimentary structures within the flysch deposits, such as cross-stratification, are evidence for deposition from east and northeast source areas towards the west and southwest. These flysch deposits have undergone low-grade dynamometamorphism, complex thrust faulting, and compression into tight and isoclinal folds (Csejtey and others, 1978; 1980) as a result of the Cretaceous orogeny.

Undifferentiated Paleocene granite and schist units are confined to the northeast quadrant of the Project area (Figure 7-1). These rocks consist of small granitic bodies, lit-par-lit type migmatite, and pelitic schist. Contacts among these units are generally gradational. The proximity of the schist to the small granitic bodies and the occurrence of lit-par-lit injections are suggestive of contact metamorphism in the roof zone of a large Paleocene pluton.

Undifferentiated Tertiary sedimentary rocks are exposed along Watana Creek (Figure 7-1). The rocks consist of fluviatile conglomerate, sandstone, and claystone with thin interbeds of lignitic coal. The lack of fossil evidence precludes definitive correlation with similar lithologic units in the southern Talkeetna Mountains outside of the site region (Figure 6-2).

During the late stages of the Cretaceous orogeny into early Tertiary time, northwest convergence of the continental blocks (Section 5) led to the intrusion of plutons (of different compositions) into the flysch and older country rocks. These plutons were intruded primarily into the Cretaceous argillite and lithic graywacke sandstone sequence as shown in Figure 7-1. Radiometric age determinations of the plutons (composed of biotite granodiorite and the biotite-hornblende granodiorite) suggest they were intruded in Paleocene time approximately 56 to 58 m.y.b.p. Comparative whole rock chemical compositions indicate that these granitic rocks may be plutonic equivalents of some of the felsic volcanic rocks in the lower portion of the overlying Paleocene to Miocene volcanic rocks, discussed below.

Undifferentiated Paleocene to Miocene volcanic rocks consist of a thick sequence of felsic to mafic subaerial volcanic rocks and related shallow intrusives. This sequence is present throughout the Project area (Figure 7-1). Lower parts of the sequence consist of small stocks, irregular dikes, lenticular flows, and thick layers of pyroclastic rocks ranging in composition from quartz latite to rhyolite, possibly equivalent to the Paleocene plutonic rocks described above. Upper parts of the sequence consist of gently dipping andesite and basalt flows interlayered with minor amounts of tuff.

Quaternary deposits mantle much of the surface shown in Figure 7-2. A detailed discussion of these Quaternary deposits and the glacial chronology of the area is presented in Section 7.2.

7.1.2 - Structure

The three main structural features identified by Csejtey and others (1978) in the Project area shown in Figure 7-1 are the Talkeetna thrust fault, a northeast-southwest trending zone of inferred shearing and an unnamed thrust fault northwest of the Talkeetna thrust fault. These structural features are believed to be the result of the Cretaceous orogeny associated with accretion of the northwestward moving Talkeetna Terrain to the North American Plate (Section 5). The accretionary process and Cretaceous orogeny produced a pronounced northeast-southwest trending structural grain which in turn controls the topography.

The allochthonous continental block was obducted onto the North American Plate several hundred kilometers. The main thrust fault, along which most movement presumably occurred, is the Talkeetna thrust fault (including the Broxson Gulch thrust fault) (Figure 7-1). Although the Susitna feature (Turner and Smith, 1974; Turner and others, 1974) is discussed in Section 8 and identified in Figure 7-1, it was not included on the original map by Csejtey and others (1978) because Csejtey found no evidence for its existence anywhere along the suggested topographic lineament (Csejtey, 1980).

Although the Talkeetna thrust fault is poorly exposed, Csejtey and others (1978) indicate a southeast-dipping fault as shown in Figure 7-1. However, interpretations of aeromagnetic data by Griscom (1978) suggest that the possible extension of the fault southwestward of the Susitna River near Talkeetna dips northwest. Studies on the Broxson Gulch thrust fault, the northeast extension of the Talkeetna thrust fault, by Stout (1965) and Stout and Chase (1980) and Chase (1980) indicate this segment dips northwest. Continued studies are needed in the project area in order to determine the fault orientation. Stratigraphic evidence indicates that the fault is intruded by Paleocene plutonic rocks, and overlain by Tertiary volcanic units that are structurally unaffected by the fault (Csejtey and others, 1978). These relationships suggests that movement on the Talkeetna thrust fault ceased by Paleocene time; however, the evidence is not conclusive.

The zone of Cretaceous shearing, as inferred by Csejtey and others (1978), lies parallel to and southeast of the Talkeetna thrust fault (Figure 7-1). These authors believe the zone may represent an old thrust zone of significant displacement which altered Jurassic plutonic rocks to cataclastic gneiss. Dips are generally southeast, and it is locally as much as 15 miles (25 km) wide. A Cretaceous to Paleocene age tonalite pluton truncates this shear zone and is not affected by it, suggesting that the shear zone is pre-Paleocene in age.

The unnamed thrust fault (northwest of the Talkeetna thrust fault) trends east-west in the northern portion of the project area (Figure 7-1). Along this fault, upper Triassic metabasalt flows and slate have been thrust southward over Cretaceous argillite and lithic graywacke sandstone. The metabasalt flows are similar in age and lithology to the metabasalt flows to the southeast. The two sequences may represent different facies of the same geologic terrain brought closer together by Cretaceous crustal shortening associated with convergence of the plates.

7.2 - Surface Geology of the Project Area

As indicated previously in Section 6.2, much of the Project area has been glaciated in Quaternary time and is now mantled by various glacial deposits (Figure 6-3). Understanding the Quaternary chronology and correlation of these deposits is important for the evaluation of the relative age or absolute age of units that may be involved in recent faulting.

For this investigation, the surface geology study area (designated here as the area shown in Figure 7-2) included both the Devil Canyon and Watana areas and major segments of the significant features described in Section 8.5 The study area shown in Figure 7-2 was selected to include sufficient geographic area to be representative of the glacial history in the Project area.

Little information is available in the published literature regarding the glacial history of, or Pleistocene deposits in the Talkeetna Mountains. The geology map of the Project area by Csejtey and others (1978) does not differentiate Quaternary sediments as shown in Figure 7-1. An undated surface geology map by the U. S. Army Corps of Engineers distinguishes till, lacustrine, and alluvial sediments, but the area of the map is limited to a zone on either side of the Watana site and reservoir area.

Because of the lack of glacial geologic information in the site area, a preliminary glacial geology study was conducted as a part of this investigation. Dr. Norman Ten Brink, of Grand Valley State College, Michigan, conducted a reconnaissance study of the area to identify the major Quaternary units and to develop preliminary criteria (based on weathering characteristics) for relative age dating of the units. Weathering characteristics have been used as a consistent and reliable relative age-dating technique for the glacial deposits on the north side of the Alaska Range (Ten Brink and Ritter, 1980; Ten Brink and Waythomas, in press). However, evaluation of weathering rates on the south side of the Range suggests that weathering is much more rapid than on the north side because of increased precipitation on the south side.

During this glacial geology study, weathering data on glacial drift of known age were collected to establish a weathering-rate base line. These weathering data were used as a basis for estimating relative ages of deposits of unknown age. Data were gathered from morainal sequences in the Butte Lake area and in the area east of Stephan Lake (Figures 7-2 and 7-3) and were compared to weathering characteristics of similar glaciogenic deposits of known age in the Sik Sik Lake area and the Amphitheater Mountains (Figure 7-3). Although these data permit approximate estimates of ages for glacial deposits in the Project area, additional field data of both the base-line weathering rates and weathering parameters are needed to provide for greater confidence in the results.

In order to better understand the glacial history, and to supplement Dr. Ten Brink's work, aerial photographic interpretation from U-2 color near-infrared photographs combined with low altitude aerial reconnaissance was conducted within the area shown on Figure 7-2 to map the surface geology. On the basis of morphologic expression and geographic position, various Pleistocene to Holocene glacial deposits and landforms were identified. Six types of deposits were identified: (1) bedrock with a veneer of till and erratics; (2) till; (3) glaciofluvial deposits; (4) lacustrine deposits; (5) ice disintegration drift; and (6) fluvial deposits (Figure 7-2). The following discussion summarizes the preliminary results of this study:

7.2.1 Pleistocene and Holocene Deposits

Bedrock with a Veneer of Till and Erratics

Bedrock of various types is inconsistently veneered by generally less than 3 feet (0.9 m) of glacial drift and scattered glacial erratics (Figure 7-2). Locally, thicker drift occurs in topographic lows such as glacial grooves. Bedrock scour, particularly of the uplands within the Devil Canyon area, indicates that the surface was glaciated but not necessarily in Wisconsin time, by flowing ice that produced streamline-molded forms such as whalebacks, stoss and lee, crag and tail, and bedrock drumlins. Smaller scale features etched into the bedrock include grooves and striations. Landforms created by glacial erosion and deposition are found over much of the upland plateau south of Devil Canyon.

Till

Ground moraine, generally thicker than 3 feet (0.9 m), and associated end moraine features cover much of the study area (Figure 7-2). Both the ground and end moraines are composed of nonstratified sand and cobbles with a silt and clay matrix, i.e., glacial till. Ground moraine is commonly characterized by large scale fluting such as in the Fog Lakes area.

Concentrations of till in elongated and narrow ridges (end moraines) are common. In the study area, the end moraines include lateral, medial, recessional, and terminal moraines, These end moraines have been used to indicate glacial extent in the study area. Numerous closely nested end moraines are present (Figure 7-2) which indicate a complex history of glacial advances, retreats, and readvances. The orientation and position of end moraines within the area indicate a southward convergence of large glaciers from the Alaska Range with local glaciers that originated in the Talkeetna Mountains.

Preliminary estimates of age, based on weathering data collected during this investigation, together with morphologic characteristics indicate that late Wisconsin ice reached maximum elevations of 4,000 feet (1,220 m) near Butte Lake, 3,500 feet (1,067 m) near the Big Lake/Deadman Creek area, and 2,700 to

2,800 feet (823 to 854 m) east of Stephan Lake at the mouth of an unnamed valley (Figure 7-2).

Ten Brink and Waythomas (in press) have subdivided late Wisconsin deposits north of the Alaska Range into four units, or stades, on the basis of weathering characteristics and radiometric age dates. Whether or not the characteristics of these stades can be applied to deposits from glaciers originating on the south side of the Alaska Range and the Talkeetna Mountains remains to be determined. However, four morainal sequences of inferred Wisconsin age have been identified in the Butte Lake area, east of Stephan Lake, and west of Clark Creek during this investigation at locations designated as (1), (2), and (3), respectively, in Figure 7-2.

Within the site region, early Wisconsin moraines are less prominent and less frequent than late Wisconsin landforms. Small lateral morainal segments in the Portage Creek, Indian River, and Chulitna River areas as well as in area (2) are all 400-600 feet (122 to 183 m) higher than late Wisconsin moraines. Constructional Illinoian glacial deposits are not distinguishable, but Illinoian till sheets may veneer bedrock, particularly on the scoured upland plateau around the Devil Canyon site and to the south.

Glaciofluvial Deposits

Glacial outwash consisting of typically well-sorted sands and gravels have been deposited by pro-glacial rivers draining active glaciers. The deposits are confined to valley bottoms, usually in the form of terraces and valley trains. Watana Creek, Deadman Creek, Prairie Creek, and the Susitna and Talkeetna

Rivers probably served as drainages for meltwater from Wisconsin glaciers and deposited extensive outwash trains.

Lacustrine Deposits

Lacustrine deposits form broad, flat plains and overlie glacial till in the Watana Creek area, just north of the Susitna River, and in the Deadman Creek/Brushkana Creek areas (Figure 7-2). The lacustrine silts and clays contain ice rafted gravel and cobbles and are locally interbedded with deltaic sediments. The southern border of lake sediments in the Watana Creek area coincides with the northern edge of the fluted ground moraine. This relationship suggests that the side of the flowing glacial ice acted as a dam blocking meltwater derived from glaciers to the north.

Ice Disintegration Drift

Ice disintegration deposits scattered throughout the study area (Figure 7-2) have a characteristically hummocky kame-and-kettle morphology. These deposits, typically ice-contact ablation drift and ice-contact stratified drift, are end members of a gradational sequence of stagnant ice deposits and their composition and degree of stratification are a function of the amount of reworking by meltwater. These deposits were formed by stagnant ice masses during deglaciation when glacier fronts were retreating. Consequently, these deposits are valuable in understanding the glacial chronology.

Fluvial Deposits

Significant fluvial deposits of Holocene age are confined to valleys of larger river systems such as those of the Susitna, Talkeetna, and Chulitna Rivers. In these valleys, reworked glacial deposits and eroded bedrock material have been deposited in active floodplains and adjacent abandoned terraces.

7.2.2 - Glacial History

The glacial chronology of the project area is complex. Unlike the systematic sequence of alpine glacial events on the north side of the Alaska Range, ice cap conditions and multi-directional glacial flow occurred throughout much of the Talkeetna Mountains. Glaciers from the south side of the Alaska Range pushed southward through the Deadman, Brushkana, and Watana Creek areas and the Butte Lake area to merge and coalesce with glaciers flowing from ice centers in the higher elevations of the Talkeetna Mountains. The chronology of the latest major glacial episode is better understood than is the chronology of earlier glaciations because the deposits are more frequent, prominent, and distinguishable. Closely nested morainal complexes in areas marked (1), (2), and (3) on Figure 7-2 indicate a late Pleistocene sequence of glacial advance, retreat, and readvance; however, ages of individual moraines are unknown.

On the basis of this preliminary study, late Wisconsin ice is believed to have reached approximately 2,800 feet (854 m) in elevation at the Stephan Lake area and to have risen gradually northward in response to topographic gradients to 3,500-feet (1,067 m) in elevation in the Big Lake area and to 4,000-feet (1,270 m) in elevation at Butte Lake. The four subdivisions (or stades) to the late Wisconsin glaciation, as suggested by Ten Brink and Waythomas (in press) may be represented by the series of four morainal units at Butte Lake (area (1) on Figure 7-2). If that is the case, geographic position and orientation of the moraines would indicate that at least during the latest two glacial stades, ice was not thick enough to flow over the topographic pass southwestward toward Big Lake. Alternatively, some of the moraines near Butte Lake may represent recessional moraines as late stage glaciers retreated northward.

Although less frequent, early Wisconsin morainal units in various parts of the study area suggest that ice may have reached 300 to 600 feet (91 to 183 m) higher in elevation than late Wisconsin glaciers. An area of glacially scoured bedrock and glacial debris overlying bedrock above the early Wisconsin limits indicate that an earlier glaciation, possibly Illinoian in age, inundated the area to approximately 4,000 feet (1,220 m) in elevation on the upland plateau north and south of the Devil Canyon site. Most drainage gullies and canyons of the upland plateau are V-shaped and fluvial in origin, suggesting a considerable time period since the surface was last glaciated.

The ancestral Susitna and Talkeetna Rivers served as sediment-loaded, proglacial rivers draining the glaciated areas and filling the downstream valleys with copious amounts of outwash. Decreased sediment load, caused by decreased glacial activity, has allowed the rivers to downcut and form river terraces. The longitudinal profiles of both rivers suggest considerable fluvial modification of portions of the river valleys has occurred since glaciers last overrode the valleys. A small deposit of what appears to be till lies near the Susitna River valley floor in the vicinity of the Devil Canyon site; this would indicate that the river valley existed prior to at least the last glaciation and that post-depositional fluvial downcutting or modification in this section of the valley is minimal.

With the beginning stages of late Wisconsin deglaciation, individual glaciers began to retreat towards their respective source areas. Glaciers from the Alaska Range may have begun to retreat sooner, due to their distant sources, than glaciers with Talkeetna Mountain sources. Ice did flow northward toward Big Lake, probably following retreat of the Alaska Range glaciers, and formed an arcuate southward terminal moraine which dams Big Lake. The northern edge of the fluted till sheet laid down by the northwestward advancing glacier coincides with the southern limit of extensive lacustrine deposits which overlie till in the Watana Creek area. This ice mass acted as a dam, blocking sediment-loaded meltwater from northward retreating glaciers, thus forming a large ice-dammed, proglacial lake. Finely laminated interbeds of silt and clay deposited in the proglacial lake are locally interbedded with deltaic sediments. Similar proglacial lake conditions may have existed in the Deadman/Brushkana Creek area where extensive lacustrine sediments also overlie glacial till.

Ice disintegration deposits floor many of the valleys suggesting that deglaciation was rapid and regional; many of the larger areas of deposits were formed by separation of ice fronts at topographic passes. Based on the preliminary results of this investigation, neoglacial activity appears to have been restricted to higher intermountain valleys and cirques. Fluvial processes continue to degrade and modify the Peistocene deposits.

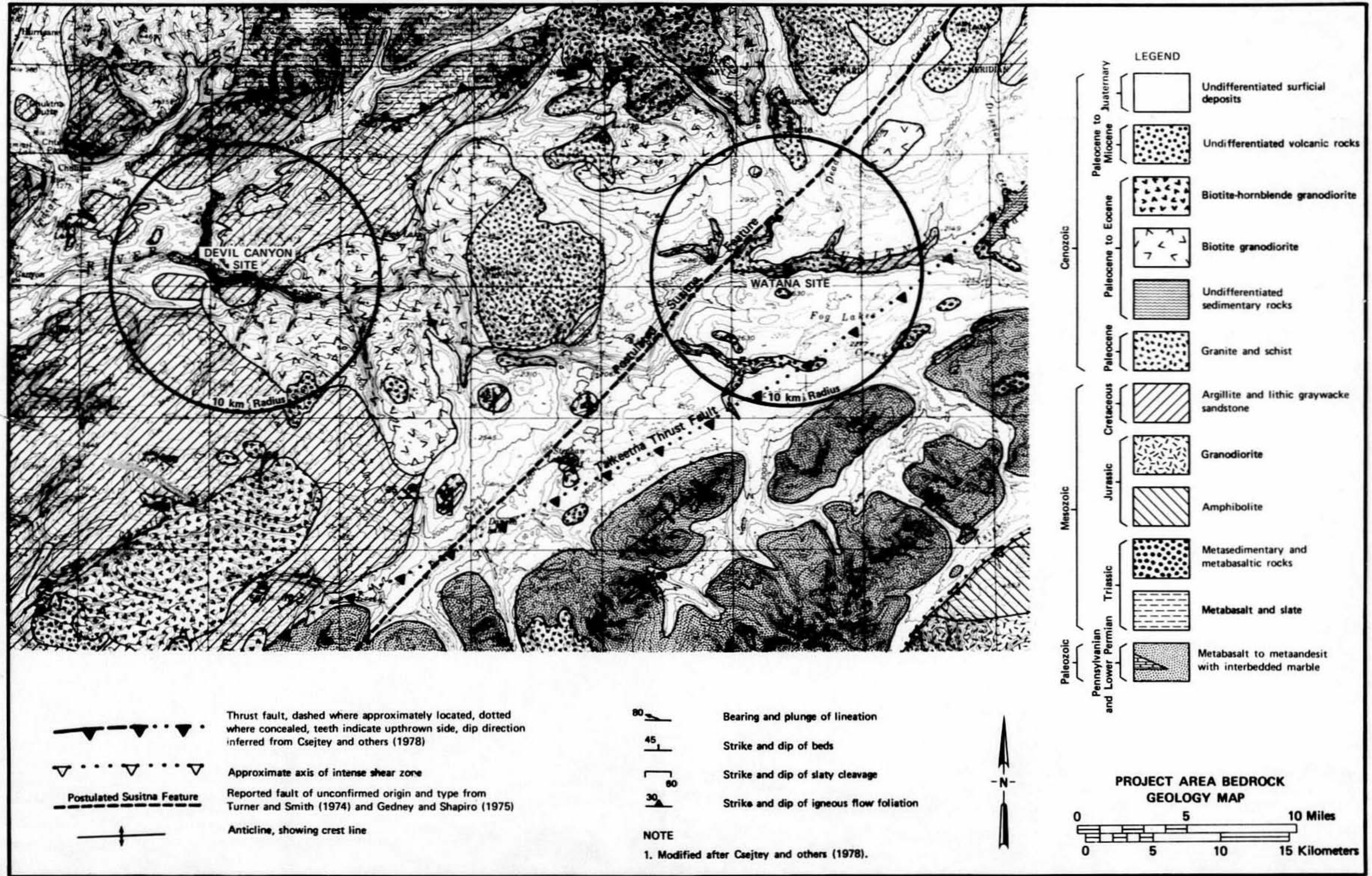

DEVIL CANYON SITE
WATANA SITE
10 km Radius
10 km Radius
Postulated Susitna Feature
Talkeetna Thrust Fault
Fog Lake
LEGEND
Cenozoic
Quaternary
Undifferentiated surficial deposits
Paleocene to Miocene
Undifferentiated volcanic rocks
Paleocene to Eocene
Biotite-hornblende granodiorite
Biotite granodiorite
Undifferentiated sedimentary rocks
Paleocene
Granite and schist
Mesozoic
Cretaceous
Argillite and lithic graywacke sandstone
Jurassic
Granodiorite
Amphibolite
Triassic
Metasedimentary and metabasaltic rocks
Metabasalt and slate
Paleozoic
Pennsylvanian and Lower Permian
Metabasalt to metaandesit with interbedded marble
Thrust fault, dashed where approximately located, dotted where concealed, teeth indicate upthrown side, dip direction inferred from Csejtey and others (1978)
Approximate axis of intense shear zone
Postulated Susitna Feature
Reported fault of unconfirmed origin and type from Turner and Smith (1974) and Gedney and Shapiro (1975)
Anticline, showing crest line
80
Bearing and plunge of lineation
45
Strike and dip of beds
60
Strike and dip of slaty cleavage
30
Strike and dip of igneous flow foliation
NOTE
1. Modified after Csejtey and others (1978).
N
PROJECT AREA BEDROCK GEOLOGY MAP
0
5
10 Miles
0
5
10
15 Kilometers

FIGURE 7-1

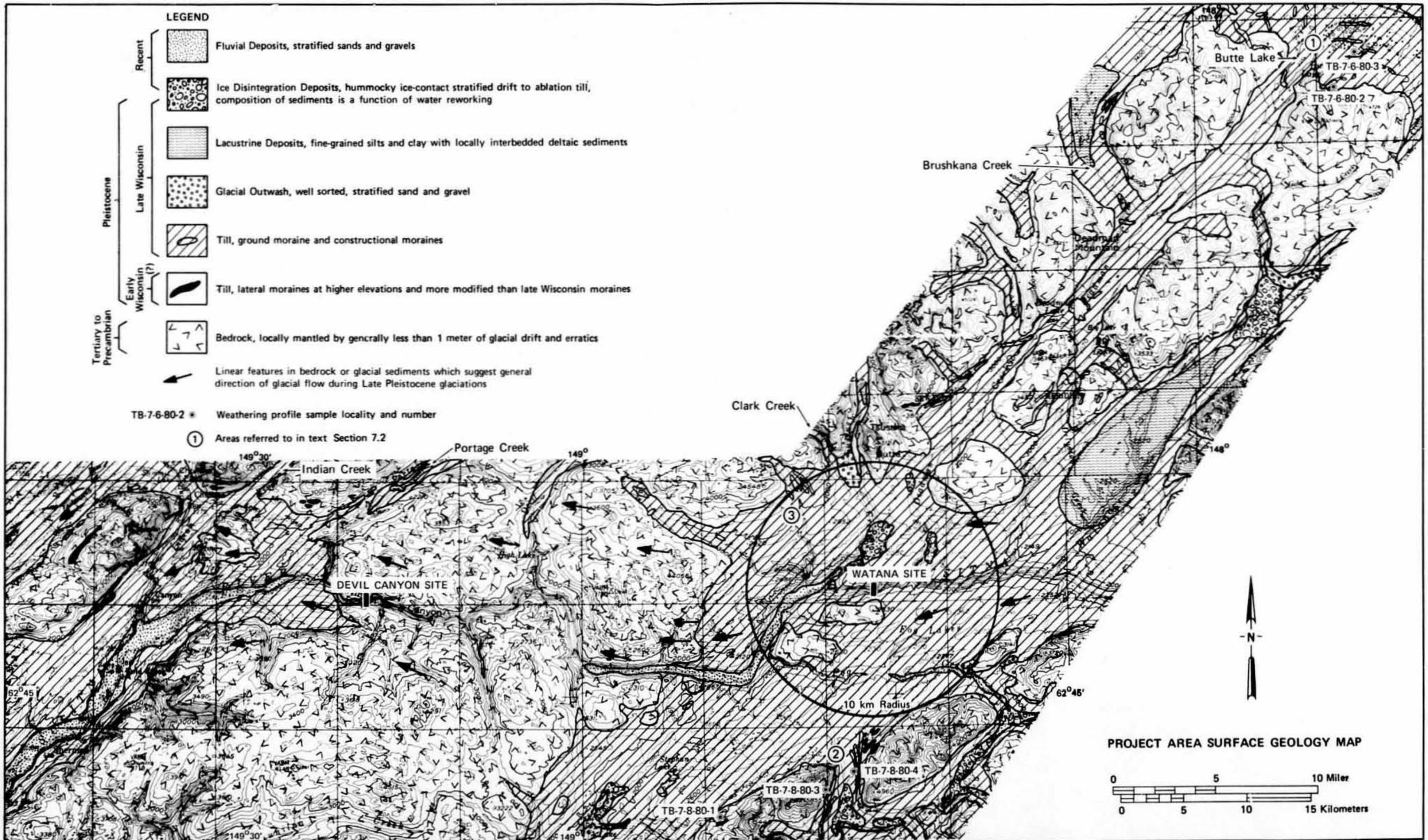


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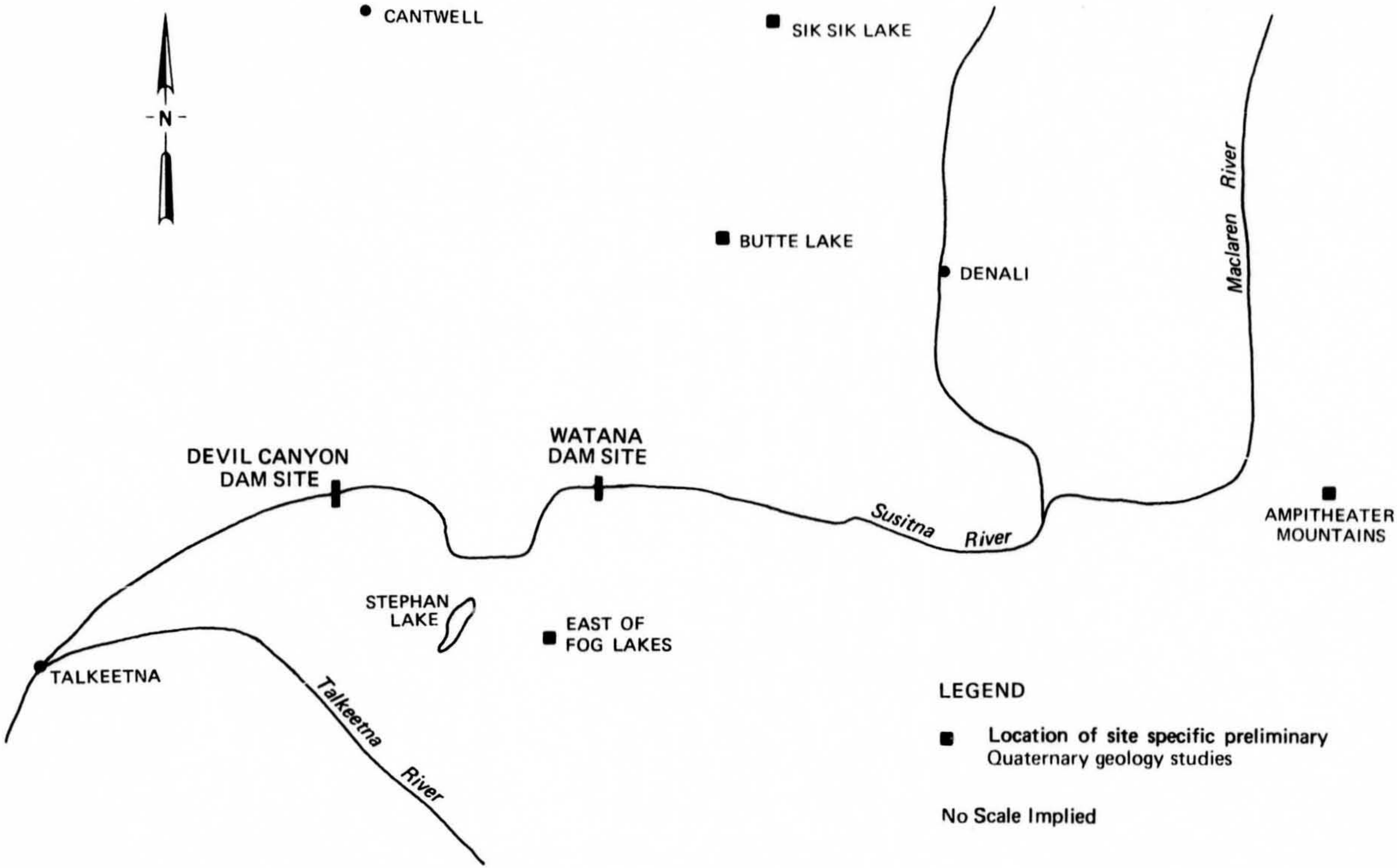
FIGURE 7-2



LOCATION MAP OF PRELIMINARY QUATERNARY GEOLOGY STUDIES

WOODWARD-CLYDE CONSULTANTS 14658A December 1980

FIGURE 7-3

8 - FAULTS AND LINEAMENTS

8.1 - Introduction

Evaluation of faults and lineaments during this study involved primarily four phases or steps as summarized earlier in Figure 2-6. The first step was a review of available literature and interpretation of remotely sensed data which led to a compilation of all mapped faults and lineaments within 62 miles (100 km) of either Project site. Length-distance screening criteria were then applied (as described in Section 3.2) to select those features of sufficient length and proximity to either site to have a potential impact on seismic design. In addition, a list of all features within 6 miles (10 km) of either site was compiled. This compilation included all features that potentially could have an impact on surface rupture through either site. All features which were too short and too far away from the sites (according to the criteria) were catalogued, but not considered further. The result of these two compilations was a group of 216 features, here called candidate features, which were to be evaluated during the 1980 field reconnaissance.

The second phase of the fault and lineament study consisted of field reconnaissance and the classification of all candidate features identified in the first step; this classification system is described in Section 8.2. The third phase was the identification of candidate significant features (described in Section 8.3). The fourth phase was the selection of significant features (also described below in Section 8.3). The outcome of these phases was the identification of boundary faults and significant features. These faults and features are discussed in Sections 8.4 and 8.5, respectively.

8.2 - Classification System

For the second phase of the fault and lineament study, a classification system was developed and adopted to permit the systematic evaluation of the candidate features during the 1980 field reconnaissance. The classification system is based on judgments (by experienced seismic geologists) as to whether or not a feature is a fault and whether or not the feature has had recent displacement. The geologic characteristics used to make the judgments are summarized in Table 8-1. A summary of how the judgments were applied to the classification system is shown in Figure 8-1.

The underlying basis of the classification system is that features should be given the "worst case" classification unless evidence is present that argues against that classification. For example, if a feature is a fault and has no overlying Quaternary deposits, it is classified in the category that implies the highest likelihood of recent displacement even though there is no evidence of recent displacement. The feature is assumed to have the potential for recent displacement until evidence of no recent displacement is obtained.

The following discussion presents the basis for the classification system which was applied to candidate features during the field reconnaissance portion of this investigation. The evidence used to classify these candidate features was documented using the procedures discussed in Appendix A. The consideration of candidate features classified as A, B, and B_L (as discussed below) on the basis of their seismic source potential and potential for surface rupture through the Project sites is discussed in Section 8.3.

Nonsignificant Feature:

The candidate feature is not a fault (applicable to lineaments only). This category includes features which could be directly related to glacial or fluvial processes or which had conclusive evidence to preclude the existence of a fault. It also includes features which were judged to be the result of the unrelated alignment of linear segments such as ridges, valleys, vegetation, and stream segments. Some features, particularly those drawn on the basis of geophysics, were not observed at all from the air or ground and were given this classification.

The evidence used to classify these candidate features was documented using the procedures discussed in Appendix A. Nonsignificant features were then eliminated from any further study.

Indeterminate Feature--Low Likelihood of Recent Displacement (B_L)

The candidate feature is considered to have a low likelihood of being a fault and having had recent displacement (applicable to lineaments only). This category includes features with linear morphologic expressions, but with no direct evidence of faulting in bedrock. These features typically did not have morphologic expression of, or displacement in overlying Quaternary units.

Indeterminate Feature--Low to Moderate Likelihood of Recent Displacement (B)

The candidate feature is considered to have a low to moderate likelihood of recent displacement. This category includes candidate features which are mapped bedrock faults but which have no morphologic expression or displacement in overlying Quaternary deposits.

Indeterminate Feature--Moderate Likelihood of Recent Displacement (A)

The candidate feature is considered to have a moderate likelihood of recent displacement. This category includes mapped or observed bedrock faults along which anomalous, linear morphologic relationships were observed in alluvial or glacial deposits. Mapped, observed, or possible bedrock faults without Quaternary deposits suitable to assess the recency of displacement were also given this classification. In addition, features with prominent linear morphologic expressions in Quaternary units and no bedrock exposures were included in this classification.

Fault with Recent Displacement

The candidate feature is a mapped or observed bedrock fault with displacement in recent Quaternary units. The only fault in this category in the site region is the Denali fault. The Castle Mountain fault, immediately south of the site region is also judged to have recent displacement. No other faults which were judged to be in this category were observed in the site region.

8.3 - Selection of Significant Features

The third step of the fault and lineament study was to make a preliminary assessment of which candidate features potentially could be significant to Project design considerations. The assessment considered the features as two discrete groups: (1) those with seismic source potential, and (2) those with the potential for surface rupture through the sites. The following preliminary significance criteria were used for this assessement.

Seismic Source Potential

Seismic source potential was assessed on the basis of the following criteria:

(a) The Denali and Castle Mountain faults are accepted as having had recent displacement. These two faults are the only faults known to have recent displacement in or adjacent to the site region. These faults were retained for additional evaluation.

(b) Among the 216 candidate features reviewed during the 1980 field season reconnaissance study, none of the nonsignificant features needs further systematic consideration. The basis for this criterion is that the nonsignificant features were judged not to be faults. Application of this criterion resulted in a group of 106 features for additional evaluation.

(c) Among the remaining 106 features, all features less than 3 miles (5 km) long were not considered further. This criterion is based on the assumption that moderate to large earthquakes (M_S >5) typically do not occur on isolated short faults (or isolated faults with short surface rupture lengths). Review of available fault rupture length data (Albee and Smith, 1966; Slemmons, 1977) shows that very few faults have had surface rupture lengths less than 3 to 5 miles (5 to 8 km) during a single earthquake of magnitude (M_S) greater than 5. Application of this criteron resulted in the deletion of two additional features from further consideration.

(d) Among the remaining 104 features longer than 3 miles (5 km), those for which the estimated preliminary maximum credible earthquake (PMCE) would generate a peak horizontal bedrock acceleration less than 15% g (at either site) were not considered further. This criterion used the PMCE on the Denali fault (approximately a magnitude (M_S) 8.5 event occurring a minimum of 40 miles (64 km) from the Devil Canyon site) as the limiting factor. This PMCE would produce peak horizontal bedrock accelerations of 17% to 21% g based on the results of preliminary earthquake engineering studies conducted during this investigation (Section 12). Consequently, features for which the estimated PMCE could not generate peak horiaontal bedrock accelerations greater than would the PMCE on the Denali fault are not expected to affect seismic design considerations. The value of 15% g was selected to accommodate uncertainties in the estimation of the PMCE for the Denali fault and the attenuation of ground motions to the sites, and to provide an additional degree of conservatism for the preliminary significance criteria evaluation.

Using the above criteria, 46 features were identified which potentially could affect seismic source considerations. The discussion below of the fourth step of the study, describes the selection of the features considered to be important to seismic design considerations.

Potential for Surface Rupture through the Dam Sites

From the group of 106 features, an evaluation was also made of the potential for surface rupture through either Project site. The criteria used were the following:

(a) Among the 216 candidate features reviewed during the 1980 field season reconnaissance study, none of the nonsignificant features needs further systematic consideration. The basis for this criterion is that the nonsignificant features were judged not to be faults. Application of this criterion resulted in a group of 106 features for additional evaluation.

(b) Among the 106 features all features which were more than 6 miles (10 km) from either Project site were excluded from additional consideration. This criterion is based on the observations of the width of surface rupture zones during historic earthquakes (as discussed in Section 3.2).

(c) A corollary to criterion (b) is the observed length of the feature represents the maximum length of the feature along which recent displacement could have occurred. This length is assumed to represent half of the length of a fault (based on the assumption that up to half the length of a fault could rupture during a single event). This additional length was added to the observed length at the closest approach of the additional length to either Project site. If any portion of the observed length or the hypothetical additional length passed within 6 miles (10 km) of either site, the feature was selected for further consideration.

From the above steps, a total of 22 features were identified which may have a potential for surface rupture through either site. Of these 22 features, 20 are already considered as part of the seismic source considerations.

From the above considerations of seismic source potential and potential for surface rupture through either site, a total of 48 features were identified. These 48 features are designated candidate significant features. They are briefly summarized in Table 8-2.

The fourth step of the fault and lineament study was to evaluate the candidate significant features individually using the significance criteria described below. This evaluation permitted refinement of the evaluation process. This refinement led to the selection of significant features, which, if they are found to be faults with recent displacement, could have a major affect on Project design considerations and, therefore, should be evaluated further in 1981.

The evaluation of candidate significant features continued to consider the features as two discrete groups. The significant criteria used for this evaluation are described below.

Seismic Source Potential

The seismic source potential of the 48 candidate significant features was evaluated on the basis of the following criteria:

(a) Their length and distance from each site. The length was used to estimate the preliminary maximum credible earthquake using procedures described in Appendix E. The distance was incorporated into the criteria as part of the attenuation relationship of ground motions to the sites. The attenuation relationship is discussed in Section 12.

(b) An assessment of the likelihood of the feature being a fault with recent displacement. This assessment is based on the classification of the features during the field reconnaissance study (described in Section 8.2).

(c) An estimation of the maximum peak horizontal bedrock acceleration at each site. This criterion was developed using the preliminary maximum credible earthquake, attenuating the ground motions to each site using the attenuation relationship described in Section 12, and estimating the effect on Project design.

Each of these criteria were broken down into individual components (for example, the classification of the features has five components--faults with recent displacement, indeterminate A, indeterminate B, indeterminate B_L, and nonsignificant). The relative importance of each component was systematically assessed. The assessments for each of the three criteria were then combined for each feature. The combined assessment for each of the 48 candidate significant features were then compared to each other and those features of potential significance to each site were selected.

The approach described above provided the methodology for systematically incorporating preliminary data into the selection of significant features. The same approach was used to evaluate the potential for surface rupture as described below.

Potential for Surface Rupture Through the Dam Sites

The surface rupture potential through each site for the 48 candidate significant features was evaluated on the basis of:

(a) whether the feature passes through the either site. This criterion assesses whether a feature passes through one of the sites. If the feature does not pass through the site, then the assessment involves judgment about how close to the site the feature passes (or twice its length passes), the orientation of the feature relative to the orientation of the proposed dam, and available information on fault type (if the feature is a fault); and

(b) an asessment of the likelihood of the feature being a fault with recent displacement in the same manner described in Item (b) for the seismic source potential evaluation.

Each of the 48 candidate significant features was evaluated within each of the two groups using each of the significance criteria described above. The evaluation of each criterion was then combined to provide an overall assessment of each feature's importance within each group. The importance of the two groups, relative to each other, was then assessed. From all of these assessments, a total combined evaluation of each of the 48 features was made. This total combined evaluation incorporates the judgments of the project geologists about the importance of each of the candidate significant features due to the feature's seismic source potential and potential for surface rupture through the sites.

From the above evaluation of the 48 candidate significant features, 13 significant features were selected for additional evaluation in 1981. The remaining 35 features are considered to be appreciably less important to the project than are the significant features.

Four of the significant features are judged to merit additional evaluation for the Watana site and nine for the Devil Canyon site. The significant features are listed in Table 8-3.

The following sections (8.4 and 8.5, respectively) discuss the faults with known recent displacement (Talkeetna Terrain boundary faults) within or immediately adjacent to the site region and the 13 significant features within the Talkeetna Terrain. Figures 8-2 through 8-5 show locations of these faults and features.

8.4 - Talkeetna Terrain Boundary Faults

Denali Fault (HB4-1)

The Denali fault is predominately a right-lateral strike-slip fault that is approximately 1,240 miles (2,000 km) long (Richter and Matson, 1971). The fault consists of three segments and has an arcuate east-west trend in the site region. Between the eastern and western segments of the fault (the Shakwak Valley and Farewell fault segments of Grantz (1966)) the fault divides into two traces or strands. The northerly strand is the Hines Creek strand as shown in Figure 8-2. The southerly strand, the McKinley strand, passes within 40 miles (64 km) north of the Watana site and 43 miles (70 km) north of the Devil Canyon site.

The fault has been the subject of numerous studies and is generally agreed to represent a major suture zone within the earth's crust as discussed by St. Amand (1957), Grantz (1966), Cady and others (1955), Richter and Matson (1971), Page and Lahr (1971), Stout and others (1973), Forbes and others (1973), Wahrhaftig and others (1975), Hickman and others (1978), and Stout and Chase (1980), among others. The total amount of displacement along the fault is the subject of continuing discussion. Some investigators suggest the amount of strike-slip displacement is relatively small (Csejtey, 1980), while others cite evidence supporting total displacements of up to 155 miles (250 km) (St. Amand, 1957).

The Hines Creek strand of the Denali fault is believed to be the older of the two strands with strike-slip movement ceasing by 95 m.y.b.p. (Wahrhaftig and others, 1975; Craddock and others, 1976). Strike-slip movement subsequently has principally occurred along the McKinley strand of the Denali fault (Wahrhaftig, 1958; Grantz, 1966; Hickman and Craddock, 1973; Stout and others, 1973). Because the McKinley strand is the closer of the two strands to the sites, and because most of the major strike-slip displacement is thought to be occurring along this strand (rather than along the Hines Creek strand), the Denali fault (in the site region) is considered for the purposes of this investigation to consist of the Farewell fault segment, the McKinley strand, and the Shakwak Valley fault segment as described by Grantz (1966). The fault is shown in Figure 5-1.

Aerial reconnaissance of the fault in the vicinity of Cantwell during this study revealed strong morphologic expressions such as scarps, offset ridges, linear valleys, and sag ponds in bedrock or surficial sediments of undefined age. The prominence of the trace west of Cantwell is shown in Figure 8-6. The linearity of these features across the topography suggests that the fault plane is close to vertical in this area.

Holocene age displacements along the McKinley strand have been studied by several investigators. In the Nenana River area, Hickman and Craddock (1973) find evidence for as much as 443 feet (135 m) of right-lateral displacement and 10 to 13 feet (3 to 4 m) of dip-slip offset, with the south side up relative to the north side, in Holocene time. These data suggest a displacement rate of approximately 0.8 inches/year (2 cm/per year) assuming that an average of 295 feet (90 meters) of displacement has occurred in the last 10,000 to 11,000 years. Stout and others (1973) measured right-lateral offsets as great as 197 feet (60 m) and as much as 33 feet (10 m) of dip-slip displacement, with the north side up relative to the south side, in Holocene units east of the Black Rapids Glacier (northeast of the site region). An estimated displacement rate based on these data would be between 0.20 and 0.24 inches/year (0.5 and 0.6 cm/year) of right-lateral motion and less than 0.06 inches/year (0.15 cm/year) of dip-slip motion during Holocene time. Other studies, including Plafker and others (1977), Hickman and others (1977; 1978), and Richter and Matson (1971), found evidence supporting a displacement rate between 0.4 to 1.4 inches/year (1.0 to 3.5 cm/year) on the McKinley strand in Holocene time.

In summary, displacement rates in Holocene time along the Denali fault locally range from less than 0.1 to 1.4 inches/year (0.25 to 3.5 cm/year). There is no documentation of displacement on the McKinley strand in historic time. Hickman and others (1978) suggest the latest movement was several hundred to several thousand years ago.

Review of historic seismicity during this investigation, including review of other published historical seismicity studies (e. g. Tobin and Sykes, 1966; Boucher and Fitch, 1969; Page and Lahr, 1971), suggests that seismic activity has occurred in the vicinity of the Denali fault. This seismicity includes microseismicity reported by Boucher and Fitch (1969) and macroseismicity (events of up to magnitude (M_S) 5 to 6 (Tobin and Sykes, 1966)). As discussed in Section 4.2, two large events (magnitude greated than 7) occurred in the general vicinity of the Denali fault. However, uncertainties in the location and focal depth of these events preclude correlation with the Denali fault.

The Denali fault has been classified during this investigation as being a fault with recent displacement. This classification is based on citations in the literature and observations made during this investigation of numerous locations where Holocene units have been displaced, as well as on the prominent morphologic expression of the fault in relatively recently uplifted terrain.

The Denali fault is the closest fault to the sites known to have recent displacement. The fault affects consideration of the seismic source potential for both sites. The fault does not affect consideration of surface rupture potential through either site because of the distance of the fault from the sites.

Castle Mountain Fault (AD5-1)

The Castle Mountain fault is an oblique-slip fault incorporating a combination of right-lateral and reverse motions with the north side up relative to the south side (Grantz, 1966; Detterman and others, 1974, 1976). The fault is approximately 124 miles (200 km) long and trends east-northeast/west-southwest about 65 miles (105 km) south of the Devil Canyon site and 71 miles (115 km) south of the Watana site (Figure 8-2). It is nearly vertical or steeply dipping to the north (Detterman and others, 1974; 1976).

The fault is present as a single trace along its mapped western section in the Susitna Lowland (Figure 8-2). Along the eastern section of the fault, in the Matanuska Valley, the fault consists of the main trace and a major splay which is known as the Caribou fault (Grantz, 1966; Detterman and others, 1976). Detterman and others

(1976) propose that the main trace represents the older and more fundamental break of the two traces while the Caribou fault is the trace along which late Cenozoic displacement has occurred. As is the case for the Denali fault, the Castle Mountain fault is generally regarded as a major suture zone within the earth's crust.

Displacement along the fault has been occurring since about the end of Mesozoic time (Grantz, 1966), approximately 60 to 70 m.y.b.p. The maximum amount of vertical displacement is approximately 1.9 miles (3 km) or more (Kelley, 1963; Grantz, 1966) and the maximum amount of strike-slip displacement is estimated by Grantz (1966) to have been several tens of kilometers, although Detterman and others (1976) cite 10 miles (16 km) as the total displacement which has occurred along the eastern traces of the fault.

During aerial reconnaissance for this study, the fault was observed as a series of linear scarps and prominant vegetation alignments in the Susitna Lowland (Figure 8-7). Along its eastern portion in the Talkeetna Mountains, the fault was observed as a lithologic contrast and by possible offset of the Little Susitna River and other streams.

Evidence of Holocene displacement is observed only in the western segment of the fault in the Susitna Lowland (Detterman and others, 1974; 1976). To date, no evidence of Holocene displacement has been reported in the Matanuska Valley, although Barnes and Payne (1956) propose that up to 0.8 mile (1.2 km) of vertical displacement has occurred in the Matanuska Valley in Cenozoic time.

In the Susitna Lowland, Detterman and others (1974) found evidence suggesting that 7.5 feet (2.3 m) of dip-slip movement has occurred within the last 225 to 1,700 years. This interpretation is based on a scarp and the excavation of trenches in which displaced soil horizons were observed. Carbon-14 age dates obtained from the scarp and soil horizons imply a dip-slip rate of displacement of 0.05 inch/year to 0.4 inch/year (0.13 cm/year to 1 cm/year). Horizontal displacement by the fault of a sand ridge (whose age within Holocene time is not known) has involved 23 feet (7 m) of right-lateral displacement (Detterman and others, 1974). Bruhn (1979) excavated two additional trenches across the fault and found 3.0 to 3.6 feet (90 to 110 cm) of dip-slip displacement with the north side up relative to the south side along predominately steeply south-dipping fault traces. A river terrace near one of the trench locations had approximately 7.9 feet (2.14 m) of right-lateral displacement. These displaced deposits are clearly of Holocene age, but no age dates were reported by Bruhn (1979).

There is no documented displacement along the Castle Mountain fault in historic time. Plafker (1969) reports no observed displacement during the 1964 Prince William Sound earthquake (described in Section 4). A magnitude (M_S) 7.0 earthquake occurred in the vicinity of the Castle Mountain fault west of Anchorage in 1933 (Figure 4-6 and Appendix C). It is not known if the earthquake was related to the Castle Mountain fault, and no investigations to look for surface displacements have been reported (Page and Lahr, 1971).

Detterman and others (1976) have reviewed historical seismicity in the vicinity of the fault for the time period 1934 through October 1974. Most of the events in the vicinity of the fault have reported focal depths of more than 19 miles (30 km) with the precision in hypocenter depths estimated by the authors to be up to $\pm$ 12 miles (20 km). The depth of these events suggests that the events may be occurring at depth below the crust. In summary, there has been seismic activity in the vicinity of the fault but no reported correlation of earthquakes with the fault.

The Castle Mountain fault has been classified during this investigation as being a fault with recent displacement. This classification is based on the morphologic expressions of the fault in Holocene deposits and the reported displacements in trenches excavated across the southwestern portion of the fault. The fault dips steeply to the north or south, or is near-vertical. The sense of displacement is one of oblique displacement comprised of north side up relative to the south side, and right lateral components.

The Castle Mountain fault is not expected to affect consideration of the seismic source potential or the surface rupture potential for either site. The Denali fault is closer to the sites than the Castle Mountain fault and has the potential for a larger earthquake (on the basis of considerations presented in Sections 11 and 12). Consequently, the seismic source potential of the Castle Mountain fault is considered to be significantly less than that of the Denali fault and therefore does not affect seismic source considerations. The Castle Mountain fault is too far from the sites to affect potential surface rupture considerations. The fault has been included in these discussions because it is a Talkeetna Terrain boundary fault with recent displacement and is immediately adjacent to the site region.

Benioff Zone

As discussed in Section 4.1, the Pacific Plate is moving northwestward at a relatively faster rate than the North American Plate. Along the Aleutian Trench in the Gulf of Alaska, the differential rate of movement is accommodated by subduction or underthrusting of the Pacific Plate beneath the North American Plate. The subducting Pacific Plate dips beneath Alaska to a depth of approximately 93 miles (150 km) as discussed by Packer and others (1975); Davies and House (1979), Agnew (1980), and Lahr and Plafker (1980).

Evidence for the subducting Pacific Plate is the zone of seismicity associated with the plate. This zone of seismicity, the Benioff zone, has been observed in the site region by Davies (1975) and Agnew (1980) and is reported in the results of this investigation (Section 9; Figure 9-9). Southeast of the site (apparently beneath the Matanuska Valley region), the Benioff zone becomes decoupled from the North American Plate and increases in dip as discussed in Section 4.3.3 and shown in Figure 5-2. Northwest of the area of decoupling, a transition zone lies between the Benioff zone and the crust. Hypocentral data obtained during this investigation show the Benioff zone to be at depths of 31 (50 km) and 37 miles (60 km) beneath the Watana and Devil Canyon sites, respectively (Figure 9-9).

The Benioff zone is considered to be a source of seismicity for both sites. This judgment is based on the association of earthquakes with the downgoing slab and the latter's proximity to the sites. The zone is not considered to affect consideration of surface rupture potential through the sites because of the depth of the zone and the decoupling from the crust at the site. The effect of the Benioff zone on the seismic source potential for both sites is discussed in Section 12.

8.5 - Significant Features

8.5.1 - Watana Site

Talkeetna Thrust Fault (KC4-1)

The Talkeetna thrust fault is a reverse or thrust fault which trends northeast-southwest and passes 4 miles (6.5 km) east of the Watana site (Figures 8-2 and 8-3). The length of this fault is at least 54 miles (87 km) and may be as long as 167 miles (270 km) if it is continuous with the Broxson Gulch thrust fault in the northeastern part of the site region (as shown by Beikman and others (1974)). Southwest of the section of the Susitna River which passes through the sites, the fault is believed to continue based on magnetic anomalies as well as bedrock mapping (Csejtey and others, 1978; Csejtey and Griscom, 1978).

The dip of the fault is uncertain. Csejtey and others (1978) show the Talkeetna thrust fault dipping to the southeast. Interpretation of aeromagnetic data by Csejtey and Griscom (1978) suggest a southeast dip. Smith (1974) and Turner and Smith (1974) do not show a dip on the fault. The Broxson Gulch thrust fault, apparently continuous with the Talkeetna thrust fault, is believed to have a northwest dip by several of the investigators who have examined the fault or compiled information for it (e. g., Turner and Smith, 1974; Stout and Chase, 1980), although Csejtey and others (1980) imply a southeast dip.

Evidence for fault displacement strongly suggests that the fault developed as a major thrust zone along which the front of an accreting land mass collided with the depression lying on the southern margin of the North American plate in Mesozoic time (Csejtey, 1980). The result, based on current interpretations, is that the volcanic units southeast of the fault were thrust upon or beneath the flysch deposits of argillite-graywacke sandstone in the site region (Section 6-1; Figure 6-2).

Stout and Chase (1980) and Chase (1980) have observed Oligocene sediments and dikes offset by the Broxson Gulch thrust fault. They postulate that 33 miles (54 km) of northwest-over-southeast thrust faulting has occurred since 38 m.y.b.p. At the southwestern end of the Talkeetna thrust fault, Csejtey and others (1978) report that the fault is overlain by Tertiary volcanic units which are not faulted. Smith (1980a; 1980b) reports evidence of the fault in units of Jurassic age in the Butte Creek area north of the Susitna River where at least two traces of the fault are present.

Field studies conducted along the fault during this investigation showed that faulting has occurred in volcanic units of reported Tertiary or Triassic age on the south bank of the Susitna River, approximately 1.5 miles (3 km) downstream of Watana Creek. In the Windy Creek region northeast of the town of Denali, sedimentary strata of reported Jurassic age were observed to be faulted against volcanic units of reported Triassic age (Turner and Smith, 1974). Bedrock notches, scarps, and saddles, strongly suggestive of bedrock faulting, are also present along the north slope, and near the head of Windy Creek.

Unlithified, semiconsolidated sediments possibly of Quaternary age were observed on the north side of the Susitna River (during this investigation) to have anomalous relationships suggestive of possible fault displacement. Some of these relationships could also be related to slumping or smallscale landslides. As shown in Figure 8-8, exposures of these deposits are adjacent to westward dipping sedimentary units of inferred Tertiary age. The age of both deposits is uncertain based on available data. The Quaternary age is based on the unconsolidated nature of the sediments. The Tertiary age is based on the proximity and visual similarity to Tertiary units exposed in Watana Creek (Figure 7-1).

The fault shows little morphologic expression in surficial units in the vicinity of the Susitna River. A very subtle alignment of relief was observed during some lighting conditions but was not observed repeatedly under similar or different conditions.

Two clusters of microseismic activity were observed east of the Talkeetna thrust fault near Grebe Mountain (Figure 9-1) as discussed in Section 9.3. The events are approximately 6 miles (10 km) east of the surface trace of the fault and at a depth of 6 to 12 miles (10 to 20 km). Focal plane mechanisms obtained from one of the clusters suggest that one of the failure planes (fault rupture planes) is oriented northeast-southwest, dips northwestward, and has a reverse (thrust) sense of displacement (Figure 9-7). No consistent motion could be determined for the second cluster (Section 9.3). The depth of the events, the locations of the events, and the orientation of the postulated fault-rupture plane suggests that the microearthquake activity is not directly related to the Talkeetna thrust fault. In addition, the fault rupture plane associated with the microearthquake activity is small (less than 0.4 $mile^2$ (1 km^2)) and would not be expected to be in spatial proximity to the Talkeetna thrust fault.

The microearthquake activity could possibly be associated with a small, subsurface fault which is conjugate to the Talkeetna thrust fault. There are however, few data available to adequately evaluate this hypothesis and to convincingly support the hypothetical relationship.

The fault has been classified during this investigation as being an indeterminate feature with a moderate likelihood of recent displacement (A). This classification is based primarily on its being mapped as a major bedrock fault; the associated aeromagnetic anomaly; evidence of related shearing in volcanic units; evidence of a shear zone along Butte Creek north of the Susitna River; bedrock notches near the head of Windy Creek; Jurassic sedimentary units faulted against Triassic volcanic units in Windy Creek; and anomalous relationships in sedimentary units (of possible Tertiary age) on the north side of the Talkeetna River.

The fault has been designated as a significant feature because of its seismic source potential for the Watana and Devil Canyon sites. It is a long feature which passes near the Watana site. The fault does not affect consideration of potential surface rupture through the Devil Canyon site because it does not pass through the Devil Canyon site. It is not expected to affect consideration of potential surface rupture through the Watana site unless studies conducted in 1981 encounter fault traces west of the presently mapped location, a northwest dipping fault plane, and/or evidence of recent displacement.

<u>Susitna Feature (KD3-3)</u>

The Susitna feature is a postulated northeast-southwest trending fault that is 95 miles (153 km) long and approaches to within 2 miles (3.2 km) of the Watana site (Figure 8-2 and 8-3). The feature was first described by Gedney and Shapiro (1975) as a prominent topographic lineament which they observed on LANDSAT imagery. These authors postulated that the lineament was a fault based in part on data assembled by Turner and Smith (1974) which is described below and also on the basis of their interpretations of seismic activity in the vicinity of the southern end of the feature.

Evidence that the feature is a fault has been inferred by Turner and Smith (1974) in the West Fork area of the south flank of the Alaska Range (Figure 8-2). The inference is based on K-Ar dates on plutonic bodies and interpreted cool-down rates associated with these plutons (Smith, 1980b). According to this hypothesis, the plutonic units on the east side of the Susitna feature, cooled down more rapidly than those on the west side of the feature suggesting that the latter was at greater depth than the former and subsequently was faulted up into contact with the units that cooled down more rapidly.

Smith (1980b) examined the Butte Lake area and did not find evidence of a fault. In addition, he has not observed evidence of the Susitna feature as a fault anywhere besides the West Fork area.

Gedney and Shapiro (1975) report that the Susitna feature corresponds to the eastern boundary of the metasedimentary units in the project area (those presumably shown by Csejtey and others (1978) as being Cretaceous age argillite and graywacke sandstone (Figure 7-1)). Gedney and Shapiro (1975) also suggest that there is seismic activity associated with the Susitna feature. In particular, they site a magnitude (M_b) 4.7 event and a magnitude (M_b) 5.0 event which occurred on 1 October 1972 and 5 February 1974, respectively. The location given by Gedney and Shapiro (1975) shows the earthquakes to be spatially close to the surface trace of the Susitna feature and to suggest a right-lateral strike-slip sense of displacement. Review of these earthquakes during this investigation however, showed that with the error bars in location reported by Gedney and Shapiro (1975), the two epicenters could be more than 8 miles (13 km) from the feature and the focal depths put the events at depths of 46 to 47 miles (75 to 76 km) (as summarized in the historical earthquake catalog in Appendix C). Even with the imprecision associated with focal depth determinations, these events appear to have occurred at depth, on the Benioff zone. The correlation of these events with the Susitna feature appears to be questionable. The seismicity near the southern end of the feature could conceivably be associated with the feature, but there is little evidence to support this association.

Csejtey and others (1978) report finding no evidence for the postulated Susitna feature, and no evidence of a fault was observed during this investigation. No evidence of a bedrock fault was observed in Tsusena Creek which is the only location with good bedrock exposures long the entire length of the feature. No morphologic expression was observed along the entire length of the feature which is suggestive of either a fault or recent displacement (Figure 8-9).

This feature has been classified during this investigation as being indeterminate with low likelihood for recent displacement (B_L). This classification is based primarily on the reported fault by Turner and Smith (1974) and the inferences by Gedney and Shapiro (1975) which suggest that a fault could be present. In contrast, there is strong circumstantial evidence to suggest that the Susitna features may not be a fault and does not have recent displacement. This evidence includes the reported absence of a fault by Csejtey and others (1978); the absence of any evidence observed during this investigation for a fault or for recent displacement; and the absence of any correlation between micro-earthquake activity and the feature based on results obtained during this investigation. Its origin, if the feature is not a fault, may be related to glacial modification and enhancement of aligned pre-glacial stream valleys.

The feature has been designated as a significant feature despite the absence of evidence that the feature is a fault. This designation results from the length of the feature and its proximity to the Watana site. Therefore, the feature is included for additional study in 1981 because of possible seismic source potential and possible potential for surface rupture through the Watana site. The feature does not affect consideration of seismic source potential and potential surface rupture at the Devil Canyon site because of its distance from the Devil Canyon site.

Additional studies are therefore considered necessary to verify that the Susitna feature is not a fault. If the feature should be found to be a fault, then additional studies will need to be considered to determine the related fault parameters and the recency of displacement as discussed below for lineament KD3-7. If the lineament is not a fault, then it will no longer affect consideration of seismic source potential and potential for surface rupture at the Watana site.

Lineament KD3-7

Lineament KD3-7 trends approximately east-west along the Susitna River for a distance of 31 miles (50 km). At its western end, the lineament passes through the Watana site (Figure 8-3). The lineament was identified by Gedney and Shapiro (1975) on LANDSAT and SLAR imagery. At the scale of the imagery, the lineament approximately corresponds to a series of somewhat linear sections of the Susitna River between approximately the confluences of Tsusena Creek on the west and Jay Creek on the east.

During this investigation, virtually no evidence of a major through-going lineament was observed. Approximately 6 miles (10 km) upstream from the Watana site, the lineament is shown by Gedney and Shapiro (1975) to cut across the south bank of the Susitna River and to trend across the low plateau northwest of Mt. Watana (Figure 8-3). On this plateau linear surficial glacial features which trend oblique to the lineament's trend are clearly continuous and show no indication of either a crosscutting lineament or fault (Figure 8-10).

Thus, no morphologic expression of the lineament was observed on the plateau. No evidence of structural control was observed on the Susitna River where the lineament is shown by Gedney and

Shapiro (1975) to cut across the river bank. Drilling results, reported by the U. S. Army Corps of Engineers (1979, plates D-34 and D-35) show shear zones 3 to 14 feet (1 to 4 m) wide in the vicinity of the lineament. Preliminary results of drilling in the vicinity of the lineament conducted during 1980 for Acres American Inc., do not preclude the presence of a through-going features; however, there is no evidence of a major structural feature.

Lineament KD3-7 has been classified during this investigation as being an indeterminate feature with a low likelihood of recent displacement (B_L). This classification is based on the absence of any evidence that the lineament is a fault or that there is possible recent displacement. The feature has been retained for additional study primarily on the basis of its proximity to the Watana site. There is virtually no geologic evidence that suggests the lineament is a fault.

The lineament has been designated as a significant feature because it is shown to pass through the Watana site and is of moderate length. Consequently, the lineament theoretically could affect consideration of seismic source potential and surface rupture potential of the Watana site. The lineament does not affect consideration of seismic source potential nor potential surface rupture at the Devil Canyon site because of its distance from the Devil Canyon site.

Additional studies are considered necessary to determine if lineament KD3-7 is a fault. If it should turn out to be a fault, then detailed studies will need to be considered to determine the recency of displacement as well as other pertinent fault parameters (such as the amount of displacement, type of displacement, orientation, etc.) If the lineament is found not to be a fault, then it will no longer effect consideration of seismic source potential or the potential for surface rupture at the Watana site.

Fins Feature (KD4-27)

The Fins feature is a shear zone which trends northwest-southeast between the Susitna River and Tsusena Creek and is nearly vertical (Figure 8-3). The feature is 2 miles (3.2 km) long and is shown as a fault or shear zone dipping 70° to 75° to the northeast on an undated U. S. Army Corps of Engineers Alaska District map (Plate D5 entitled "Watana Reservoir Surficial Geology"). The Fins feature is prominently exposed on the north side of the Susitna river as a series of vertical shear zones which has a total width of approximately 200 feet (61 m). The shear zone is approximately 2,500 feet (762 m) upstream from the proposed Watana dam axis and is in a granitic unit (specifically, a dioritic pluton) mapped as being Paleozoic in age by Csejtey and others (1978) as shown in Figure 7-1.

Evidence of the feature has not been observed on the south side of the Susitna River. However, the south bank does not have the prominent bedrock exposures which are present on the north bank in this area.

The Fins feature observed on the north bank of the Susitna River appears to correlate with a moderately to highly weathered, oxidized shear zone present on the northeast bank of Tsusena Creek approximately 2 miles (3.2 km) upstream from the confluence with the Susitna River. Joint measurements were obtained during the 1980 field season by Acres American Inc. on the Susitna River (location WJ-3) and by both Acres American Inc. and Woodward-Clyde Consultants in Tsusena Creek (locations WJ-4 and JW-3, respectively). These measurements show a prominent northwest-southeast trending set of joints which dip steeply northeast to southwest.

Observations during this investigation at Tsusena Creek included that of a 6.5-foot- (2-m-) wide fault zone (within the oxidized zone) which is oriented N30°W and dips 72°NE. The fault zone is in granitic units of reported Paleocene age (Figure 7-1) and contains mylonite and possibly pseudotachylite. Elsewhere in the oxidized zone, small scale faults oriented northwest-southeast with a northeast dip and slickensides were observed. The oxidized zone is shown in Figure 8-11. No evidence of the feature was observed northwest of the Tsusena Creek exposure; however, prominent exposures similar to that at Tsusena Creek are lacking.

The Fins feature appears to underlie a morphologic depression in surficial units between the Susitna River and Tsusena Creek. It is also coincident, in part, with a buried paleochannel which is filled with glacial deposits. Evidence for the paleochannel is based on seismic refraction studies conducted by Dames and Moore (1975) and Woodward-Clyde Consultants (1980).

The Fins feature has been classified during this investigation as being an indeterminate feature with a moderate likelihood of recent displacement (A). This classification is based primarily on the observed shear zones in the Susitna River and Tsusena Creek and on the morphologic depression in glacial sediments that appears to coincide with the feature.

The feature has been designated as a significant feature because of its proximity to the Watana site and resultant surface rupture potential through the site. The feature is considered to be too short to affect consideration of seismic source potential (as discussed in Section 2.4.2). The feature does not affect seismic source or surface rupture considerations for the Devil Canyon site because of its distance from the Devil Canyon site.

8.5.2 - Devil Canyon Site

Lineament KC5-5

Lineament KC5-5 trends north-northwest/south-southeast for a distance of 12 miles (20 km) and approaches within 4.5 miles (7 km) east of the Devil Canyon site (Figure 8-5). The lineament was initially identified in part by Gedney and Shapiro (1975) on LANDSAT imagery. Subsequent examination of U-2 photography and aerial reconnaissance during this investigation resulted in the extension of the lineament at its northern and southern ends. The lineament is expressed morphologically as a linear stream drainage and low saddle or shallow depression south of the Susitna River and as a linear stream drainage north of the Susitna River (Figure 8-5).

North of the Susitna River, the lineament was observed during the field reconnaissance study to be expressed as a broad linear valley with small lakes and ponds. This valley and related stream drainage align with a tributary stream valley south of the Susitna River. This stream has a bedrock fault exposed in the bottom of the valley near the confluence with the Susitna River. From the air, the fault was observed to be expressed as a sheared zone of oxidation (and perhaps mineralization) within granitic bedrock. Access limitations precluded a ground study of the fault.

At the southern end of the lineament, a step or scarp was observed (Figure 8-12). Ground reconnaissance of this scarp showed that joints at the outcrop are oriented parallel to the orientation of the lineament (N10°W). Decomposed igneous rock is present at the top of the scarp and hard, strong rock is present at the base. A discontinuous cover of till overlies the ground surface in the vicinity of the scarp. The scarp appears to be related either to joint control or possible slumping. No evidence of fault control was observed.

The lineament appears to be controlled by a bedrock fault along at least part of its length and by joint control or slumping along its southern section. No evidence of recent displacement was observed. However, the paucity of geologically recent deposits precludes a definitive evaluation of the recency of displacement based on the results of the investigation to date.

Lineament KC5-5 has been classified during this investigation as being an indeterminate feature with a low to moderate likelihood of recent displacement (B). This classification is based primariy on the presence of bedrock faulting locally along the lineament and the general lack of deposits suitable for determination of the recency of displacement.

The lineament has been designated as a significant feature because of its seismic source potential for the Devil Canyon site. The lineament does not affect consideration of the potential for surface rupture of either the Devil Canyon or Watana sites because it does not pass through the sites. The lineament does not affect consideration of seismic source potential at the Watana site because of its distance from the Watana site.

Additional studies are considered necessary to determine if the exposures of apparent faulting are related to the lineament and what portion of the lineament is fault controlled. If the lineament or portions of the lineament are fault controlled, then studies need to be considered to determine the related fault parameters and recency of displacement as discussed above for lineament KD3-7. If the lineament is not a fault, or is fault controlled over a significantly shorter length than its present mapped length, then it will no longer affect consideration of seismic source potential at the Devil Canyon site.

Unnamed Fault (KD5-2)

An unnamed fault has been mapped by Richter (1967) for a distance of 3 miles (5 km). As described by Richter (1967) the fault is oriented N70°E, dips 30°NW, and approaches within 3.5 miles (5.6 km) northwest of the Devil Canyon site (Figure 8-5). Richter mapped the fault as having normal displacement which downdropped argillite on the northwest relative to quartz monzonite on the southeast (the age of these units is Mesozoic and Cenozoic, respectively, as shown in Figure 7-1). The fault is marked by clay gouge, slickensides, and limonite (orange to yellow iron oxide) stain.

The fault was observed on U-2 photography during this investigation to be a short, linear depression with a prominent oxidized zone with shearing at the southwest end of the depression (Figure 8-13). Aerial and ground reconnaissance during this investigation showed evidence of faulting in the argillite in the vicinity of the oxidized zone.

The age of the youngest unit involved in the faulting, the Cenozoic granodiorite, suggests that the displacement has occurred in the last several million to tens of millions of years.

Data appropriate to determining how recent the displacement occurred, within this Cenozoic time framework, was not obtained during this investigation.

Fault KD5-2 has been classified during this investigation as being an indeterminate feature with low to moderate likelihood of recent displacement (B). This classification is based on the presence of a mapped fault along which there is no prominent morphologic expression.

The fault has been designated as a significant feature because of its seismic source potential for the Devil Canyon site. The lineament does not affect consideration of the potential for surface fault rupture through either the Devil Canyon or Watana sites because it does not project through these sites, nor does it affect consideration of seismic source potential at the Watana site because of its distance from the Watana site.

Additional studies are considered necessary to better define the length of the fault and to locate units or surfaces of suitable age to better define the time of latest displacement along the fault. In addition, the relationship of these units or surfaces relative to the fault should be evaluated to determine the recency of displacement along the fault. If the fault is found to be shorter than its present length or is found to have evidence that no recent displacement has occurred, then it will no longer affect consideration of seismic source potential at the Devil Canyon site.

Lineament KD5-3

Lineament KD5-3 trends northeast-southwest for a distance of 51 miles (82 km) and approaches within 3.6 miles (5.8 km) northwest of the Devil Canyon site (Figures 8-2 and 8-4). Part of the lineament is identified as a fault by Kachadoorian and Moore (1979). The remainder of the lineament was identified by Gedney and Shapiro (1975) on SLAR and LANDSAT imagery. Subsequent examination of U-2 photography during this investigation showed the lineament to be expressed morphologically as a prominent linear segment of Portage Creek and as a prominent linear bench along the south bank of the Susitna River southwest of Portage Creek.

Ground and aerial reconnaissance studies conducted during this investigation along Portage Creek showed the lineament to consist of a prominent linear, elevated depression along the northwest bank of Portage Creek (Figure 8-14). At the northeast end of the lineament, mineralized zones were observed in Portage Creek. Further to the south, along the northwest side of the creek, an apparent shear zone was observed which could not be reached on the ground. The shear zone may be related to the lineament, although that observation remains to be confirmed. Elsewhere along this linear depression, it appeared to be underlain by bedrock and to represent a glacial meltwater side channel.

Near the confluence of Portage Creek and the Susitna River, the lineament trends across a low plateau and is expressed as a bench or terrace. Some mining activity is being conducted on this plateau. The nature of the mine and the geologic relationships exposed in the mine were not available at the time of this report.

No evidence of fault control was observed in intermittent rock exposures and river alluvium where the lineament crosses the Susitna River; however, folding in argillite and sandstone was observed southwest of Portage Creek. From this area to Gold

Creek, the lineament is represented by a meltwater side channel in glacial moraine deposits along the south bank of the Susitna River. South of Gold Creek, the lineament is expressed in bedrock as a bluff or terrace along which there was an observed consistent pattern of stream deflections or offsets. In the vicinity of Curry, a pronounced change in lithologic texture and color and perhaps structural fabric was observed.

In addition to the observations described above, there is circumstantial evidence which suggests that another lineament (designated KD6-4 during this investigation) may be a splay of lineament KD5-3. Lineament KD6-4 is a lineament identified on LANDSAT and SLAR imagery by Gedney and Shapiro (1975). The lineament trends east-west along most of its length and northeast-southwest at its eastern end. The eastern end of the lineament (as it is presently observed), lies parallel to lineament KD5-3 and on the opposite (north) side of the Susitna river. Evidence of possible bedrock faulting was observed along sections of the lineament, and there are local anomalous morphologic relationships in glacial units (e.g., deeply eroded drainage channels with no observed source).

On the basis of observations made during field reconnaissance for this investigation, it is considered possible that lineament KD6-4 is a splay of lineament KD5-3. For the purposes of additional evaluation, lineament KD6-4 will be considered and designated as the southwestern splay of lineament KD5-3.

Lineament KD5-3 and the southwestern splay have been classified during this investigation as being an indeterminate feature with low to moderate likelihood of recent displacement (B). This classification is based on: local expressions of mineralized and shear zones along the lineament which are suggestive of fault control; the fault segment shown by Kachadoorian and Moore (1979) that corresponds with a portion of the lineament; the presence of mining activity suggestive of possible fault control; and the lithologic contrast at the southwestern end of the lineament. There is no evidence of displacement in glacial and fluvial deposits along the lineament, and many segments of the lineament appear to be related to glacial processes. Thus, there is local evidence of bedrock fault control along sections of the lineament and few data which serve to define the recency of displacement.

The lineament has been designated as a significant feature because of its seismic source potential for the Devil Canyon site. The lineament does not affect consideration of the potential for surface rupture through either the Devil Canyon or Watana sites because it does not project through these sites, nor does it affect consideration of seismic source potential for the Watana site because of its distance from the Watana site.

Additional studies are considered necessary to determine if lineament KD5-3 is a fault. If it is a fault then detailed studies will need to be considered to determine the related fault parameters and recency of displacement as discussed above for lineament KD3-7. If the lineament is not a fault, then it will no longer affect consideration of seismic source potential at the Devil Canyon site.

Lineament KD5-9

Lineament KD5-9 trends west-northwest/east-southeast for a distance of 2.5 miles (4 km) and approaches within one mile (1.6 km) south of the Devil Canyon site (Figure 8-5). The lineament initially was identified on SLAR imagery by Gedney and Shapiro (1975). Subsequent examination of U-2 photography during this investigation showed the lineament to be expressed morphologically as a linear alignment of a stream drainage, several small lakes, and marshland.

The western segment of the lineament, expressed by the stream drainage, cuts across the structural grain of the terrain in which it is located. Along the middle segment, the lineament is expressed as linear shoreline. Locally, the lineament is expressed as a glacial trimline (Figure 8-15). Glacial moraine deposits were observed between two of the lakes along the alignment; no evidence of fault displacement was observed in these deposits.

East of the lakes, the lineament is a shallow depression which aligns with a knickpoint (with waterfalls) in Cheechako Creek. Where the lineament was examined on the ground (approximately 0.6 miles (1 km) west of the intersection with lineament KD5-45), the orientation of schistosity was observed to be parallel with the alignment of the lineament.

The lineament is classified as being an indeterminate feature with low likelihood of recent displacement (B_L). This classification is based on the judgment that this lineament did not have any clear-cut evidence of fault control. There is circumstantial evidence suggestive of fault control, e.g., the knickpoint in Cheechako Creek. These is also circumstantial evidence that even if the lineament is a fault it does not have recent displacement because glacial moraine deposits are not displaced. However, definitive evidence which precludes the presence of a fault and which precludes recent displacement has not been obtained.

The lineament has been designated as a significant feature on the basis that it could affect consideration of seismic source potential at the Devil Canyon site. The lineament does not affect consideration of surface rupture potential through the Devil Canyon site because it does not pass through the Devil Canyon site. The lineament does not affect consideration of seismic source potential or potential surface rupture at the Watana site because of its distance from the Watana site.

Additional studies are considered necessary to determine if lineament KD5-9 is a fault. If it is a fault then detailed studies will need to be considered to determine the related fault parameters and recency of displacement as discussed above for lineament KD3-7. If the lineament is not a fault, then it will no longer affect consideration of seismic source potential at the Devil Canyon site.

Lineament KD5-12

Lineament KD5-12 trends northeast-southwest for a distance of 14.5 miles (24 km) and approaches within 1.5 miles (2.4 km) upstream of the Devil Canyon site (Figures 8-4 and 8-5). The lineament initially was identified, in part, on SLAR imagery by Gedney and Shapiro (1975) as a linear stretch of Cheechako Creek south of the Susitna River. The lineament was extended northward across the Susitna River; this judgment was based on morphologic relationships observed on U-2 photography during this investigation. North of the Susitna River, the lineament is expressed in part as a linear depression in which lie several small lakes, and in part as a linear stream drainage (Figure 8-16). This depression cuts across the predominant structural grain of this area.

During the field reconnaissance study, the lineament was observed at its northeast end to coincide approximately with a bedrock contact between granitic intrusive rocks on the southeast and argillite to slate grade metamorphic rocks on the northwest. Detailed mapping is necessary to confirm this observation, which is based on reconnaissance level observations on the ground.

No evidence of a fault, or structural control was observed where the lineament crosses the Susitna River. The northeast wall of Cheechako Creek, where the lineament is shown by Gedney and Shapiro (1975), was examined on the ground from a distance of approximately 1,000 feet (305 m). No evidence of fault control was observed in the granitic rocks of reported Cenozoic age (Figure 7-1); however, the resolution of this observation is limited by the distance of the observation and the access limitations imposed by the canyon walls.

At the southwest end of the lineament, a shear zone (approximately 200 feet (61 m) wide) was observed within the stream drainage associated with the lineament. Whether the shear zone is related to the lineament is unknown at this stage of the investigation.

Lineament KD5-12 has been classified during this investigation as being an indeterminate feature with low likelihood of recent displacement (B_L). This classification is based primarily on the shear zone at the southwestern end of the lineament and on the presence of a linear depression cutting across the structural grain of the area. It is also based on the absence of any evidence of recent displacement, which suggests that even if a bedrock fault is present, there doesn't appear to be recent displacement.

The lineament has been designated as a significant feature because it could affect consideration of the seismic source potential for the Devil Canyon site. The lineament does not affect consideration of the potential for surface rupture at either the Devil Canyon or Watana sites nor does it affect consideration of seismic source potential at the Watana site because it does not pass through the Devil Canyon site and because of its distance from the Watana site.

Additional studies are considered necessary to determine if lineament KD5-12 is a fault. If it is a fault, then detailed studies will need to be considered to determine the related fault parameters and recency of displacement as discussed above for lineament KD3-7. If the lineament is not a fault, then it will no longer affect consideration of seismic source potential at the Devil Canyon site.

Lineament KD5-43

Lineament KD5-43 trends east-west for a distance of 1.5 miles (2.4 km) and passes through the left abutment of the Devil Canyon site (Figure 8-5). The lineament is expressed morphologically as a short prominent depression, approximately 300 feet (91 m) wide, which is oriented parallel to the Susitna River. Within the depression are two small lakes with a low saddle of glacial material between them.

The depression associated with the lineament was considered as a potential spillway during initial feasibility studies conducted by the U. S. Bureau of Reclamation (USBR) in 1957 and 1958 (U. S. Bureau of Reclamation, 1960). During the USBR study, five borings were drilled across the depression on the saddle between the two lakes. An additional boring was drilled on the southwest shore of the eastern lake and a test pit was excavated in the saddle near the northwest shore of the eastern lake during this study.

In 1978, Shannon and Wilson conducted a seismic refraction traverse along the saddle for the U.S. Army Corps of Engineers (1979). During the 1980 feasibility study, Acres American Inc. drilled an angle boring southward from the north shore of the eastern lake. The boring was drilled beneath the lake for a distance of 501 feet (153 m) across the axis of the depression. As part of this feasibility study, Woodward-Clyde Consultants (1980) conducted two north-south seismic refraction traverses across the eastern lake and a northwest-southeast traverse at an oblique angle to the north-south traverses and the axis of the depression.

The data obtained from these studies show that a buried bedrock channel is present beneath the eastern part of the depression. The channel has a maximum depth of approximately 90 feet (27 m) and is filled with 80 feet (24 m) of sand and gravel (glacial outwash) which is overlain by approximately 10 feet (3 m) of silt, sand, gravel, and cobbles (glacial till).

One of the borings drilled in the center of the buried valley during the USBR study encountered "sheared rock" for the 20-foot (6-m) distance the boring was drilled in rock. The boring (D-2) drilled by Acres American Inc. did not encounter evidence of a fault or shear zone beneath the depression.

During this investigation, the lineament was observed to be a linear depression with glacial deposits lying between the two lakes (Figure 8-18). The canyon wall of Cheechako Creek at the east end of the lineament was examined from the air. No evidence of faulting was observed, but the airborne nature of the observation and vegetation cover preclude a definitive interpretation.

No evidence of displacement was observed from the air on the Susitna River canyon wall at the west end of the lineament. However, access limitations and vegetation cover limit the confidence in this interpretation.

Ground reconnaissance studies conducted along the lineament during this investigation included fracture analyses in bedrock on both sides of the depression and ground traverses of the saddle between the two lakes. The fracture analyses showed that fractures on both sides of the depression have similar orientations. The dominant orientation is N35°W with a steep northeast to southwest dip.

Ground traverses of the saddles between the two lakes showed that several linear depressions are present in the surficial glacial moraine deposits. The depressions are approximately 50 to 100 feet (30 to 61 m) wide and 10 feet (3 m) deep. The axes of these depressions are aligned parallel to the lineament trend. The origin of these depressions is probably related to glaciofluvial processes; however, a fault origin cannot be precluded on the basis of available data.

Considering the above information and data, the depression associated with lineament KD5-43 appears to be a meltwater side-channel that may be structurally controlled. According to this interpretation, the depression may have developed due to differential erosion along a prominent structure such as a fracture zone or bedrock fault. Subsequent glacial and/or meltwater processes served to enhance and probably deepen the depression, and it was later filled with sediments during a late glacial event (perhaps in late Wisconsin time).

Lineament KD5-43 has been classified during this investigation as being an indeterminate feature with low likelihood of recent displacement (B_L). This classification is based on the presence of a prominent linear depression, a buried bedrock valley with a shear zone in the upper 20 feet (6 m), linear depressions in the glacial moraine deposits which fill the depression, similar fracture orientations on both sides of the depression, and the absence of a fault zone beneath the depression based on the drilling conducted in 1980.

The lineament has been designated as a significant feature because of the potential for surface rupture through the Devil Canyon site. The lineament does not affect consideration of seismic source potential for the Devil Canyon site because its short length precludes its being a source of a moderate to large earthquakes (on the basis of rupture-length versus magnitude relationships, as discussed in Section 2.4.2. The lineament does not affect consideration of seismic source potential or potential surface rupture through the Watana site, because of its distance from the Watana site.

Additional studies are considered necessary to confirm that lineament KD5-43 is not a fault. The results of drilling conducted by Acres American Inc. during 1980 (boring D-2) strongly suggest that the lineament is not a fault. However, because the lineament passes through the Devil Canyon site, additional data should be acquired to increase the level of confidence in this interpretation.

Lineament KD5-44

Lineament KD5-44 trends north-south for a distance of 21 miles (34 km) and approaches within 0.3 miles (0.5 km) upstream of the Devil Canyon site (Figure 8-5). The lineament initially was identified south of the Susitna River as two discontinuous lineaments on SLAR imagery by Gedney and Shapiro (1975). One of the lineaments followed, in part, the northern end of Cheechako Creek whose confluence with the Susitna River is immediately upstream from the Devil Canyon site. Air photo interpretation conducted during this investigation identified a lineament with a similar alignment along a stream drainage whose confluence with the Susitna River is opposite that of Cheechako Creek.

During the field investigation, it was the opinion of the Woodward-Clyde Consultants' geologists that the two lineaments identified by Gedney and Shapiro (1975) and the lineament identified by Woodward-Clyde Consultants should be considered as a single lineament. Therefore the field investigation and the subsequent analysis of the lineament have considered the feature as a single lineament, 21 miles (34 km) long.

The lineament is expressed morphologically as a linear series of aligned stream drainage segments, small lakes, and shallow depressions or saddles in rolling terrain. Evidence of possible fault control is suggested by the apparent termination of a dike on the north wall of the Susitna River; a possible bedrock scarp on the south bank of the Susitna River; and discolored rock zones along Cheechako Creek.

The dike described above is exposed on the north wall of the Susitna River on the east side of the drainage associated with the lineament (Figure 8-19). On the basis of the work conducted to date, the dike appears to terminate or die out at the east side of the drainage. Whether the termination is fault related, a function of dike orientation and the orientation of the exposure, or due to the dike naturally dying out is yet to be determined.

Seismic refraction studies were conducted by Shannon and Wilson in 1978 on the point bar that juts northward into the Susitna River from the west bank of Cheechako Creek. These studies included two survey lines oriented parallel to the Susitna River and at right angles to the lineament. The results of the study suggest that a buried step or scarp in bedrock steps from a depth of approximately 100 feet (30 m) below the point bar (on the downstream side) to a depth of 600 to 650 feet (183 to 198 m) on the upstream side (U.S. Army Corps of Engineers, 1979, Exhibit D-1). On the basis of these two seismic refraction lines, the buried scarp can be inferred to have a buried relief of approximately 500 to 550 feet (152 to 168 m) and its base is oriented approximately N25°W to N30°W, subparallel to the trend of lineament KD5-44. The southwest side of the step is up relative to the northeast side.

Along Cheechako Creek, zones of light colored, fractured, and highly weathered or pulverized rock were observed from the air during this investigation. The origin of these rock zones could be due to faulting. However, other origins such as weathering of a mineralized zone could also explain the observed rock zones.

Along the lineament only one morphologic anomaly was observed during this investigation that may be indicative of recent displacement if the lineament is a fault. A terrace of fluvial or glaciofluvial deposits is present along the lineament south of the Susitna River. A linear shallow depression, approximately 500 feet (152 m) long, is present in this terrace with an alignment parallel to that of the lineament.

Examination of exposures on the margins of the terrace showed no evidence of faulting; however, the coarse-grained, cobbly nature of the deposit and access limitations prevented exhaustive examination of the exposure during this reconnaissance investigation. The origin of this depression is probably related to stream processes which occurred at a time when the creek in this area flowed along the surface of the terrace. However, a fault origin cannot be precluded on the basis of the data obtained to date.

Lineament KD5-44 has been classified during this investigation as being an indeterminate feature with a moderate likelihood of recent displacement (A). This classification is based on the apparent termination of the dike on the north wall of the Susitna River, the buried bedrock scarp at the mouth of Cheechako Creek, the zones of discolored rock south of the Susitna River, and the anomalous depression in the terrace along the lineament.

The lineament has been designated as a significant feature because of its seismic source potential for the Devil Canyon site as well as the potential for surface rupture through the site. The lineament does not affect consideration of seismic source potential or potential for surface rupture at the Watana site because of its distance from the Watana site.

Additional studies are considered necessary to determine if lineament KD5-44 is a fault. If it is found to be a fault, then detailed studies will need to be considered to determine the recency of displacement as well as other pertinent fault parameters as discussed above for lineament KD3-7. If the lineament is found not to be a fault, then it will no longer affect consideration of seismic source potential or the potential for surface rupture at the Devil Canyon site.

Lineament KD5-45

Lineament KD5-45 trends approximately east-west for a distance of 19.5 miles (31 km) and approaches within 0.8 mile (1.3 km) of the left abutment of the Devil Canyon site (Figures 8-4 and 8-5). The lineament was identified during this investigation as a prominent north-facing linear bluff along the south bank of the Susitna River (Figure 8-20). Aligned with this bluff is a small, linear stream drainage at the west end of the lineament, a linear topographic depression along the eastern portion of the lineament, and several small lakes along the lineament.

Ground and aerial reconnaissance conducted during this investigation showed that the lineament corresponds primarily to the front of the hills (i.e., range-front) along the south bank of the Susitna River (Figure 8-4) and locally is expressed as a linear trough approximately 150 feet (46 m) wide and 10 feet (3 m) deep. The lineament is underlain by argillite and glacial till. Water was observed flowing at a rate of approximately 3 to 5 gallons per minute (11 to 19 liters per minute) out of the till at the base of the trough. No evidence of displacement was observed in the till.

The lineament has been classified during this investigation as being an Indeterminate feature with low to moderate likelihood of recent displacement (B). This classification is based on the prominent morphologic expression of the lineament and the absence of conclusive evidence which precludes fault control, or recent displacement if the feature is a fault.

Lineament KD5-45 has been designated as a significant feature because of its proximity to the Devil Canyon site and because of its relatively long length. Consequently, the lineament could affect consideration of seismic source potential at the Devil Canyon site. The lineament does not affect consideration of potential surface rupture at the Devil Canyon site because of its distance from the Devil Canyon site. The lineament does not affect consideration of seismic source potential nor potential surface rupture at the Watana site because of its distance from the Watana site.

Additional studies are considered necessary to determine if lineament KD5-45 is a fault. If it is found to be a fault, then detailed studies will need to be considered to determine the fault-related parameters and recency of displacement as discussed above for lineament KD3-7. If the lineament is not a fault, then it will no longer affect consideration of seismic source potential and potential surface rupture at the Devil Canyon site.

TABLE 8-1

SUMMARY OF GEOLOGIC CHARACTERISTICS USED TO CLASSIFY CANDIDATE FEATURES

Field Evidence	Recent Displacement	Classification[1] Indeterminent A[2]	B[3]	B_L[4]	Non-Significant
Observed Quaternary displacement along a mapped or observed fault	X				
Prominent morphologic expression of probable fault-related features in Quaternary units		X			
Mapped or observed fault with subtle or discontinuous morphologic expression of possible fault-related features but no suitable Quaternary cover to access recency of displacement		X			
Lineament with morphologic expression of possible fault-related features in Quaternary units with no suitable exposure to confirm or preclude recent displacement					
Mapped or observed fault with no morphologic expression			X		
Mapped or observed fault with no evidence of displacement in Quaternary units			X		
Lineament with possible faulting in bedrock, but no displacement of Quaternary units.			X		
Lineament with no observed bedrock faulting but lacking a sufficient number of outcrops to adequately preclude fault control. No observed surface morphologic expression in or displacement of Quaternary units.				X	
Lineament attributed to glacial or fluvial processes					X
No linear features discernible					X
Chance alignment of unrelated features					X
A lineament with an observed exposure of bedrock and/or Quaternary units which preclude existence of a fault					X

Notes:
1. Section 8.2 describes the basis for the classification terminology.
2. Indeterminate-moderate likelihood of recent displacement.
3. Indeterminate-low-to-moderate likelihood of recent displacement.
4. Indeterminate-low likelihood of recent displacement.

TABLE 8-2

BOUNDARY FAULTS AND CANDIDATE SIGNIFICANT FEATURES

Feature[1] Number	Feature[2] Name	Fault (F) or Linea-ment (L)	Clas-sifi-cation[3]	Fault[4] Type	Length[5] (km)	Distance[6] (km) from Devil Canyon	Distance[6] (km) from Watana	Comments [7]
BOUNDARY FAULTS								
AD5-1	Castle Mt.	F	R	Oblique-Slip	200	105	115	Scarp, vegetation alignment in Quaternary, possible offset streams, 90-240 cm displacement in Holocene units (Detterman and others, 1976).
-	Benioff Zone	F	R	Subduction Zone	-	60	50	Subducting Pacific plate which is being underthrust beneath the North American Plate (Lahr and Plafker, 1980).
HB4-1	Denali	F	R	Strike-Slip	2000	70	64	Break in slope, linear streams, trench, saddles, lithologic contrast, continuous linear scarp, offset Quaternary deposits (Hickman and others, 1978).
CANDIDATE SIGNIFICANT FEATURES								
HA2-1		L	B_L		41	56	19	Break in slope, ridge, trench, vegetation line, linear stream segment, discontinuous scarps.
HA4-3		L	B		43	42	12	Break in slope, trench, vegetation line, sinuous scarp, possible offset stream, possible sag pond.
HA6-1		F	B	Normal	105	34	65	Break in slope, vegetation line, scarp, mountain front (Csejtey and others, 1978).
HA6-5	Chulitna	F	B	Thrust	116	38	70	Saddles, grooves, lithologic contrast (Hawley and Clark, 1973).
HA6-6	Upper Chulitna	F	B	Thrust	45	40	75	Ridge, lithologic contrast (Hawley and Clark, 1973).
HA6-6a	Upper Chulitna Splay	F	B	Thrust	16	43	70	Lithologic contrast (Hawley and Clark, 1973).
HA6-13		F	A	Thrust	27	75	45	Lithologic contrast, scarp (Hawley and Clark, 1973).
HB5-1		L	B_L		40	38		Break in slope, lithologic contrast, offset stream.
KB6-5		F	A	Thrust	21	70	40	Break in slope, saddles, possible offset of moraine (Steele and LeCompte, 1978).
KB6-66		L	A		23	66	34	Break in slope, trench, vegetation line, bench, lithologic contrast, discontinuous scarps, linear streams.
KC3-1		F	B	Thrust	61	56	26	Break in slope, saddles, oxidized zone scarp linear streams (Csejtey and others, 1978).
KC4-1	Talkeetna	F	A	Thrust	354	25	6.5	Linear streams segment, line of flakes, vegetation line, lithologic contrast (Csejtey and others, 1978).
KC4-23		L	B		84	28	37	Linear streams, sheared zone.
KC4-26		L	B		12	37	7	Lithologic contrast, scarp, possible fault in bedrock.

TABLE 8-2 (CONTINUED)

BOUNDARY FAULTS AND CANDIDATE SIGNIFICANT FEATURES

Feature[1] Number	Feature[2] Name	Fault (F) or Linea-ment (L)	Clas-sifi-cation[3]	Fault[4] Type	Length[5] (km)	Distance[6] (km) from Devil Canyon	Watana	Comments[7]
KC5-1		L	B_L		18	31	48	Break in slope, linear streams.
KC5-2		L	A		21	21	41	Linear streams, trench.
KC5-3		L	B		51	15	35	Break in slope, linear streams, trench, saddles, discontinuous scarps, possible fault observed in bedrock.
KC5-5		L	B		20	7	31	Linear stream, scarp.
KC5-7		L	A		19	11	42	Linear streams, possible stream offset, scarp.
KC5-37		L	B_L		13	24		Saddles, possible sheared bedrock.
KC5-63		L	A		18	27	46	Linear streams, trench, possible lithologic contrast, break in slope.
KD1-1		F	B	Thrust	22	85	45	Vegetation contrast, break in slope (Csejtey and others, 1978).
KD2-1	Talkeetna Splay	F	B	Thrust	34	61	21	Saddles, lithologic contrast, possible offset of ridge (Kachadoorian and Moore, 1979).
KD2-2		L	B		16	69	29	Saddles, lithologic contrast, vegetation line.
KD3-1		F	B		95	27	16	Break in slope, saddles, lithologic contrast (Kachadoorian and Moore, 1979).
KD3-2		F	B		18	42	4.5	Linear stream segment (Beikman, 1974).
KD3-3	Susitna	F	B_L		153	25	3.2	Break in slope, saddle, linear streams, scarp, (Turner and Smith, 1974).
KD3-6		L	B		27	51	10.5	Break in slope, submarine scarp in Big Lake, discontinuous scarp, observed small shear in bedrock, saddles.
KD3-7		L	B_L		50	35	0.0	Linear stream segment, trench, break in slope, vegetation line.
KD3-15		L	A		5	32	8	Break in slope, ridge, trenches, saddles, discontinuous scarps, lithologic contrast.
KD3-16		L	B_L		13	43	11	Depression, vegetation line, scarp.
KD4-3		L	B_L		14	17	11	Break in slope, linear stream segment.
KD4-4		L	B		17	16	23	Linear stream, lithologic contrast, oxidized and sheared zone.
KD4-5		L	A		25	14	11	Break in slope, trench, saddles, vegetation line, discontinuous scarps.
KD4-6		L	B_L		22	34	10	Trenches, discontinuous scarp, linear stream, break in slope.
KD4-27	Fins	F	A		3.2	37	0.0	Depression, oxidized zone, fault exposed in Tsusena Creek, (undated U.S. Army Corps of Engineers map).

TABLE 8-2 (CONTINUED)

BOUNDARY FAULTS AND CANDIDATE SIGNIFICANT FEATURES

Feature Number[1]	Feature Name[2]	Fault (F) or Lineament (L)	Classification[3]	Fault Type[4]	Length[5] (km)	Distance[6] (km) from Devil Canyon	Distance[6] (km) from Watana	Comments[7]
KD5-1		F	B	Thrust	25	14	23	Break in slope, ridge, trench, saddles, lithologic contrast, oxidized zone (Kachadoorian and Moore, 1979).
KD5-2		F	B	Normal	5	5.6	38	Break in slope, saddles, line of ponds, oxidized zone (Richter, 1967).
KD5-3		F	B		82	5.8	23	Break in slope, lithologic contrast, depression, saddles, scarp, sheared zone (Kachadoorian and Moore, 1979).
KD5-9		L	B_L		5	1.6	39	Linear streams, trench.
KD5-12		L	B_L		24	2.4	28	Linear depression, saddles, possible lithologic contrast, linear streams, linear scarp.
KD5-42		L	B		5	0.8	35	Break in slope, linear stream, trench.
KD5-43		L	B_L		2.4	0.0	38	Linear depression, line of lakes.
KD5-44		L	A		34	0.5	37	Linear streams, linear scarp, saddles, depression in alluvium, possible lithologic contrast, possible offset dike.
KD5-45		L	B		31	1.3	41	Linear streams, trench, saddles.
KD6-1	Chulitna River	F	B	Normal	105	24	54	Break in slope, vegetation line, depression scarp (Csejtey and others, 1978).
KD6-4		L	B		22	13	51	Lithologic contrast, saddles.
TC1-3		F	B		27	26	65	Trench, saddles, lithologic contrast, linear lakes, break in slope, vegetation line, depression (Griscom, 1979).

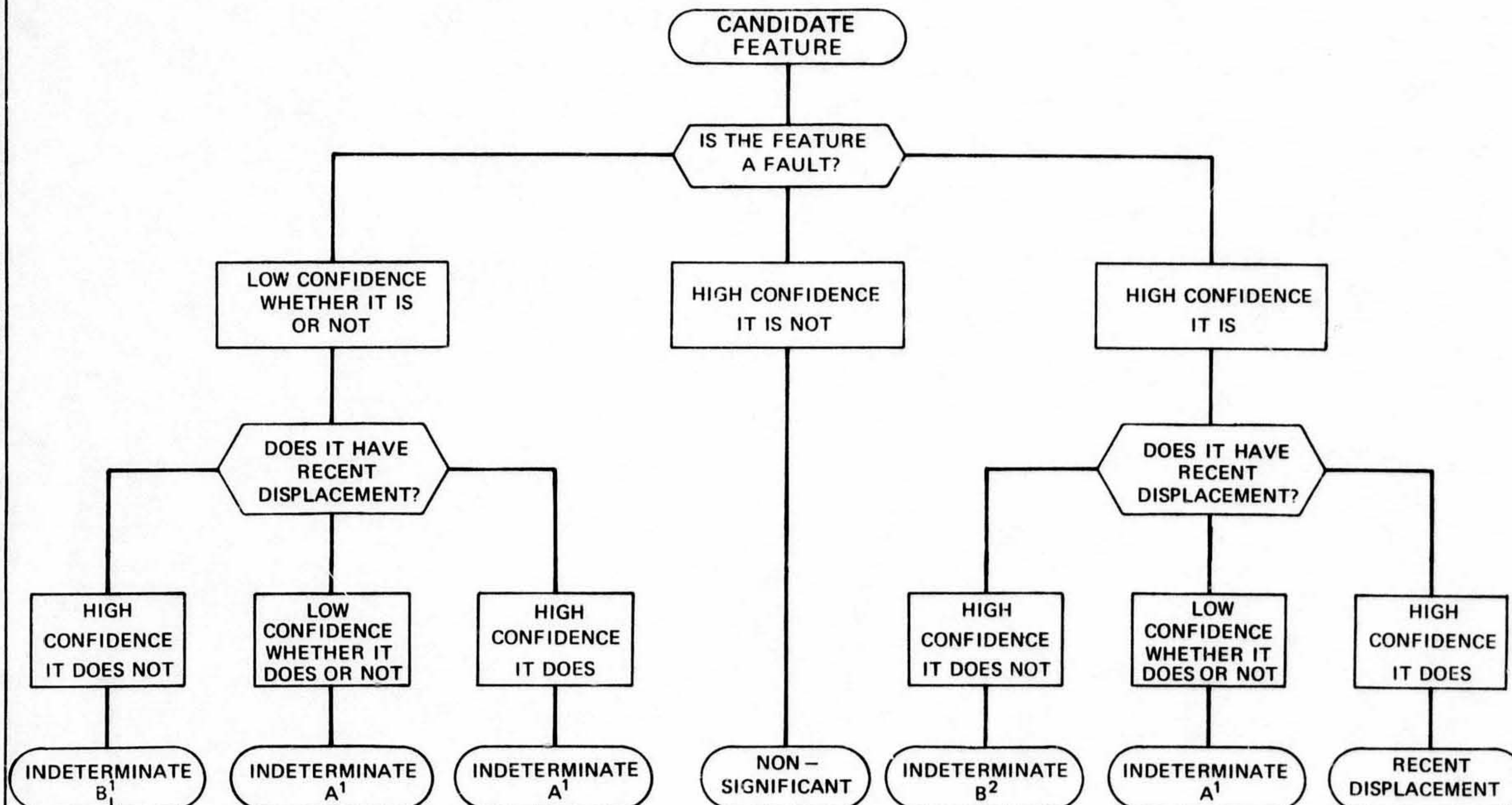
Notes:
1. Appendix A explains alpha-numeric code number.
2. Feature name given where known.
3. Classification notation:
   R - Fault with recent displacement;
   A - Fault or lineament with moderate likelihood of recent displacement;
   B - Fault or lineament with low to moderate likelihood of recent displacement;
   B_L - Fault or lineament with low likelihood of recent displacement.
   Section 8.2 describes the basis for these classifications.
4. Fault type given where known.
5. Lengths measured from 1:250,000 and 1:63,380 scale base maps as appropriate.
6. Distances measured from 1:250,000 and 1:63,380 scale base maps as appropriate.
7. Comments are based on remotely sensed data interpretation and field reconnaissance. Cited references provide information on faults.

TABLE 8-3

SUMMARY OF BOUNDARY FAULTS AND SIGNIFICANT FEATURES

Feature[1,2] No.	Feature Name[3]	Fault (F) or Linea- ment (L)	Clas- sifi- cation[4]	Length[5] (km)	Distance[6] (km) from Devil Canyon	Watana
BOUNDARY FAULTS						
AD5-1	Castle Mountain Fault	F	R	200	105	115
-	Benioff Zone	F	R	-	60	50
HB4-1	Denali Fault	F	R	2000	70	64
WATANA SIGNIFICANT FEATURES						
KC4-1	Talkeetna Thrust	F	A	354	25	6.5
KD3-3	Susitna Feature	F	B	153	25	3.2
KD3-7	-	L	B_L	50	35	0.0
KD4-27	Fins Feature	F	A	3.2	37	0.0
DEVIL CANYON SIGNIFICANT FEATURES						
KC5-5	-	L	B	20	7	31
KD5-2	-	F	B	5	5.6	38
KD5-3	-	L	B	82	5.8	23
KD5-9	-	L	B_L	5	1.6	39
KD5-12	-	L	B_L	24	2.4	28
KD5-42	-	L	B	5	0.8	35
KD5-43	-	L	B_L	2.4	0.0	38
KD5-44	-	L	A	34	0.5	37
KD5-45	-	L	B	31	1.3	41

Notes:
1. Appendix A explains alpha-numeric code number.
2. Feature locations are shown in Figures 8-2 through 8-5.
3. Feature name is given where known.
4. Classification notation:
   - R - Fault with recent displacement;
   - A - Fault or lineament with moderate likelihood of recent displacement;
   - B - Fault or lineament with low to moderate likelihood of recent displacement;
   - B_L - Fault or lineament with low likelihood of recent displacement.
5. Length is that measured in Figures 8-2 through 8-5 except for the Denali fault length which was obtained from Richter and Matson (1971).
6. Distance is the closest approach of the surface trace of the fault or lineament as measured on the base maps referred to in Note 2.

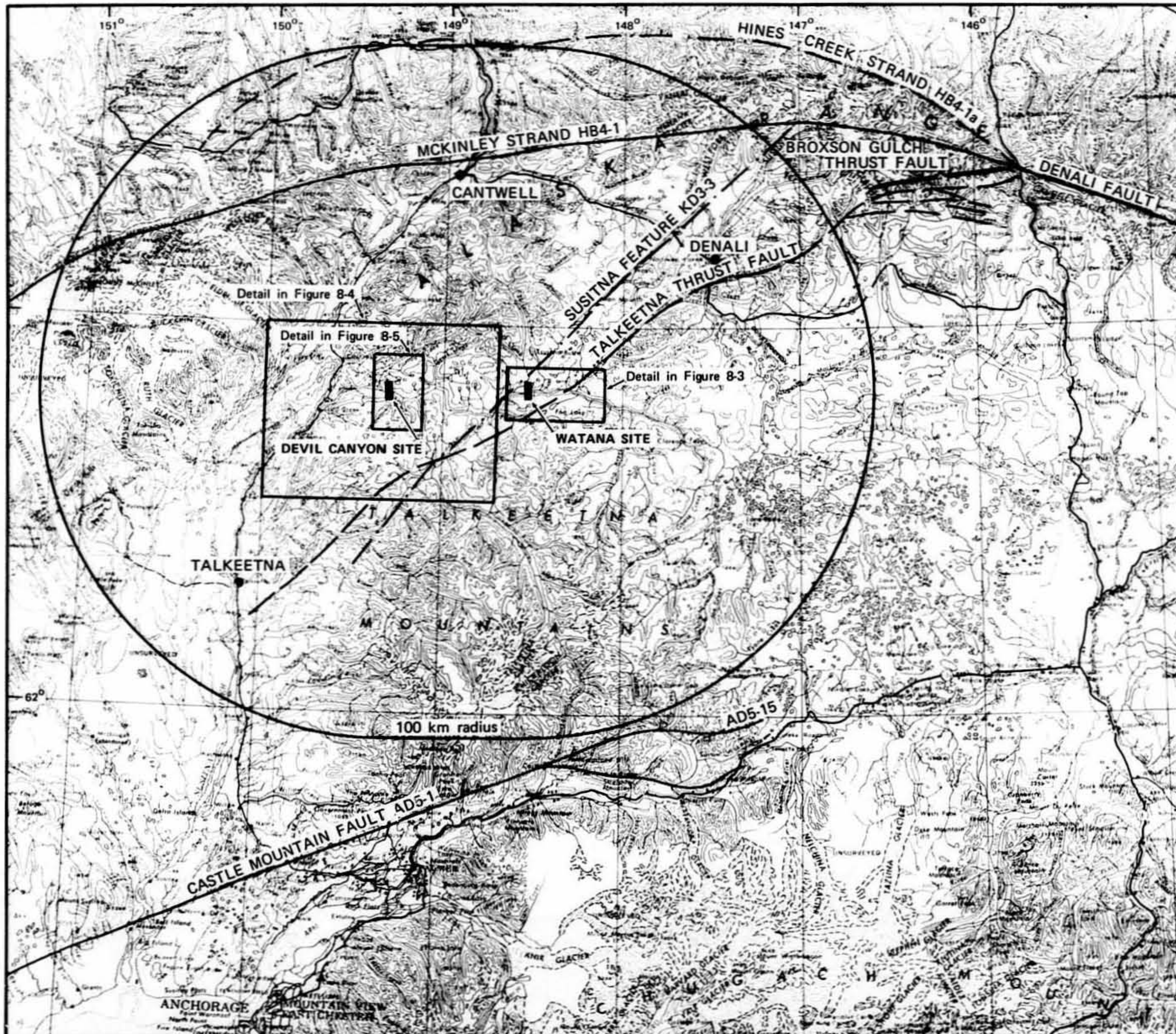


NOTES

1. Indeterminate A – Moderate to high likelihood of recent displacement.
2. Indeterminate B - Low to moderate likelihood of recent displacement.
3. Indeterminate B_L – Low likelihood of recent displacement.
4. Table 8-1 presents the criteria on which confidence levels are based.
5. Section 8-2 describes the basis for the classification terminology.

FIELD CLASSIFICATION OF CANDIDATE FEATURES

FIGURE 8-1



LEGEND

BOUNDARY FAULTS

Faults with recent displacement

SIGNIFICANT FEATURES

Indeterminate A feature

Indeterminate B feature

NOTES

1. Explanation of significant feature classification system is presented in Section 8-2.
2. Explanation of alpha-numeric symbols is presented in Appendix A.

N

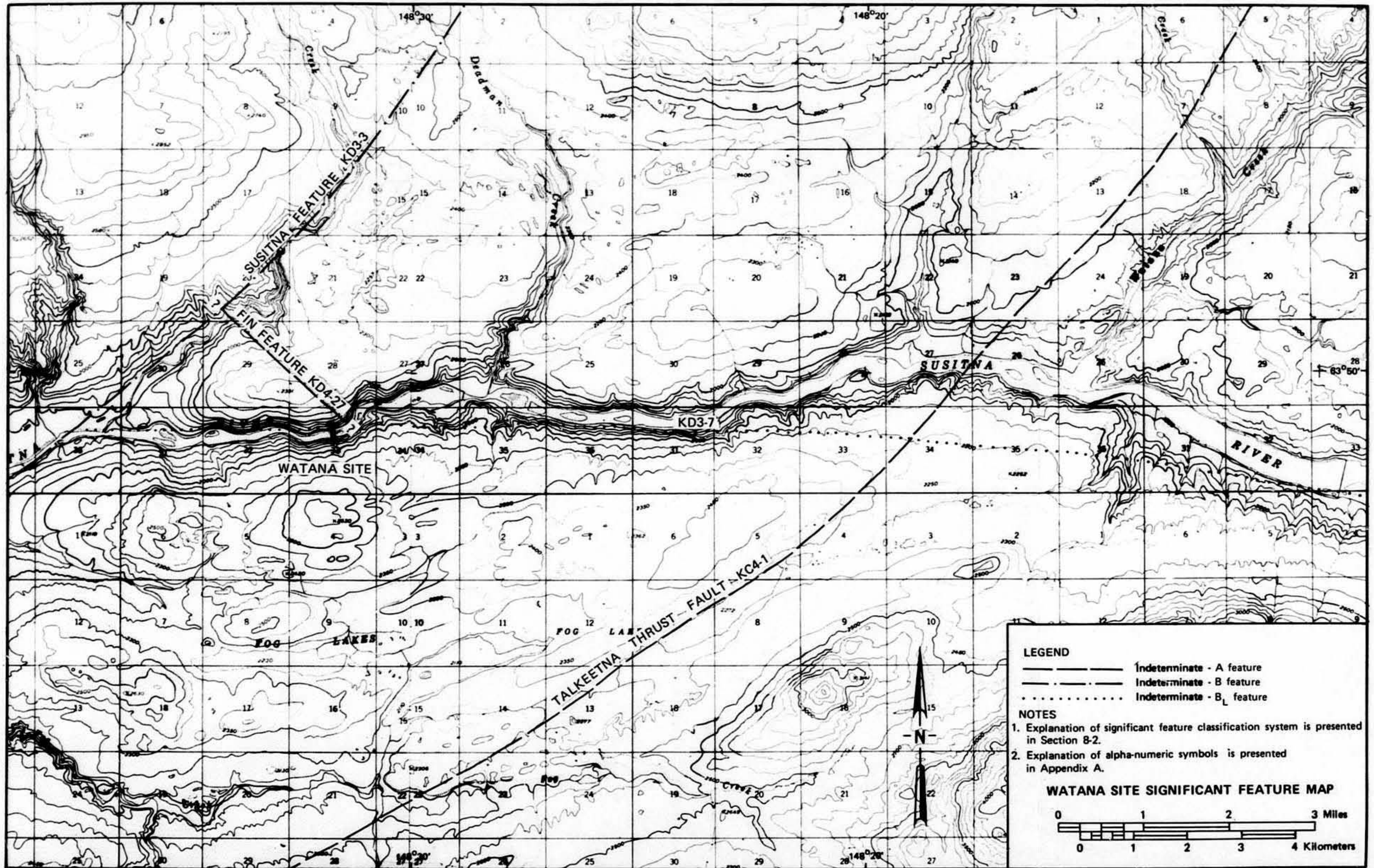
BOUNDARY FAULT AND SIGNIFICANT FEATURE MAP FOR THE SITE REGION

0 10 20 30 40 50 Miles

0 10 20 30 40 50 Kilometers

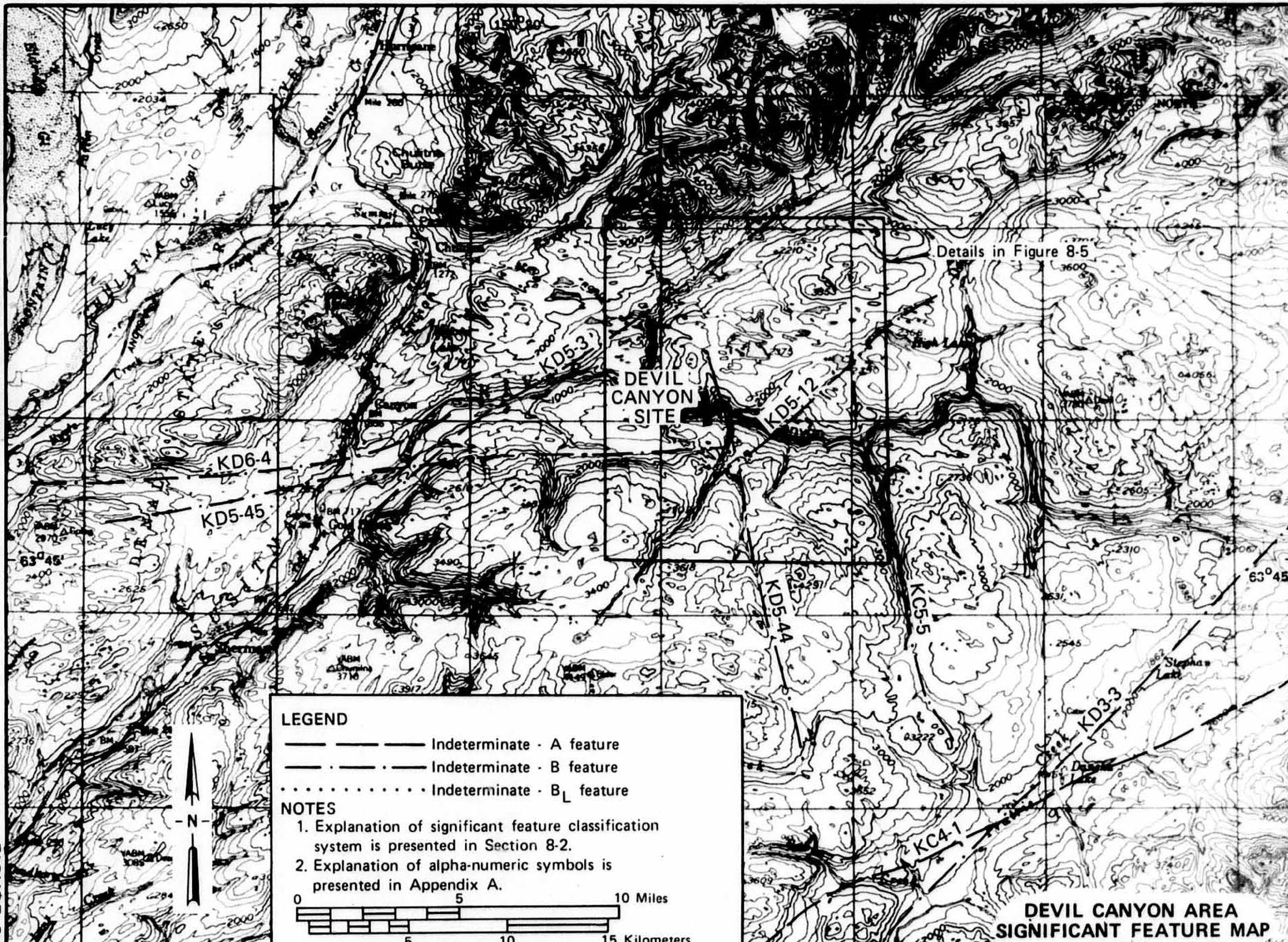
WOODWARD-CLYDE CONSULTANTS 14658A December 1980

FIGURE 8-2



WOODWARD-CLYDE CONSULTANTS 14668A December 1980

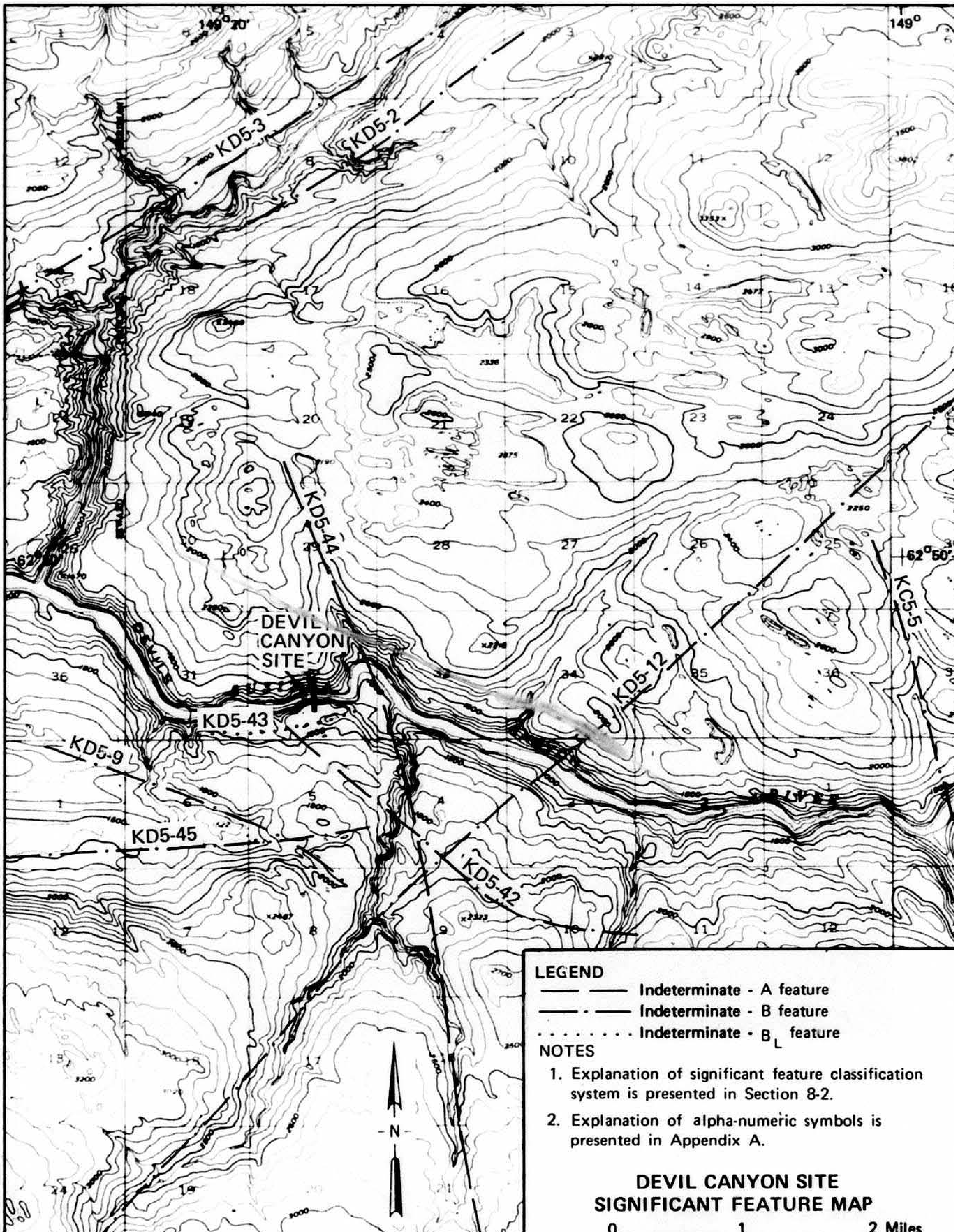
FIGURE 8-3



DEVIL CANYON AREA SIGNIFICANT FEATURE MAP

WOODWARD-CLYDE CONSULTANTS 14658A December 1980

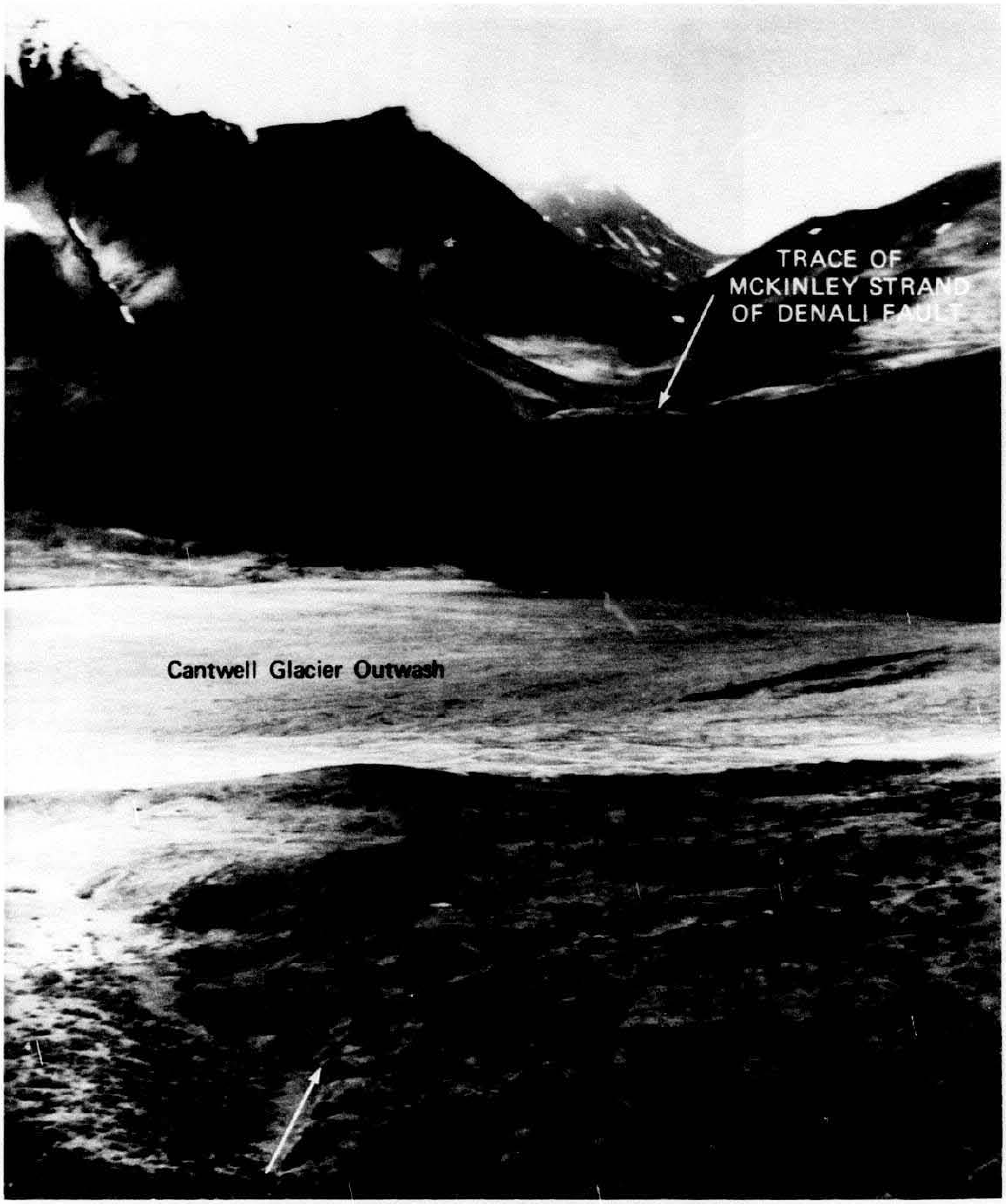
FIGURE 8-4



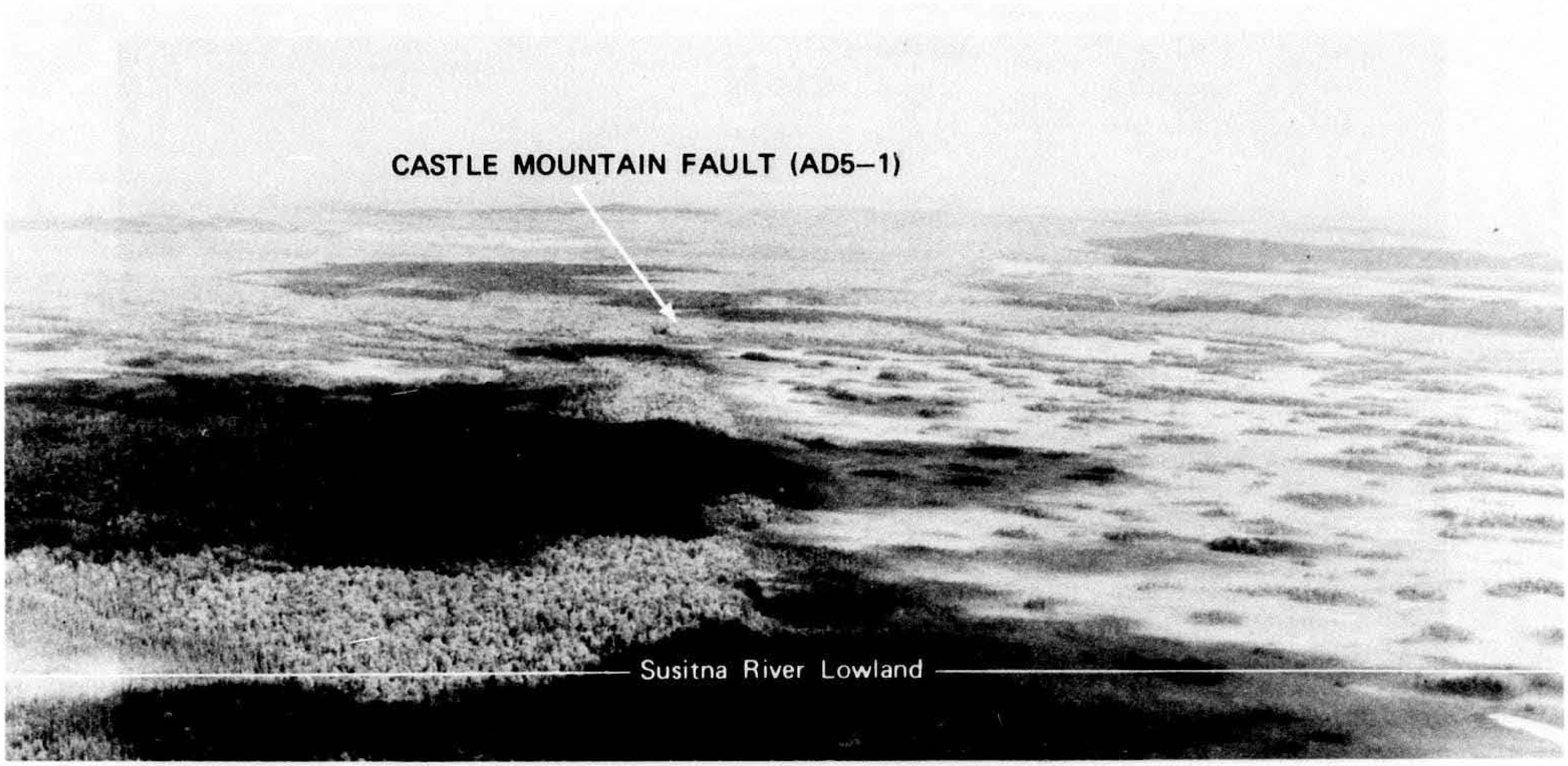
DEVIL CANYON SITE
SIGNIFICANT FEATURE MAP

WOODWARD-CLYDE CONSULTANTS 14668A December 1980

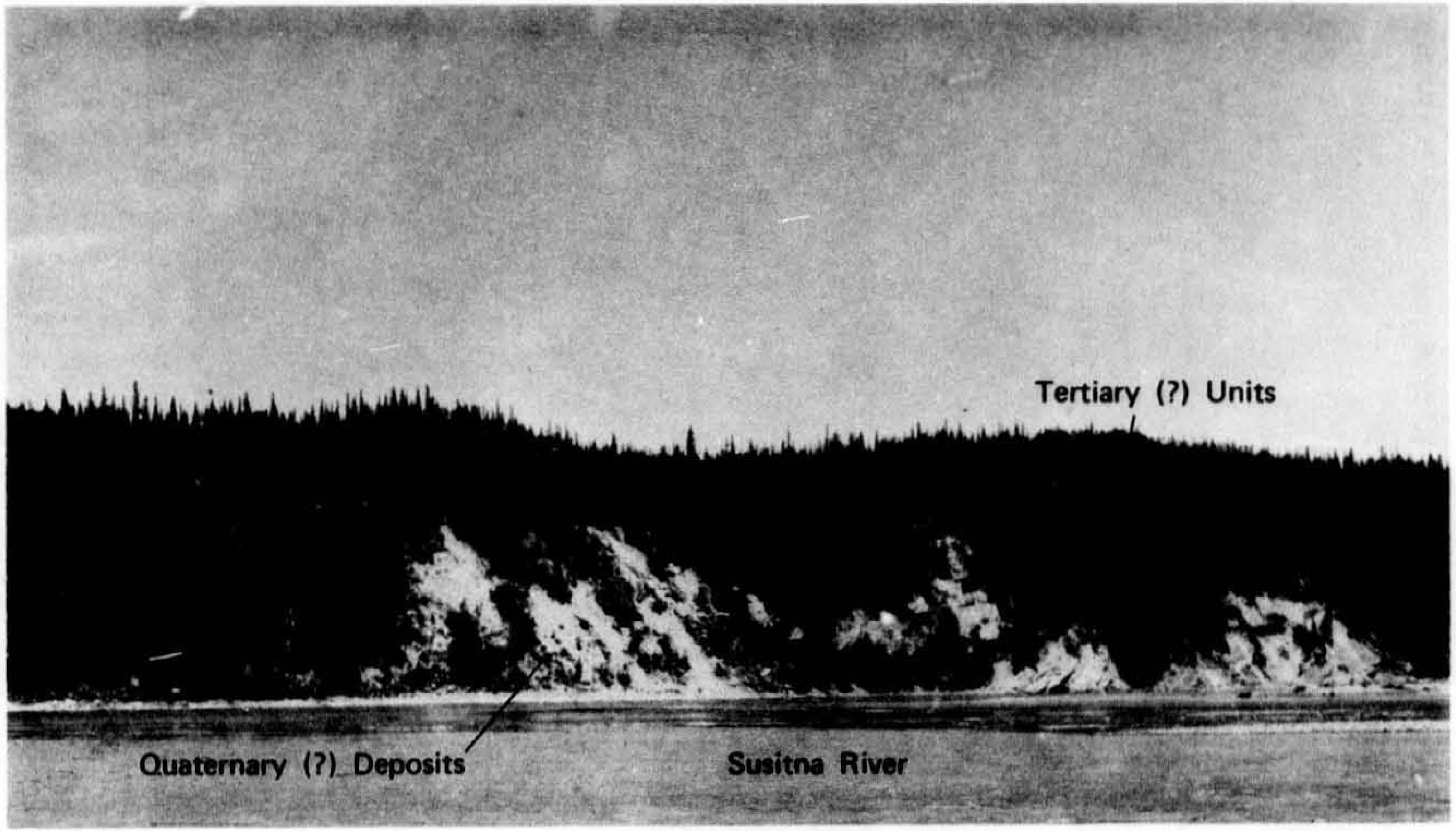
FIGURE 8-5



AERIAL VIEW OF MCKINLEY STRAND OF DENALI FAULT NEAR THE CANTWELL GLACIER



AERIAL VIEW OF CASTLE MOUNTAIN FAULT (AD5–1)



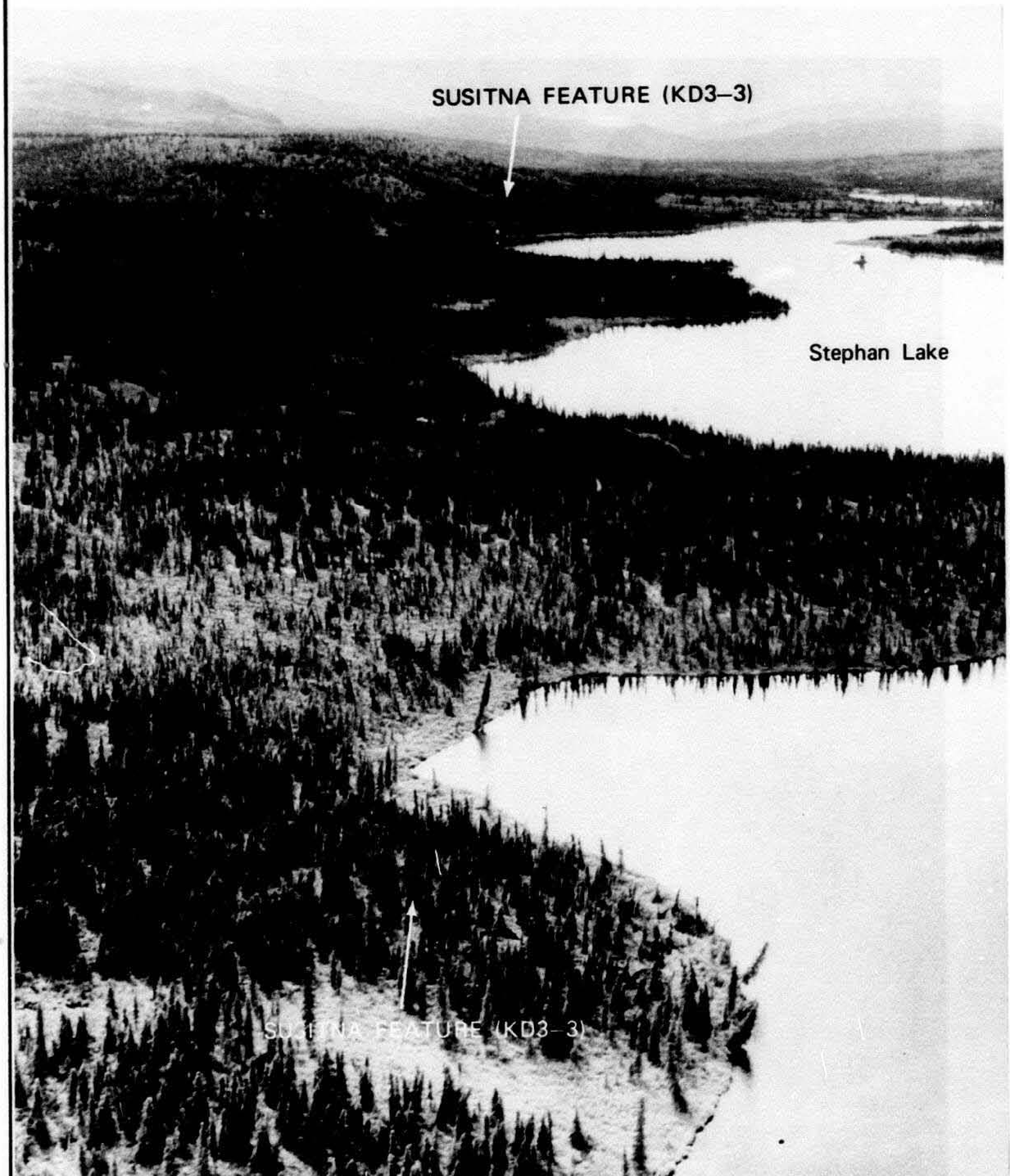
View is North

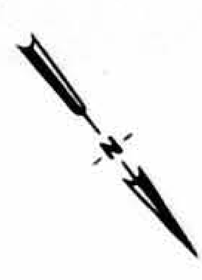
NOTE

1. Location of Talkeetna Thrust fault within the area of this photograph remains to be determined.

0 50 100 Feet

VIEW OF TALKEETNA THRUST FAULT LOCATION ON THE SUSITNA RIVER

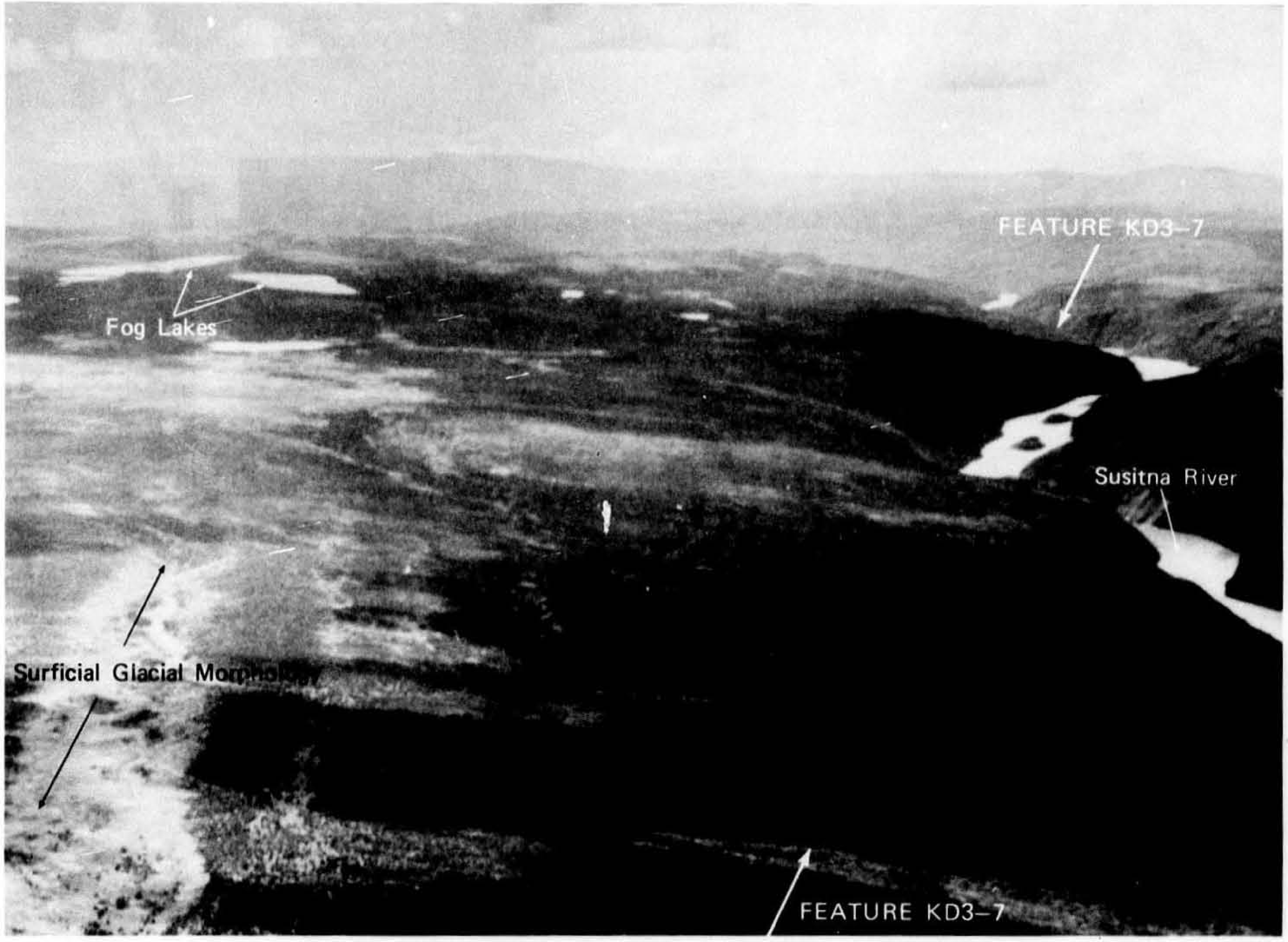




NOTE

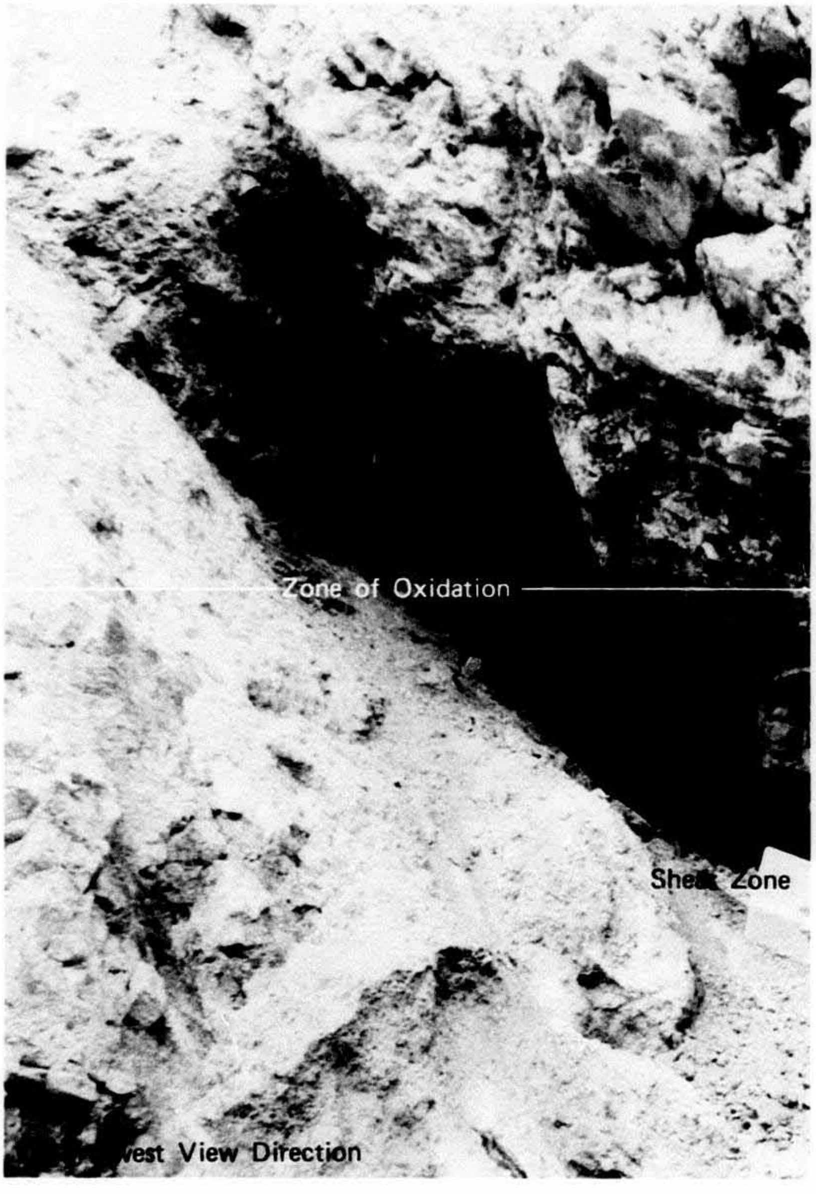
1. The Susitna Feature (KD3-3) location shown on this photograph is approxmate. No single morphologic expression of the feature has been observed.

AERIAL VIEW OF SUSITNA FEATURE (KD3–3)



NOTE
1. The location of feature KD3-7 shown on this photograph is approximate. No single morphologic expression of the feature has been observed.

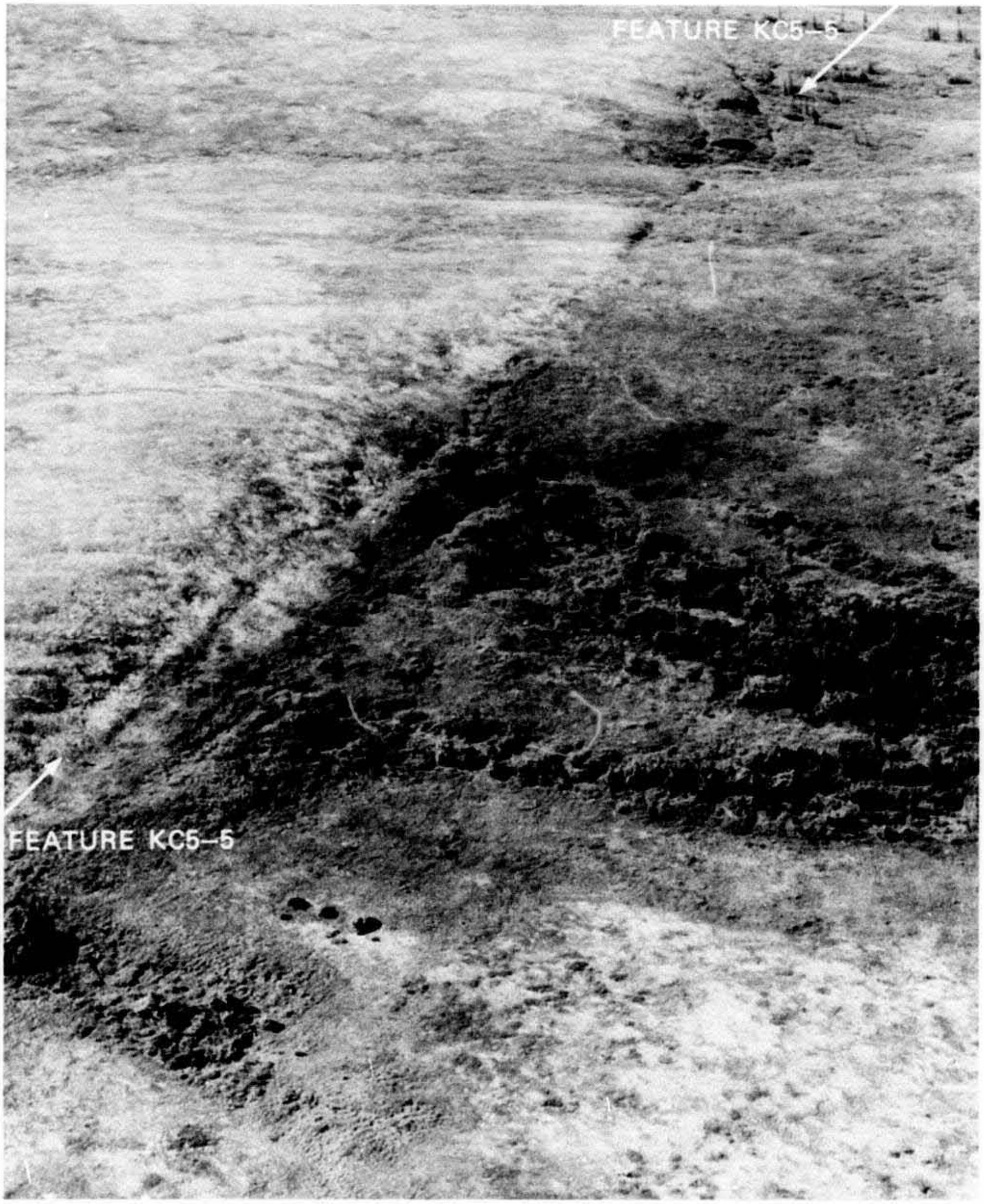
AERIAL VIEW OF FEATURE KD3–7



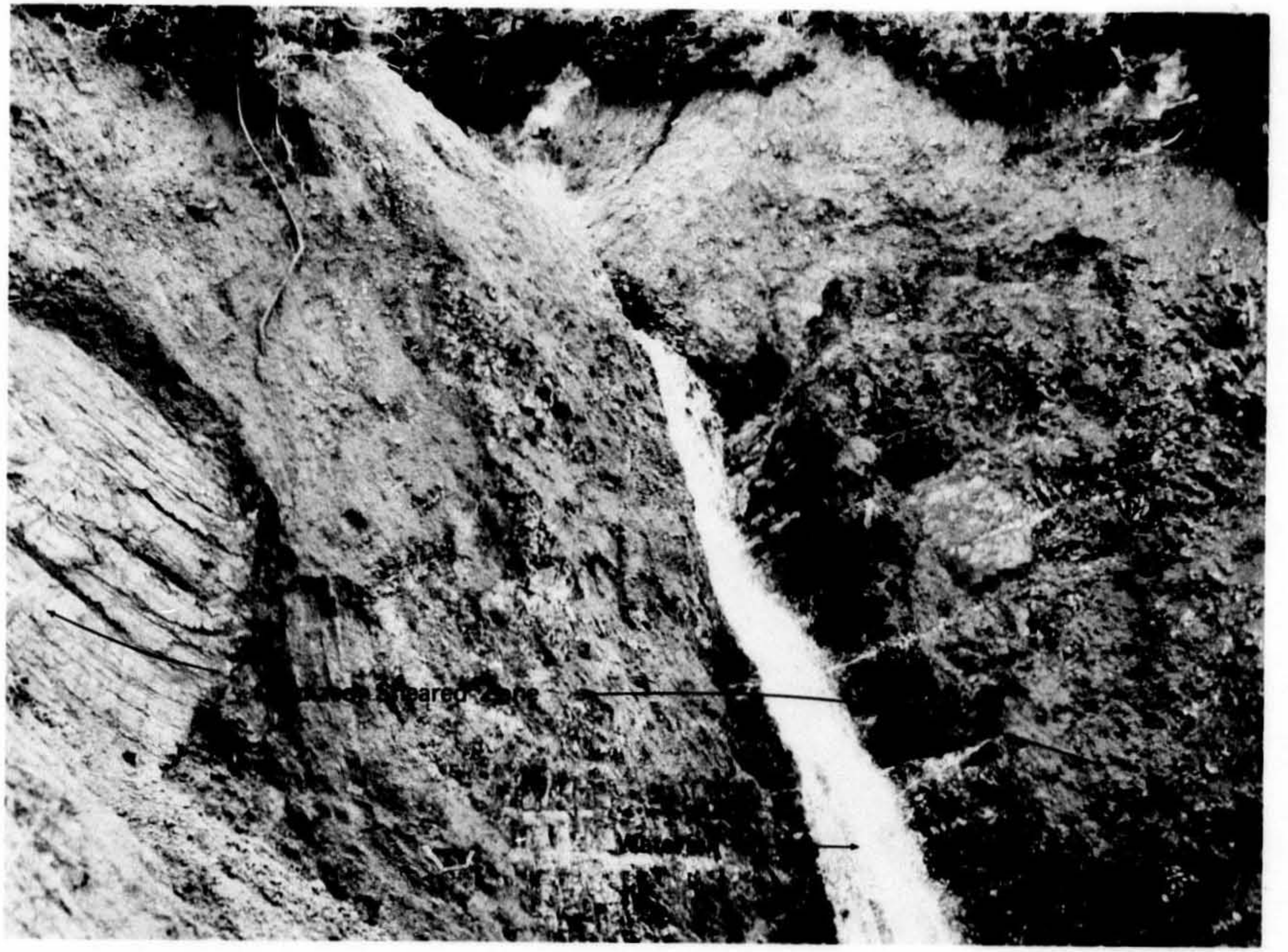
0 1 2 Feet

Approximate Scale

VIEW OF FINS FEATURE (KD4–27) AT TSUSENA CREEK



AERIAL VIEW OF FEATURE KC5–5

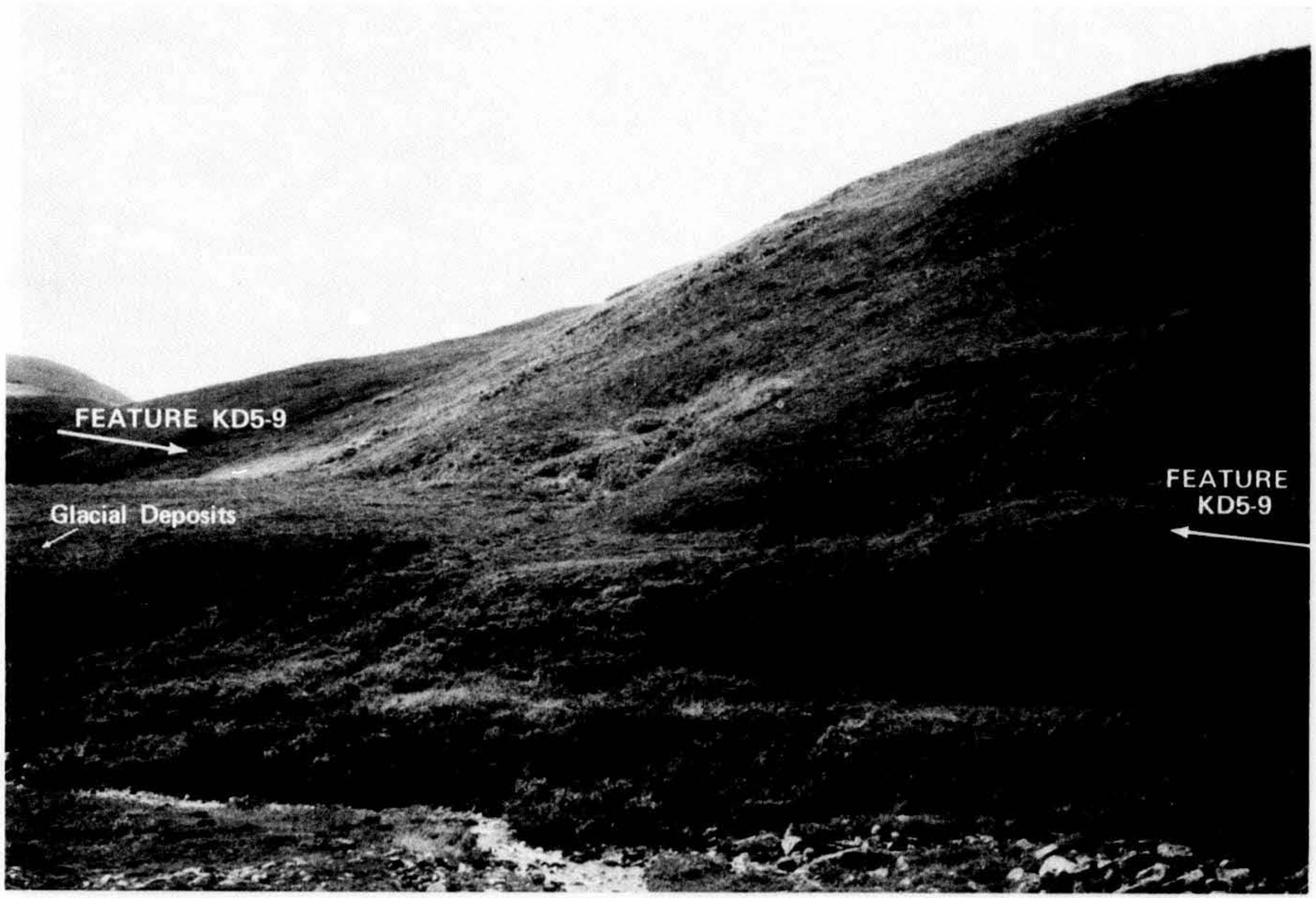


Southeast View

0 50 Feet
Approximate Scale

VIEW OF OXIDIZED, SHEARED ZONE ALONG FEATURE KD5–2

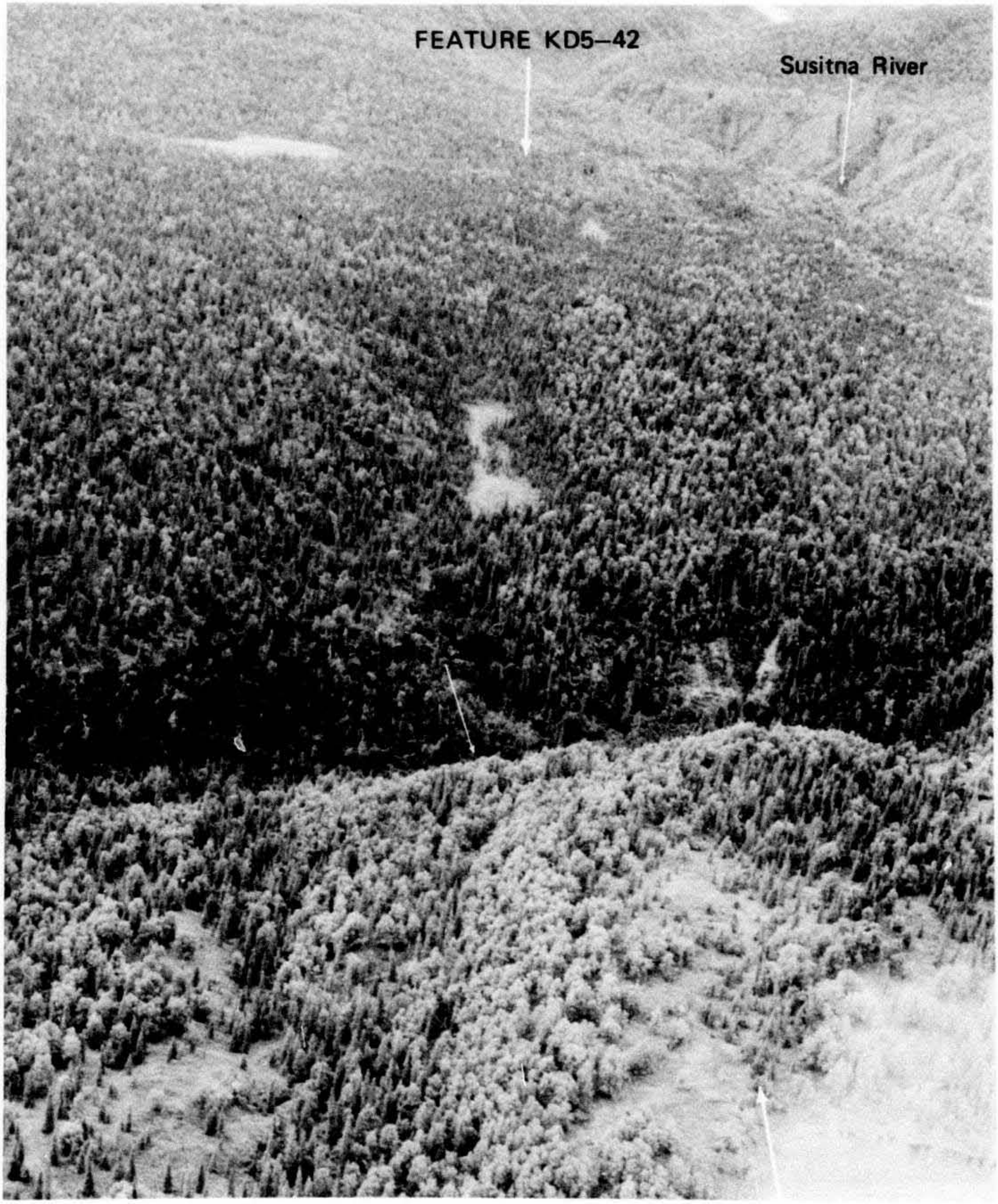
AERIAL VIEW OF FEATURE KD5–3



Southwest View

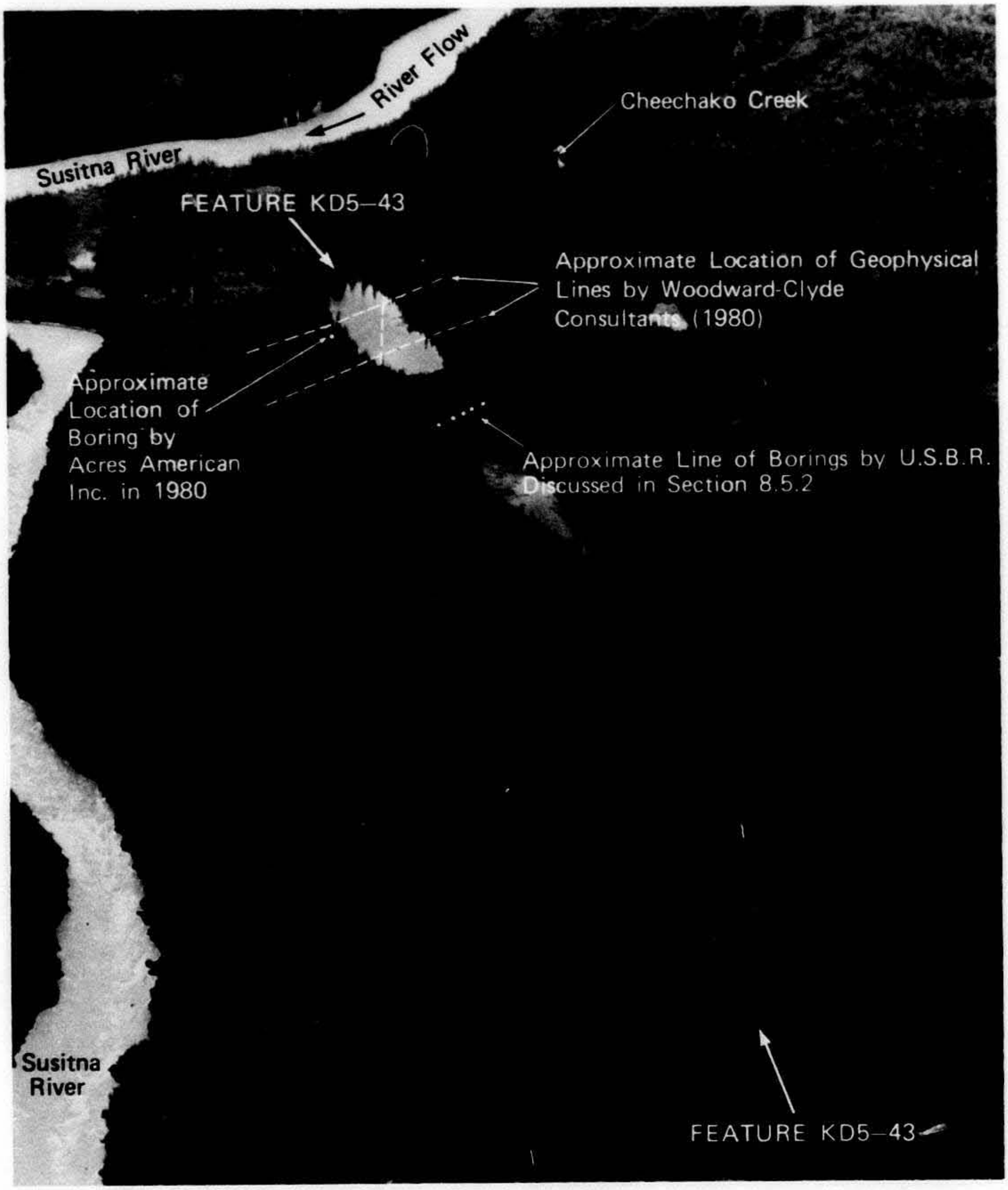
VIEW OF FEATURE KD5-9

AERIAL VIEW OF FEATURE KD5–12



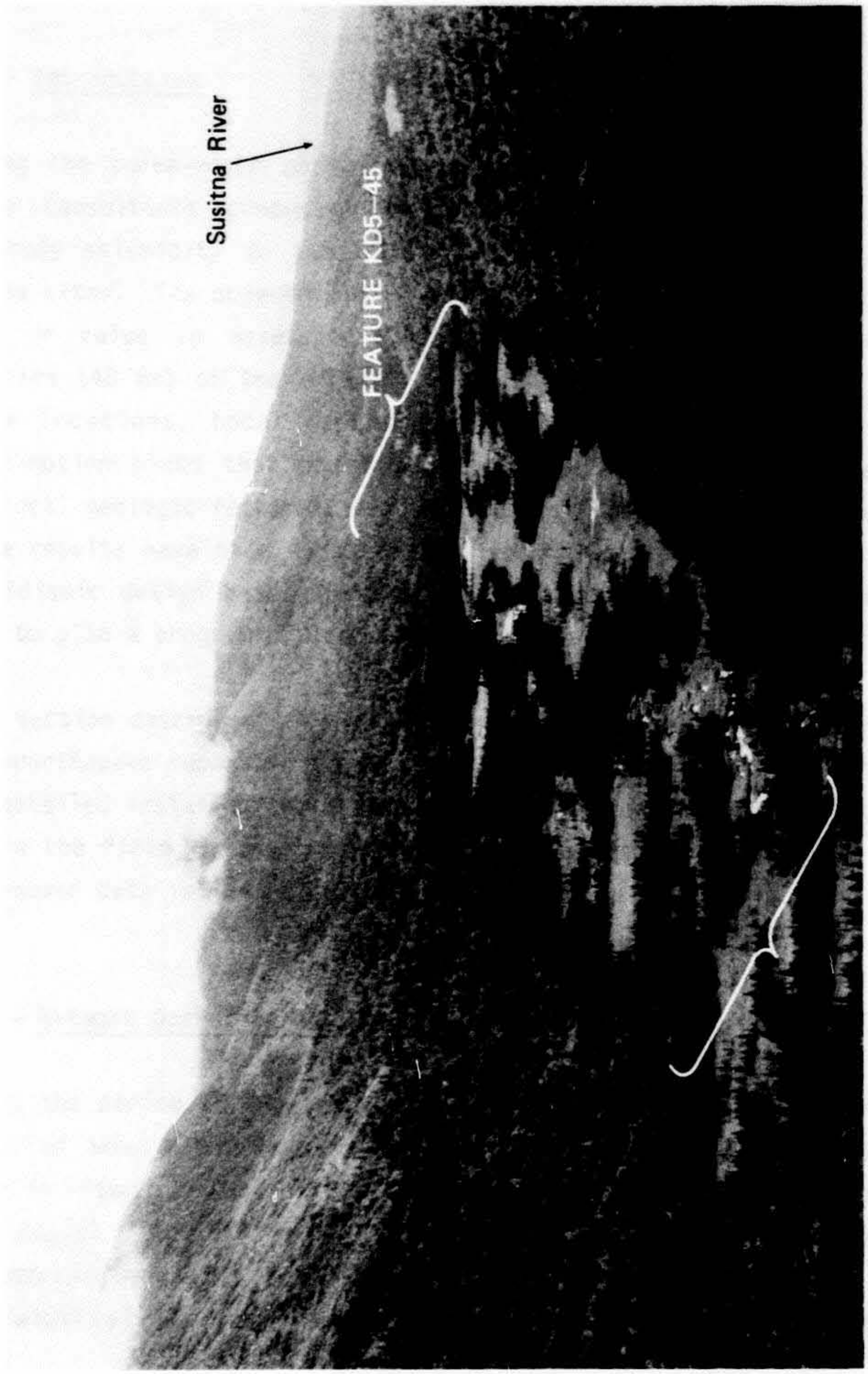
FEATURE KD5–42

AERIAL VIEW OF FEATURE KD5–42



AERIAL VIEW OF FEATURE KD5–43

AERIAL VIEW OF FEATURE KD5–44



AERIAL VIEW OF FEATURE KD5–45

9 - SHORT-TERM MICROEARTHQUAKE MONITORING PROGRAM

9.1 - Introduction

During the three-month period 28 June to 28 September 1980, Woodward-Clyde Consultants conducted microearthquake recording and analysis to study seismicity in the vicinity of the proposed Devil Canyon and Watana sites. The objective of the study was to collect microearthquake data of value in assessing earthquake sources within approximately 30 miles (48 km) of the sites. The data were used to calculate earthquake locations, focal depths, local Richter magnitudes (M_L), and first-motion plots that could be interpreted with respect to regional and local geologic features, tectonic models, and historical seismicity. These results have been combined with seismic geology results to assess the seismic design bases for the Project. These results will also be used to plan a program of long term seismic monitoring.

This section describes the installation and operation of the short-term microearthquake recording system and the analysis of the data therefrom. The detailed installation, operation, and maintenance procedures carried out in the field are described in Appendix B, and the catalog of microearthquake data is listed in Appendix D.

9.2 - Network Operation and Data Analysis

During the period 25 June to 4 July 1980, ten seismograph stations were installed around the Watana and Devil Canyon sites, at the locations shown in Figures 9-1 and B-1. Three stations were subsequently moved in late August 1980 to increase coverage in a section of the southern microearthquake study area (Table B-1; Figures 9-1 and B-1). Data from eight of the ten stations were telemetered into the Watana Base

Camp (telemetry paths are shown in Figure B-1) where seismographs continuously recorded data on smoked drum recorders. Two of the ten stations recorded data at their respective field sites and required servicing every other day by helicopter. This station configuration and instrumentation provided a reliable field operation and produced a high-quality data set. The seismic records were read at the field camp and local earthquakes were located with a portable microcomputer. The field data analyses provided the latitude, longitude, depth of the focus, and local Richter magnitude (M_L) of each processed earthquake.

After the field season, the earthquakes were reprocessed by Woodward-Clyde Consultants using data analysis procedures described in Appendix B. Final locations were cataloged as shown in Appendix D.

Between 28 June and 28 September 1980, a total of 268 earthquakes were located within an area bounded by 62.3° to 63.3° north latitude, 147.5° to 150.4° west longitude, designated the microearthquake study area. Of these 268 earthquakes, 98 occurred below a depth of 19 miles (30 km) depth in the dipping Benioff zone, and 170 occurred in the crust above 19 miles (30 km). In addition, a number of regional events were located outside of the network boundaries. These earthquakes are shown along with the local events in Figures 9-1 and 9-2. The accuracy of earthquake locations is considered to be very good (within a few kilometers) for those events that occurred within the network, but the accuracy of location of earthquakes outside the network decreases as the distance from the network increases. The detection level falls off by approximately one magnitude unit outside of the microearthquake study area shown by the dashed box in Figures 9-1 and 9-2.

As discused in Section 4, the seismic activity in the site region is associated with either the crustal zone of the Talkeetna Terrain or with the Benioff zone dipping to the northwest beneath the Talkeetna Terrain. These two source areas will be used to discuss the microearthquake study results.

9.3 - Crustal Earthquake Sources

Figure 9-1 presents a map view of all 170 local earthquakes and 27 regional events located above a depth of 19 miles (30 km), in relation to the proposed Project and the seismometer network. Also shown are the Denali fault and the significant features identified in Section 8. Several aspects of the crustal seismicity are discussed below.

The magnitude of earthquakes shown in Figure 9-1 is quite low, with the minimum detection level at about magnitude (M_L) 1-1/4, as shown in Figure 9-3a. Earthquakes as small as magnitude (M_L) 0.0 were also detected and located within the microearthquake study area. The slope of the frequency magnitude curve in Figure 3a is 1.48. This value is larger than is often observed in other tectonic regions and suggests that there is an unusually large number of small earthquakes compared to the number of larger events. The largest earthquake in the crust was of magnitude (M_L) 2.8 and occurred approximately 7 miles (11 km) northwest of the Watana site on 2 July 1980.

Figure 9-4 shows the rate of occurrence per day of located microearthquakes. While there is a daily fluctuation from 0 to 9 events per day, there does not appear to be any long-term variation during the course of the three-months.

Apart from the two prominent clusters of microearthquakes that occurred near station GRB, the seismicity is broadly distributed over the central portion of the microearthquake study area. There do not appear to be any lineations of microearthquakes suggestive of the presence of faults with recent displacement. In addition, the seismic activity does not appear to bear any relationship to the locations or orientations of the significant features identified in Section 8.

Several shallow earthquakes were located in the vicinity of the proposed Project sites. As previously stated, a magnitude (M_L) 2.8 earthquake occurred approximately 7 miles (11 km) from the proposed Watana site on 2 July 1980 at 1042 Univeral Coordinate Time (UCT). Five smaller events have also been located within 6 miles (10 km) of the Watana site (Figure 9-1). A magnitude (M_L) 1.66 earthquake occurred within 3 miles (5 km) of the Devil Canyon site on 12 September 1980 at 0428 UCT. In addition, six smaller events occurred in the Devil Canyon area (Figure 9-1).

The near-regional events shown in Figure 9-1 are included to point out that the portion of the Talkeetna Terrain that contains shallow seismicity is of limited extent. The level of activity falls off to the west of stations HUR and CNL, to the north of the dashed-line boundary of the microearthquake study area, and to the east of station WAC. Although the resolution is decreasing to the south near 62° north latitude, there appears to be continuing microseismicity. This general area of seismic activity is geographically associated with the Talkeetna Mountains.

Two clusters of microearthquake activity were observed during the study period and are annotated in Figure 9-1. Figures 9-5 and 9-6 show vertical cross-sections through the northern cluster and the southern cluster, designated No. 1 and No. 2, respectively, indicating that these are indeed localizations of activity. Cluster No.1 is comprised of 55 earthquakes, or almost one third of the total detected shallow seismicity of the region, while cluster No. 2 is comprised of 25 earthquakes, or 15% of the total. The two clusters together contain 48% of the total number of shallow events detected during the three-month study period. As can be seen in Figures 9-5 and 9-6, there is a clear separation between Benioff zone seismicity and the two crustal clusters of seismicity.

The sequence of events occurred in the following order: The first 44 identifiable cluster events occurred in cluster No. 1 beginning on 5 July 1980. The first earthquake identified with cluster No. 2

occurred on 18 August 1980. The last microearthquake associated with cluster No. 1 occurred on 16 September 1980, while the activity of cluster No. 2 continued to 25 September 1980. Because the network was removed by 28 September 1980, it is not known whether activity in these two clusters continued beyond that time. There doesn't appear to be any evidence, such as events migrating across the space between the two clusters, to suggest that there is a strong mechanical connection between the two clusters.

The principal stress orientation and possible causative fault planes for the crustal microearthquake activity have been investigated using first motion plots. The two clusters of events are the most likely to have coherent composite mechanisms. The data and interpretation of cluster No. 1 are shown in Figure 9-7. The sense of P-wave first motion for each earthquake seems to be fairly consistent. Two possible planes of motion exist, one striking N23°E with a dip of 50° to the northwest, and the other striking N17°W with a dip of 48° to the northeast. The maximum compressive stress axis (P) and maximum tensile stress axis (T) are also shown.

From the fault plane solution alone, it is difficult to determine which of the two planes is parallel to the actual fault direction. On the basis of geologic structural trends, the plane most likely to be parallel to actual movement is probably the one striking N23°E. The interpretation of movement along this plane is one of thrusting with a rightlateral component of displacement. The maximum compressive stress is oriented almost east-west, with little or no plunge. The N23°E plane is also the one with strike most similar to the Susitna lineament and Talkeetna thrust fault, as shown in Figure 9-1. However, the dip of the N23°E plane is to the northwest; if the plane were projected to the ground surface, it would lie substantially to the southeast of the cluster and the two surface features. Thus, cluster No.1 does not seem to be related to either the Susitna lineament or the Talkeetna thrust fault.

For cluster No.2, a focal mechanism plot was also made, but no consistent motion could be ascertained from the data (Figure 9-7). It appears that all the stations in Figure 9-7 show both compressive and dilatational first motion. This suggests that the mechanism of faulting has fluctuated locally over a geologically brief period. Such fluctuations are not uncommon during swarms of microearthquakes.

Two additional, less spatially grouped composite focal mechanisms were plotted. Figure 9-8a is for four events located to the west-northwest and within 6 miles (10 km) of station SBL. The mechanism is not fully consistent with, and is not well-constrained by the first-motion. The maximum compressive stress is oriented west-northwest/east-southeast, and the style of faulting is normal faulting with substantial oblique displacement. The events in Figure 9-8b are taken from many locations of the microearthquake study area (Figure 9-1). These seven events also show west-trending compression, but the style of faulting is oblique reverse.

In general, the crustal earthquake activity seems to be caused by an east-west or west-northwest/east-southeast oriented compressive stress acting on the region. This activity does not appear to be related to recognized faults or lineaments. The activity is representative of minor adjustments within the crust.

To further assess the possible relationship between the identified significant features or other geologic features and the crustal microearthquake activity, a cross-section (line C-C' shown in Figure 9-9) was plotted. The activity was projected on a northwest-trending plane (line C-C'), thus optimizing the view of the Benioff zone and also looking along the strike of the larger faults and lineaments of Figure 9-1. The only suggestion of a vertical distribution of activity lies above cluster No 1; this appears to be a fortuitous lineation based upon a few scattered events to the northeast being superposed on the cluster. The region marked aseismic front is discussed in Section 9.4.

A preliminary assessment of the largest earthquake that could occur in the site region without causing surface rupture has been made by comparing the characteristics of the site region with those of coastal California (a seismically active region). In coastal California, seismicity data suggest the crust is approximately 3 to 9 miles (5 to 15 km) thick and that small to moderate earthquakes (magnitude (M_L) greater than 3 to 4) occur in zones associated with faults with recent displacement (McNally, 1978; McNally and Hadley, 1978). Earthquakes smaller than magnitude (M_L) 3 to 4 tend to have a random spatial distribution.

In the site region the zone of crustal seismicity appears to be thicker than that of coastal California, i.e., 5 to 12 miles (8 to 20 km) versus 3 to 9 miles (5 to 15 km) respectively. The thicker brittle crust of the Talkeetna Terrain thus suggests that somewhat larger earthquakes, up to magnitude (M_L) 5-1/2, may occur without association with surface faults with recent displacement. Such lower crustal events would be constrained to rupture planes deeper than about 6 miles (10 km). Earthquakes larger than these (larger than magnitude (M_L) 5-1/2), would be expected to have rupture dimensions and displacements large enough to produce evidence of surface fault displacement in recent geologic time.

9.4 Benioff Zone Seismicity

The existence of a subcrustal zone of seismicity is clearly demonstrated in Figure 9-9. The deeper zone dips in the direction of approximately N45°W at an angle of 20°. The depth of 19 miles (30 km) separates the crustal zone from the deeper seismicity; the map view of the deep zone is shown in Figure 9-2. A total of 98 subcrustal events were located within the microearthquake study area shown in Figure 9-2. An additional 16 earthquakes were detected and located to the south of the microearthquake study area. The event selection procedures (discussed in Appendix B) excluded very deep activity to the west and north of the microearthquake study area. Several aspects of the Benioff zone are discussed below.

The spatial distribution in Figure 9-2 is comparatively uniform, with no prominent lineations or clusters. The eastern extent of the Benioff zone is strongly defined near 148° west longitude.

It is clear by inspection of Figures 9-1, 9-2, and 9-9 that the Benioff zone is characterized by much more frequent larger microearthquakes than is the shallow crustal zone. Thirteen Benioff zone earthquakes were assigned a magnitude (M_L) of 3.0 or larger, the largest of which had a magnitude (M_L) of 3.68 and occurred on 13 July 1980, at 0557 UCT beneath station GRB. The magnitude frequency distribution for the Benioff zone is shown in Figure 9-3b. The b-value of 0.68 is comparable with that observed in many areas worldwide.

The frequency of occurrence of larger events (magnitude (M_L) $\geq$ 3.5) during the three-month study was low, based on the numbers of smaller events; one event of magnitude (M_L) 4-1/2 would have been expected based on Figure 9-3b. The contrast in level of seismicity in the crustal and Benioff zones shown in Figures 9-3a and 9-3b is consistent with the historical difference noted in Section 4.3 with the Benioff zone being about an order of magnitude more active than the crustal zone.

The cross-section of Figure 9-9 is perpendicular to the N45°W strike direction of the Benioff zone as determined by Agnew (1980). This view of the microearthquake data shows the Benioff zone to be a very thin seismic region, averaging about 6 miles (10 km) thick with a maximum thickness of about 9 miles (15 km).

The Benioff zone seismicity appears to become more closely related to the crustal zone to the southeast of the line marked aseismic front in Figure 9-9. The aseismic front may be associated with an aseismic belt in the crustal zone, as noted in other subduction zones. For example, Yoshii (1975) noted that the boundary between the aseismic mantle and the highly active region adjacent to the trench, which he named the "aseismic front," seems to be common to most Benioff zones. The zone of high seismicity on the trench side of the front seems to be associated with high Q (described in Section 9.5) and high seismic velocities according to Yoshii (1975). Yamashina and others (1978) show that the aseismic front can be defined by microseismicity as well as by large earthquakes. Yoshii (1975) defined the aseismic front to be a discontinuity in the seismicity of the mantle. However, Yamashina and others (1978) have also discerned a similar phenomenon in the crust between the volcanic front and the aseismic front in Japan, which they name the aseismic belt. They believe this feature is typical of most island arcs and cite the Aleutian arc as one example.

The aseismic belt is an area several tens-of-miles (tens-of-kilometers) wide with low to non-existent shallow seismicity, explained as a mechanically unstrained area (Yamashina and others, 1978, in Figure 3, p. S448) in the crust. Geodimeter traverse surveys and strain measurements in Japan show that this zone undergoes extension perpendicular to the trench, perhaps due to a minor inland uplift produced by partial decoupling between the crust and the subducting plate. This unstrained region is limited to shallow depths in the crust (Yamashina and others, 1978). Earthquakes that may occur in this zone do not seem to be caused by the same stress regime as in the subducting plate or trenchward of the aseismic front.

For the site region, the apparent aseismic front is located southeast of the Project at approximately the 28-mile (45-km) depth interval of Pacific Plate subduction (Figure 9-9). The aseismic belt is located about 6 miles (10 km) southeast of the Watana site. These two features were predicted for the Alaskan subduction zone by Yamashina and others (1978) but have not been reported prior to this study.

In order to assess the stress regime acting within the Benioff zone, first-motion projections were prepared both for single events as well as for composited groups of events (the methodology is discussed in Appendix B). In order to maximize reliability, only the larger events were considered in this study. The most prevalent mechanism, both for single events and for composited events, is shown in Figure 9-10a. Seven events fit the same mechanism. The minimum compression (T) axis dips at 30° to the northwest, and the direction of maximum compression dips at 60° to the southeast. The fault planes of this mechanism indicate either southeast-dipping, very shallow, normal faulting or steep, northwest-dipping, normal faulting. The latter is more reasonable physically and suggests that the Benioff zone is breaking up by faulting due to down-dip gravitational sinking. Down-dip extension was also noted by Bhattacharya and Biswas (1979), on the basis of studies of larger regional earthquakes. There is no apparent spatial pattern to the events composited in Figure 9-10a.

An additional composite mechanism fits three events and is shown in Figure 9-10b. A more oblique style of movement is suggested here. The P and T axes are horizontal and vertical, respectively. The fault planes are compatible with either gravitational sinking or low-angle compression, although the former mechanism is more consistent with the mechanism plotted in Figure 9-9a.

On the basis of focal mechanism and hypocenter data, it appears most consistent to consider the seismicity of the subducting plate beneath the microearthquake study area to be occurring in the interior of the dipping plate and not along its upper or lower surfaces. Dip-slip movement in subducting slabs has been attributed to simple unbending of the plate (Yoshii, 1979) and also to gravitational sinking (Yoshii, 1979; Sleep, 1979).

Because there are no physically observed geologic data, such as fault lengths and displacements, that can be used to assess preliminary maximum earthquake magnitudes in the Benioff zone, constraints must be inferred from the seismologic data and tectonic model for the region. The thinness of the Benioff zone and the evidence for internal deformation rather than interplate thrusting suggest that, in the subcrustal region beneath the Project sites, the largest physically realizable earthquakes would have fault rupture dimensions on the order of 9 miles by 62 miles (15 km by 100 km). These dimensions correspond to earthquakes in the magnitude (M_S) range of 7 to 7-1/2 (based on other historical earthquakes worldwide and on relationships such as those of Wyss (1979)).

The considerations discussed above suggest that a preliminary maximum credible earthquake of magnitude (M_S) 7 to 7-1/2 could be associated with the deeper position of the Benioff zone below the Project sites. Larger earthquakes on the Benioff zone, such as the 1964 Prince William Sound event of magnitude (M_S) 8.4, are earthquakes associated with thrust fault rupture that usually occur along the Benioff zone below and trenchward of the crustal aseismic belt. However, the significance of the zones of low seismicity in the crust (Section 9.3) and the subduction zone (Section 4 and Figure 4-2) is not fully understood. At present it is theoretically possible to postulate that large interplate earthquakes could occur as close to the Project sites as the aseismic front shown in Figure 9-9. This is a closest distance of 31 miles (50 km) and 40 miles (65 km) to the Watana and Devil Canyon sites, respectively.

9.5 - Comparison of Susitna Project Area Attenuation with That of Comparable Tectonic Areas Worldwide

Anelastic Absorption (Q)

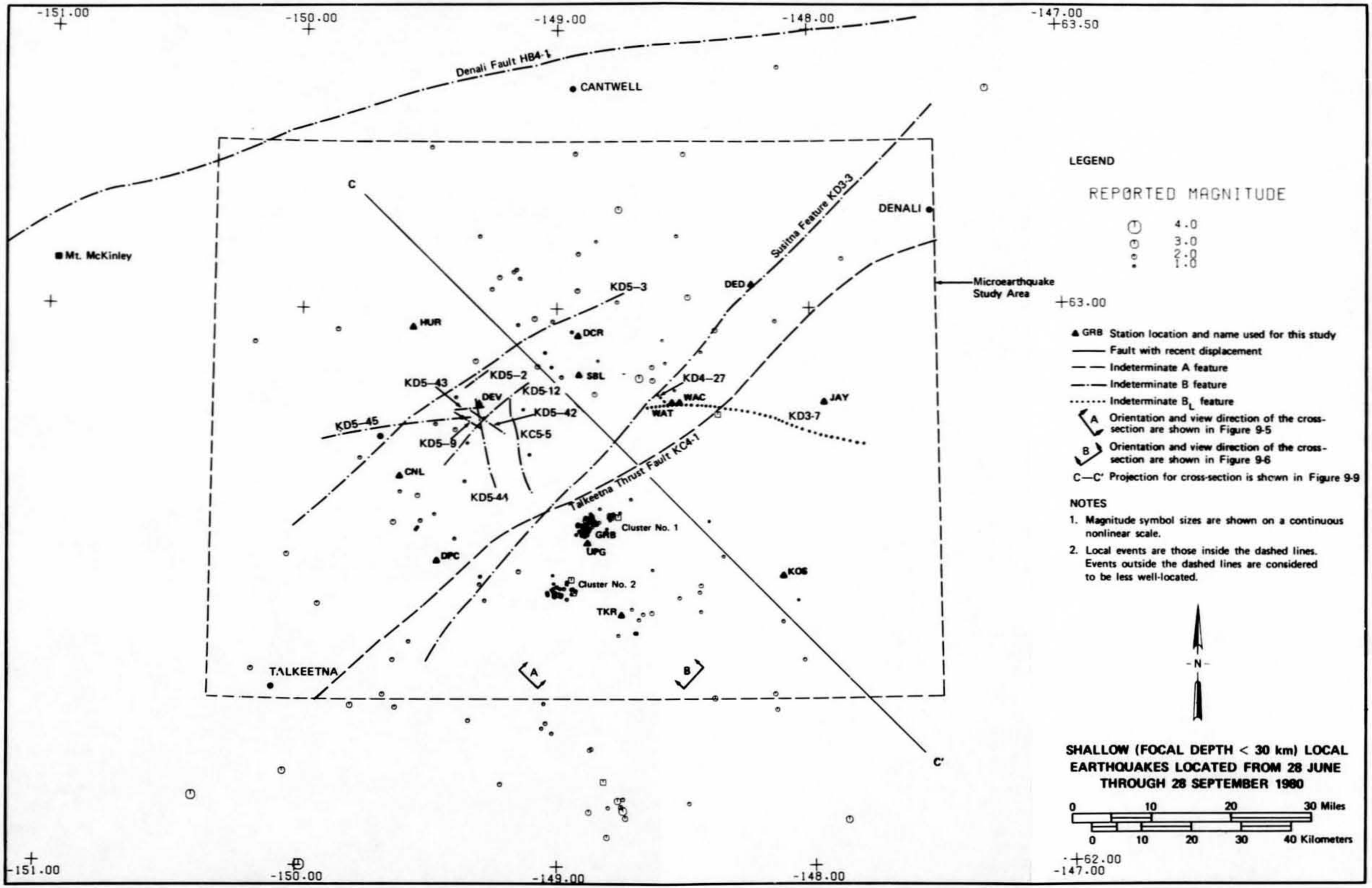
Barazangi and Isacks (1971) determined a Q value of 1000 for the wedge of the overriding plate between the Tonga trench and the Tonga ridge. Hasegawa and others (1979) found a similar value in the region oceanward of the aseismic front in northern Honshu and a value of 350 for the remaining region between the aseismic front and the volcanic front, which overlies the subducting plate in the depth range 31 to 62 miles (50 to 100 km). This region is equivalent to that beneath the Project sites.

The Q value of 350 contrasts strongly with the value of 1000 landward of the volcanic front in northern Honshu. The tentative assignment of a Q value of 350 for the region below the Project sites is compatible with the relatively low attenuation of shear waves observed in the neighboring Skwentna region to the southwest by Davies (1975).

Decay of Acceleration Amplitudes with Distance

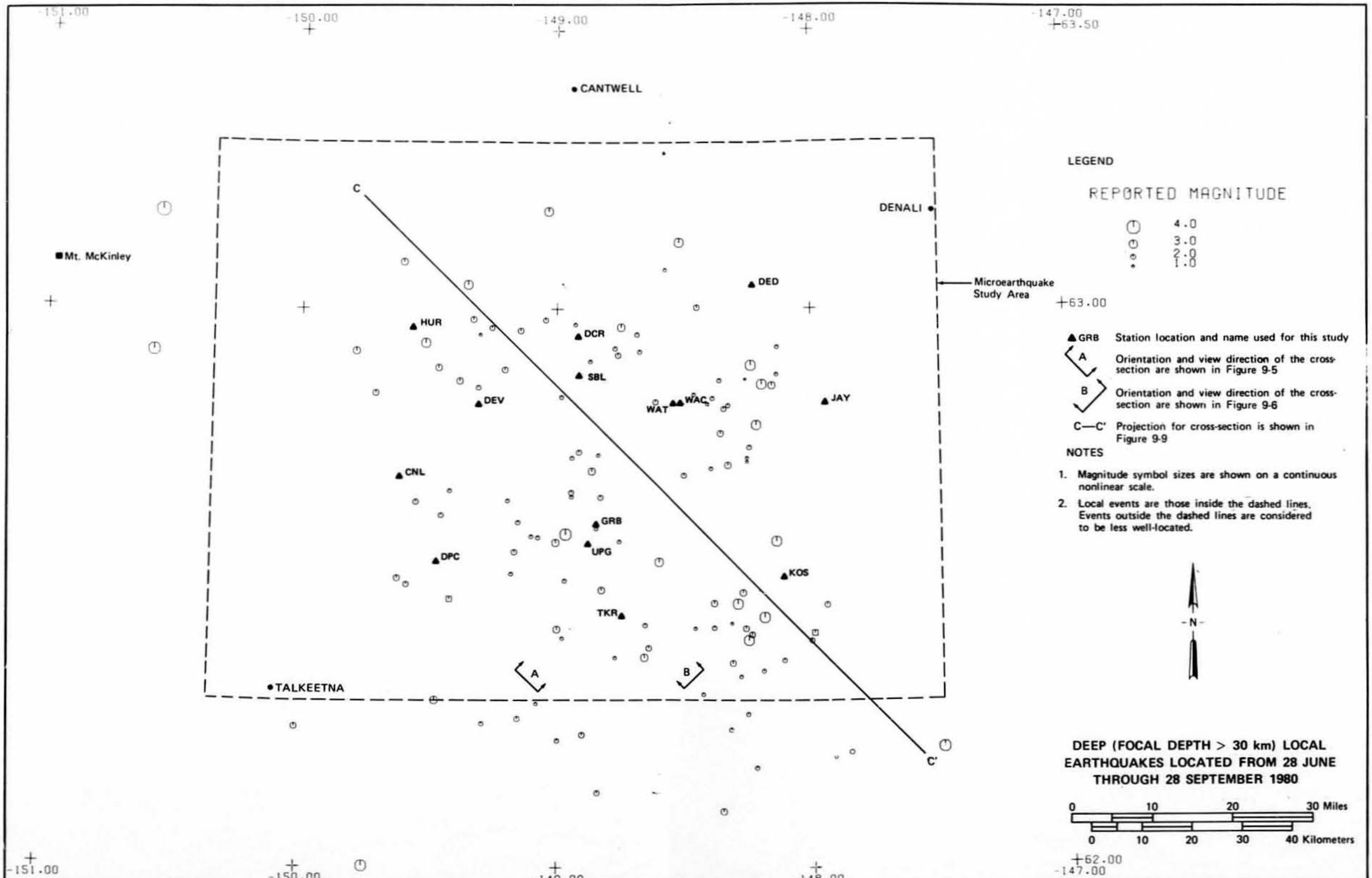
Japanese accelerograms recorded at large distance (31 to 62 miles (50 to 100 km)), measured from rupture zones with depths of at least 12 miles (20 km), show acceleration values that are considerably larger than those from shallow earthquakes at similar distances in California (Woodward-Clyde Consultants, 1978). The sparse Japanese groundmotion data for shallow earthquakes are in closer agreement with the California data than with the Japanese data from deeper sources. The Alaskan data, which are sparse for both shallow and deeper events, are nevertheless consistent with differences implied by the Japanese data. This suggests that a real difference in ground motions does exist for earthquakes of equivalent magnitude but different depth. This difference could be caused by: (a) differences in focal mechanism (radiation pattern); (2) dynamic and static fault parameters (slip velocity, rupture velocity, stress drop); (3) anelastic absorption (Q) of the travel path; (4) geometrical spreading or focusing due to path structure; (5) size and distribution of heterogeneities; or possibly other reasons.

A detailed examination of the causes of the difference in ground motion amplitudes is beyond the scope of the present study. It is therefore assumed for the present purposes that worldwide strong motion data from deeper Benioff zone events are appropriate for use in estimating ground motion parameters for analogous events in Alaska.



SHALLOW (FOCAL DEPTH < 30 km) LOCAL EARTHQUAKES LOCATED FROM 28 JUNE THROUGH 28 SEPTEMBER 1980

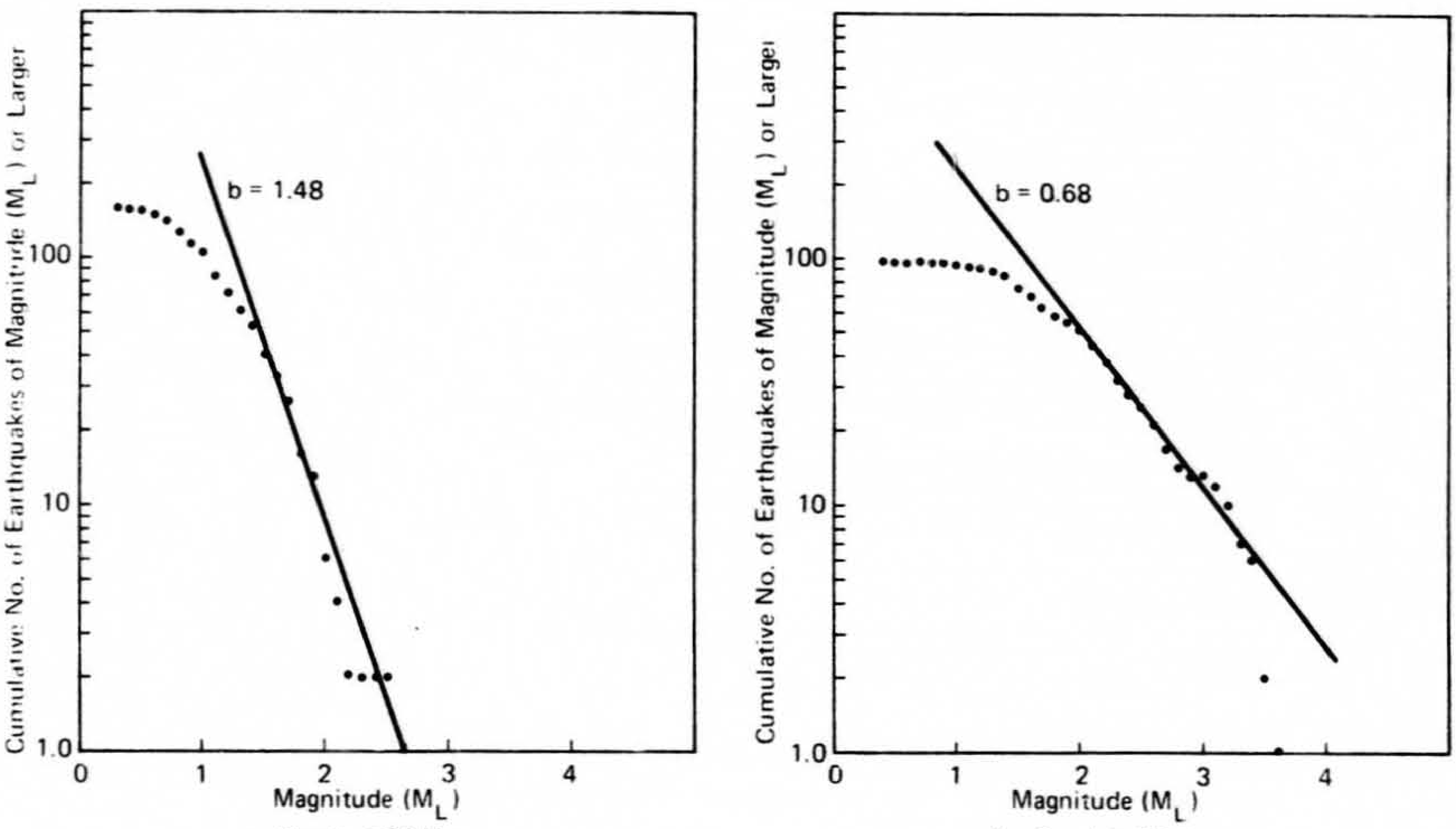
FIGURE 9-1



DEEP (FOCAL DEPTH > 30 km) LOCAL EARTHQUAKES LOCATED FROM 28 JUNE THROUGH 28 SEPTEMBER 1980

WOODWARD-CLYDE CONSULTANTS 14658A December 1980

FIGURE 9-2



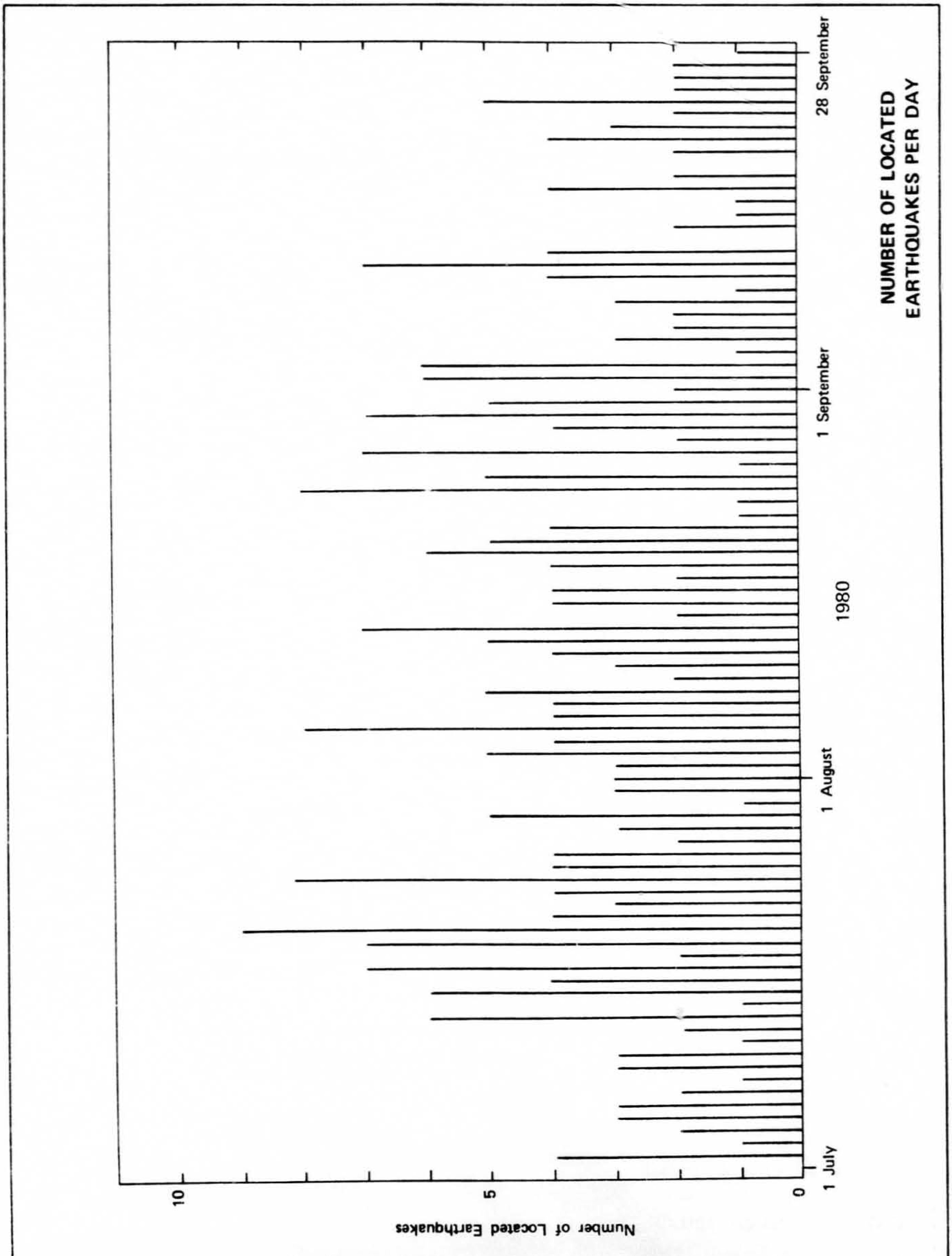
a. Depth < 30 Km

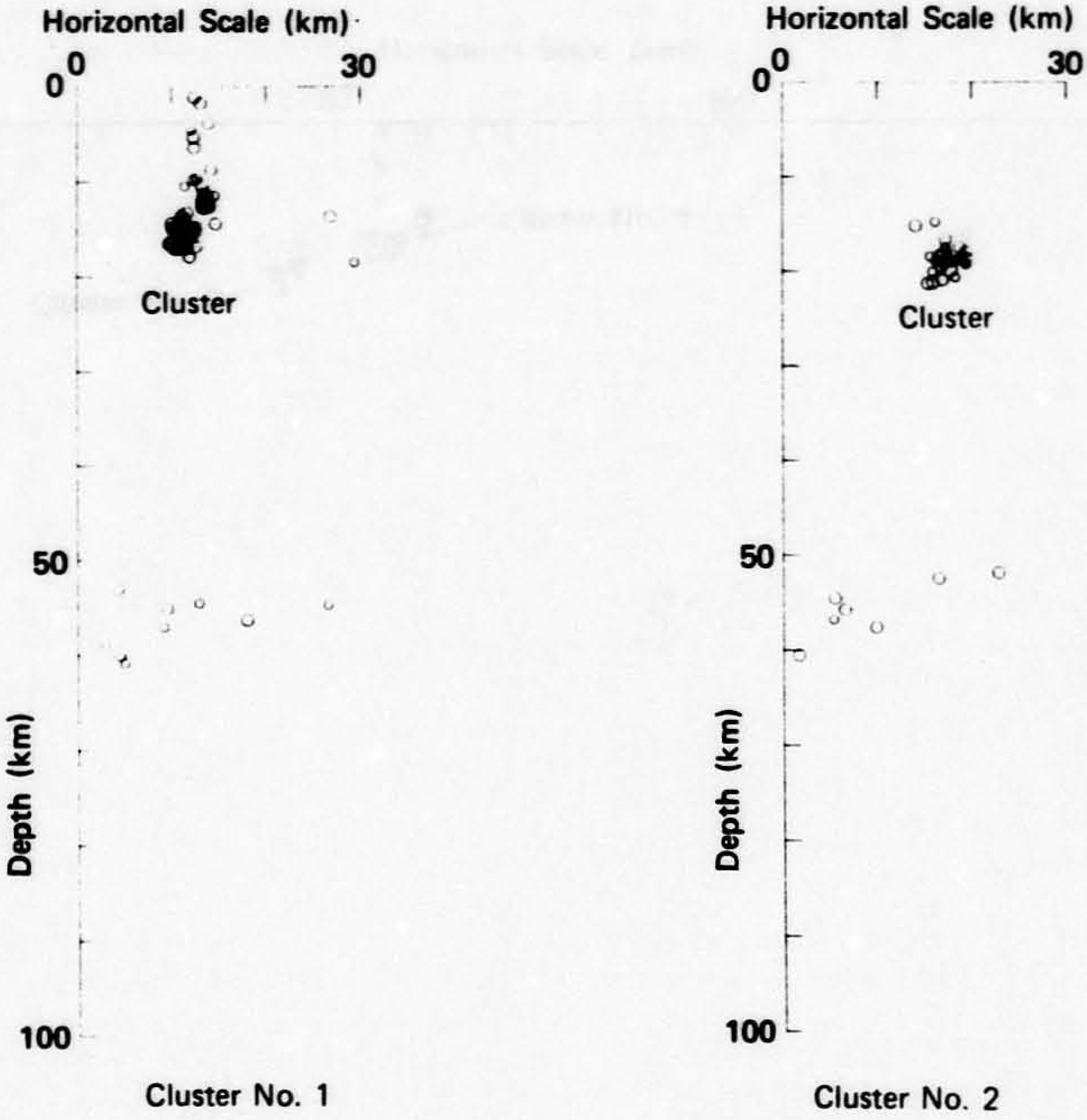
b. Depth ≥ 30 Km

NOTE

1. Microearthquake study area is shown in Figures 9-1 and 9-2.

FREQUENCY—MAGNITUDE PLOTS FOR EARTHQUAKES IN MICROEARTHQUAKE STUDY AREA FROM 28 JUNE TO 28 SEPTEMBER 1980

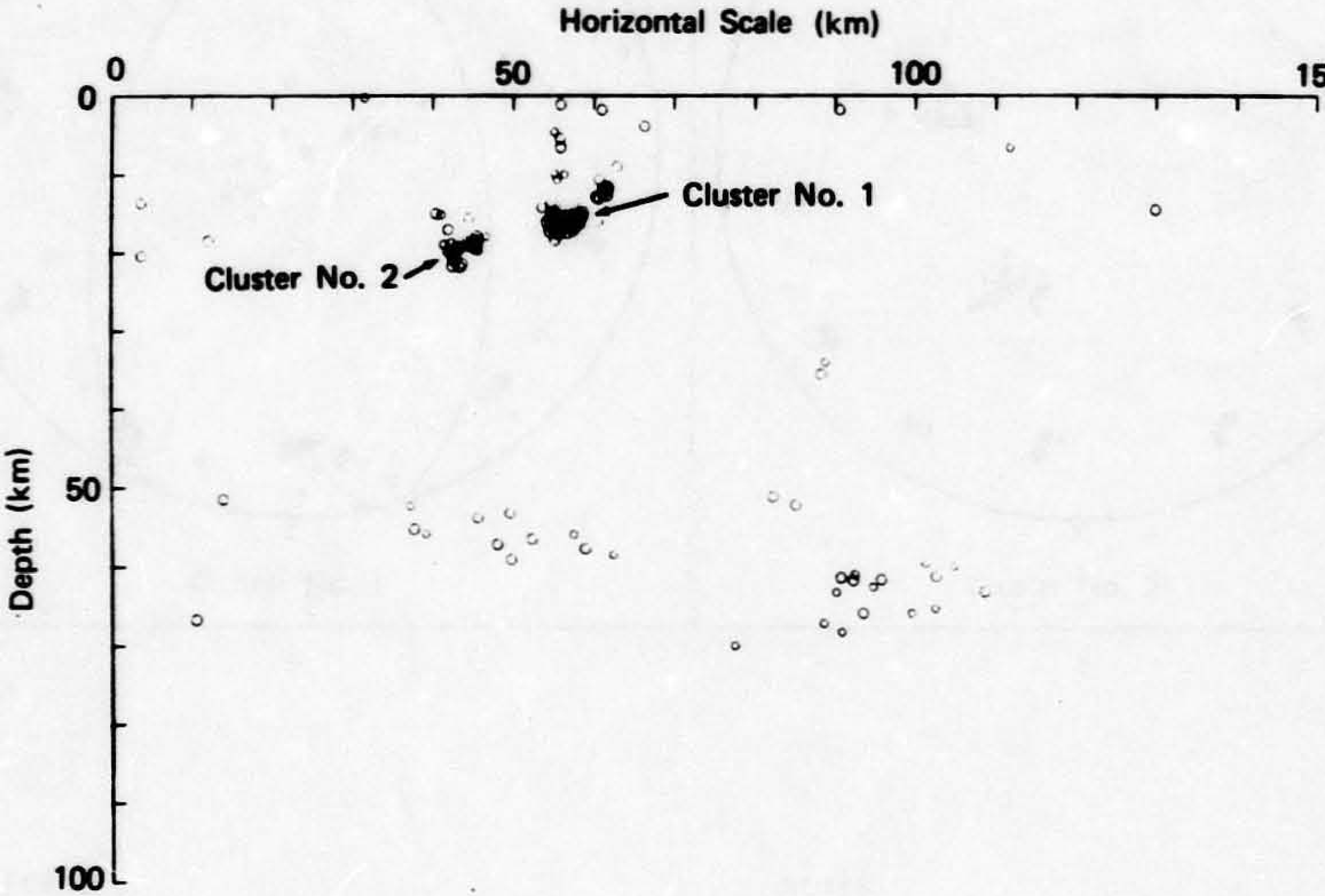

NUMBER OF LOCATED
EARTHQUAKES PER DAY
Number of Located Earthquakes
0
5
10
1 July
1 August
1 September
28 September
1980



NOTES

1. Spatial location of clusters shown in Figure 9-1, view direction A.
2. Composite focal plane mechanisms for clusters Nos. 1 and 2 are shown in Figure 9-7.

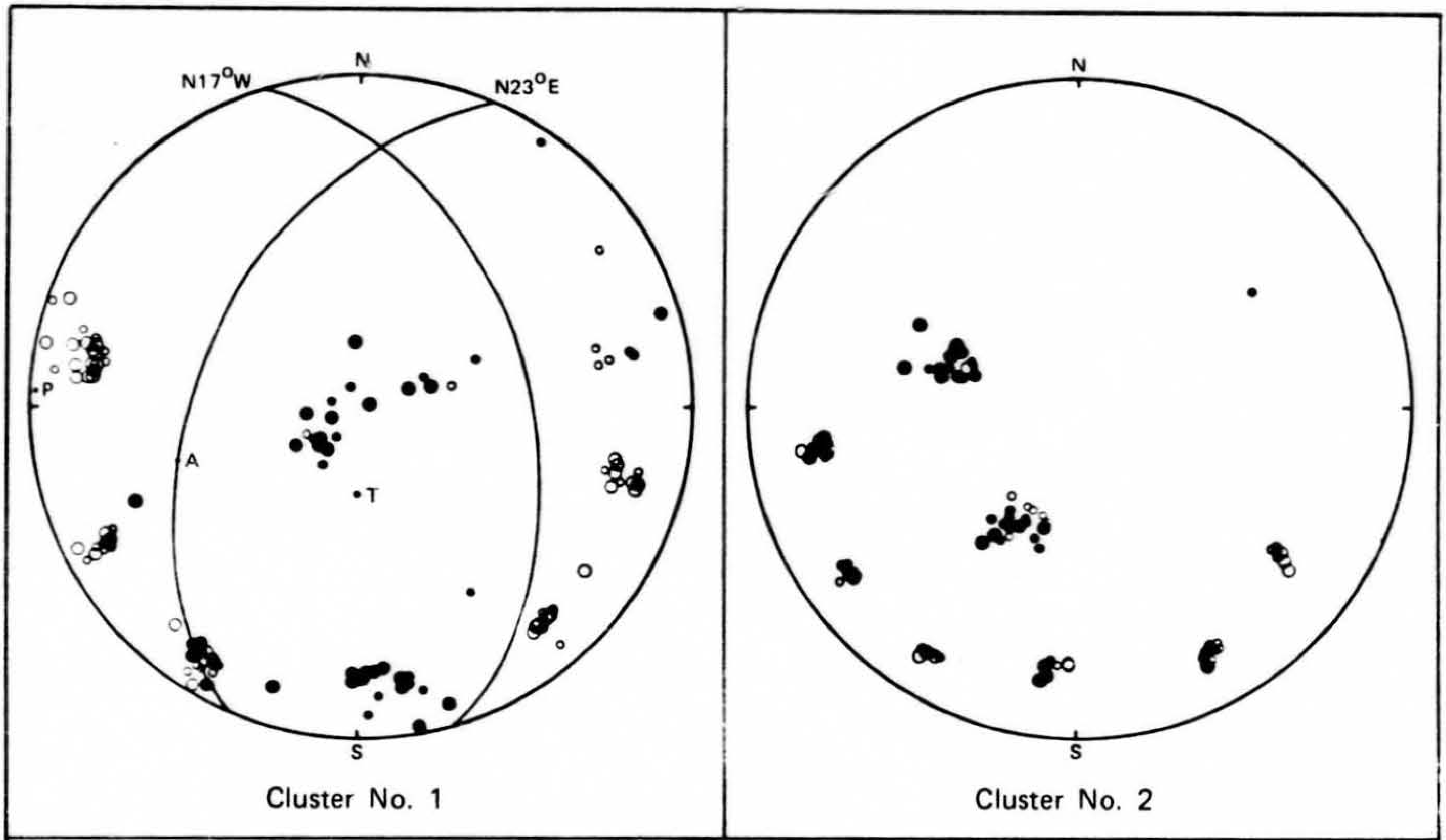
N45°E SECTIONAL VIEW OF MICROEARTHQUAKE CLUSTERS ONE AND TWO



NOTES

1. Spatial location of clusters shown in Figure 9-1, view direction B.
2. Composite focal plane mechanisms for clusters Nos. 1 and 2 are shown in Figure 9-7.

N45°W SECTIONAL VIEW OF MICROEARTHQUAKE CLUSTERS ONE AND TWO



a. b.

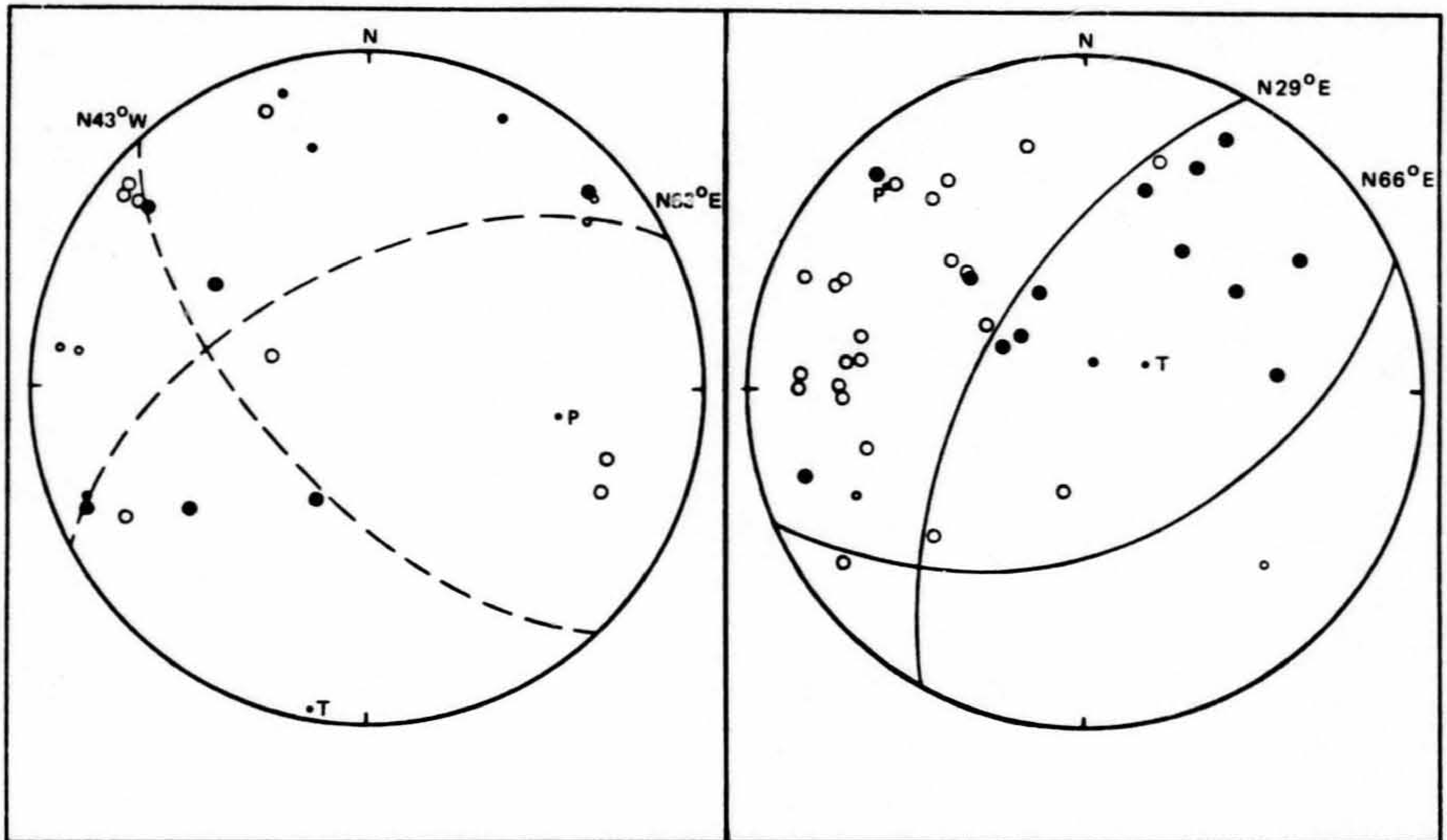
LEGEND

- • T — Minimum Compressive Stress Axis
- • P — Maximum Compressive Stress Axis
- ● — Compression– high confidence in interpretation
- • — Compression– low to moderate confidence in interpretation
- ○ — Dilatation– high confidence in interpretation
- ∘ — Dilatation– low to moderate confidence in interpretation

NOTES

1. Cluster locations are shown in Figure 9-1.
2. Lower hemisphere plots.
3. Focal plane mechanism plotting methodology is discussed in Appendix B.
4. Microearthquakes used to plot the focal plane mechanism are listed in Appendix D.

COMPOSITE FOCAL MECHANISM PLOTS OF MICROEARTHQUAKE CLUSTERS ONE AND TWO



a. b.

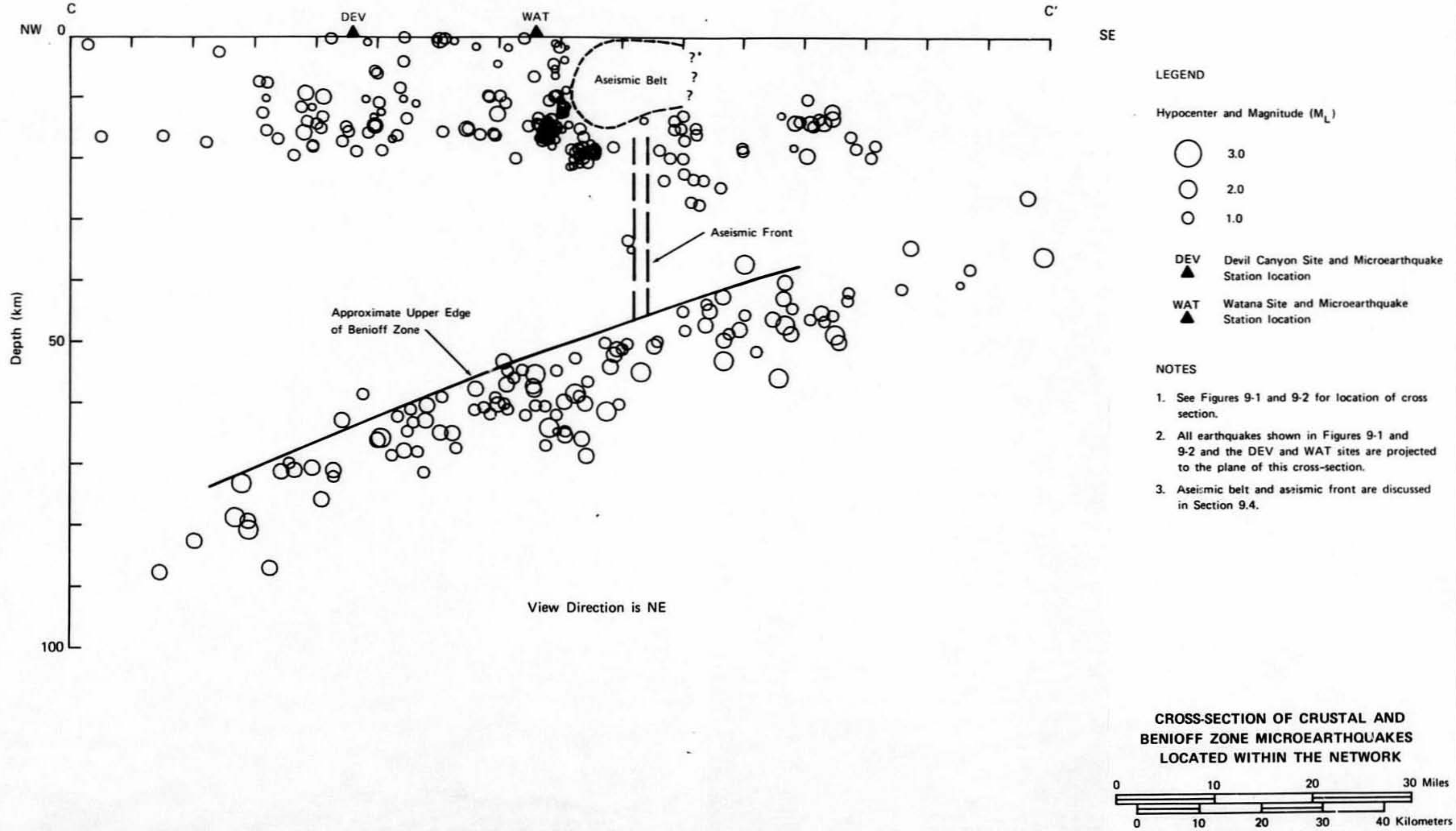
LEGEND

- •T Minimum Compressive Stress Axis
- •P Maximum Compressive Stress Axis
- ● Compression— high confidence in interpretation
- • Compression— low to moderate confidence in interpretation
- ○ Dilatation—high confidence in interpretation
- ∘ Dilatation—low to moderate confidence in interpretation

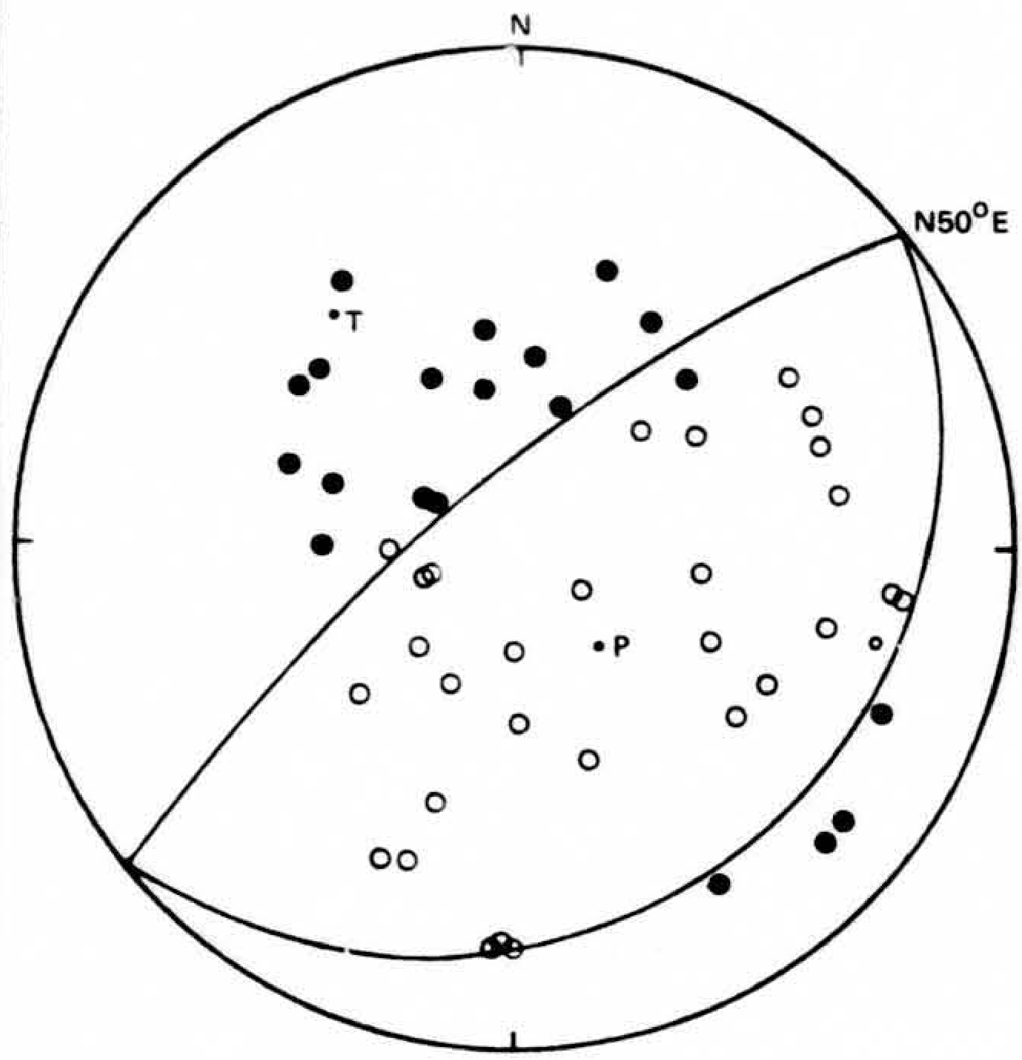
NOTES

1. Lower hemisphere plots.
2. Focal plane mechanism plotting methodology is discussed in Appendix B.
3. Plot a. includes microearthquakes 49,116,197, and 210 as listed in Appendix D.
4. Plot b. includes microearthquakes 2,14,75,117, 148,172, and 250 as listed in Appendix D.
5. Dashed fault planes are of lower reliability than solid ones.

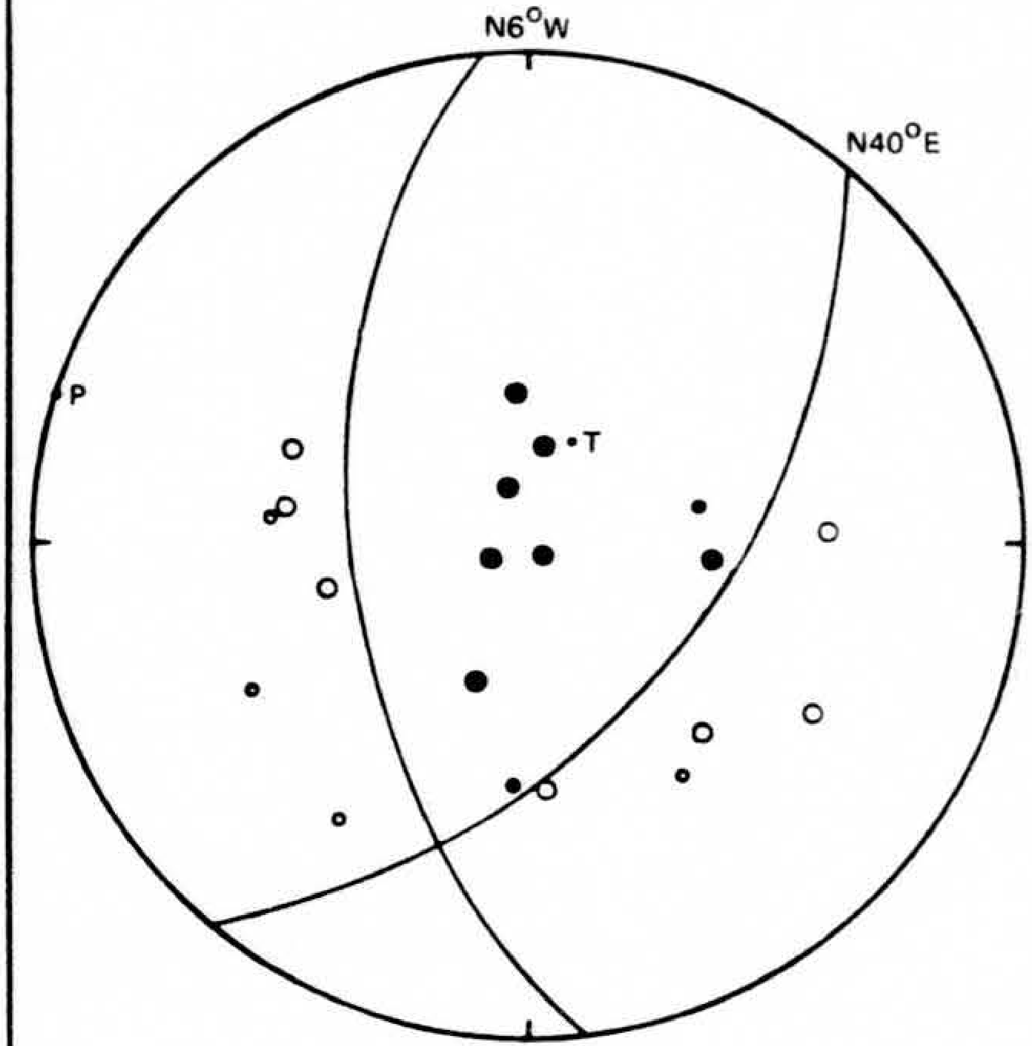
FOCAL MECHANISM PLOTS OF SELECTED MICROEARTHQUAKES (FOCAL DEPTH < 30 km)



CROSS-SECTION OF CRUSTAL AND BENIOFF ZONE MICROEARTHQUAKES LOCATED WITHIN THE NETWORK



a.



b.

LEGEND

- • T Minimum Compressive Stress Axis
- • P Maximum Compressive Stress Axis
- ● Compression– high confidence in interpretation
- • Compression– low to moderate confidence in interpretation
- ○ Dilatation–high confidence in interpretation
- ∘ Dilatation–low to moderate confidence in interpretation

NOTES

1. Lower hemisphere plots.
2. Focal plane mechanism plotting methodology is discussed in Appendix B.
3. Plot a. includes microearthquakes 20, 32,62,72,85, 127, and 152 as listed in Appendix D.
4. Plot b. includes microearthquakes 16,24, and 31 as listed in Appendix D.

COMPOSITE FOCAL MECHANISM PLOTS OF SELECTED MICROEARTHQUAKES (FOCAL DEPTH >30 km)

FIGURE 9-10

10 - RESERVOIR-INDUCED SEISMICITY (RIS)

10.1 - Introduction

The objective of this part of the investigation is to make a preliminary evaluation of the potential for the possible future occurrence of reservoir-induced seismicity (RIS) in the vicinity of the proposed reservoirs. Reservoir-induced seismicity is defined here as: the phenomenon of earth movement and resultant seismicity that has a spatial and temporal relationship to a reservoir and is triggered by nontectonic stress.

In the early 1940s in a study of Hoover Dam in the United States (Carder, 1945), a relationship was first recognized between the level of water impounded by a dam and the rate of occurrence of local earthquakes. Since that time, similar relationships have been reported for 63 other reservoirs around the world. A review of these reported cases (Packer, Lovegreen, and Born, 1977; Packer and others, 1979) has resulted in 55 cases being classified as either accepted or questionable cases of RIS. These 55 cases are included in Table 10-1 and are plotted as a function of water depth and volume in Figure 10-1.

Several reservoir-induced seismic events (at Kremasta, Greece; Koyna, India; Kariba, Zambia-Rhodesia; and Xinfengjiang, China) have exceeded magnitude (M_S) 6. Damage occurred to the dams at Koyna and Xinfengjiang, and additional property damage occurred at Koyna and Kremasta.

Recent studies of the occurrence of RIS (Simpson, 1976; Packer, Lovegreen, and Born, 1977; Withers, 1977; Packer and others, 1979) have shown that RIS is influenced by the depth and volume of the reservoir, the filling history of the reservoir, the state of tectonic stress in the shallow crust beneath the reservoir, and the existing pore pressures and permeability of the rock under the reservoir. Although direct measurements are difficult to obtain for some of these factors, indirect geologic and seismologic data, together with observations about the occurrence of RIS at other reservoirs, can be used to assess the potential for and possible effects of the occurrence of RIS at the proposed Project reservoirs.

The scope of this study includes: (a) a comparison of the depth, volume, regional stress, geologic setting, and faulting at the Devil Canyon and Watana sites with the same parameters at comparable reservoirs worldwide; (b) assessment of the probability of RIS at the sites based on the above comparison; (c) a description of the relationship between reservoir filling and the length of time to the onset of induced events and the length of time to the maximum earthquake; (d) discussion of the significance of these time periods for the sites; and (e) a preliminary assessment of the potential for landslides resulting from RIS.

For this study, the two proposed reservoirs have been considered to be one hydrologic entity. The hydrologic influence of the two reservoirs is expected to overlap in the area between the Watana site and the upstream end of the Devil Canyon reservoir. Thus, from a hydrologic standpoint, they can be considered as one reservoir with a resultant potential for reservoir-induced seismicity. The combined reservoir will be approximately 87 miles (140 km) long and will have the parameters shown below based on U. S. Army Corps of Engineers (1978) data:

Parameter	Devil Canyon	Watana	Combined
Max. Water Depth	551 ft (168m)	725 feet (221m)	725 ft (221m)
Max. Water Volume	1.05×10^6 acre feet ($1296 \times 10^6 m^3$)	9.62×10^6 acre feet ($11,876 \times 10^6 m^3$)	10.67×10^6 acre feet ($13,172 \times 10^6 m^3$)
Stress Regime	Compressional	Compressional	Compressional
Bedrock	Metamorphic	Igneous	Igneous

The combined hydrologic body of water then will be a very deep, very large reservoir within a primarily igneous bedrock terrain that is undergoing compressional stress. For comparative purposes, a deep reservoir has maximum water depth of 300 feet (92 m) or greater; a very deep reservoir is 492 feet (150 m) deep or greater; a large reservoir has maximum water volume greater than $1x10^6$ acre feet ($1234x10^6m^3$), and a very large reservoir has a volume greater than $8.1x10^6$ acre feet ($10,000x\ 10^6m^3$).

This part of the report is divided into three sections. The first section (10.2) discusses the phenomenon of RIS and the relationships among reservoir impoundment, geologic conditions, and the occurrence of RIS. The second section (10.3) presents an assessment of the probability of RIS occurrence at the Project. The third section (10.4) discusses some implications of RIS occurrence for the Project.

10.2 - State-of-the-Knowledge in RIS

Theoretical analysis of RIS, based on observations of reported cases, suggests two primary causal links between impoundment of a reservoir and the occurrence of induced seismicity: increased stress below the reservoir due to imposed reservoir load, and increased pore water pressures due to hydraulic head imposed by the reservoir, resulting in loss of strength (Kisslinger, 1976). These models indicate that the imposed stress and pore water pressure changes are generally very small and are insufficient to initiate new fractures (Bell and Nur, 1978; Withers and Nyland, 1978); however, where existing stress or pore pressure levels are near failure, the imposed changes may trigger the failure of existing fractures (Withers and Nyland, 1978; Zoback and others, 1979). Accordingly, the occurrence of RIS should be related to existing stress and pore pressure levels, which in turn may be related to such parameters as water depth, reservoir volume, geologic setting, faulting, and regional stress. A discussion of each parameter follows. The discussion is based on accepted and questionable cases of RIS. An accepted case of RIS is defined as a reported case of RIS which has an accepted spatial and temporal relationship of seismicity to impoundment of the reservoir. A questionable case is one for which the temporal and spatial relationship has not been confirmed.

Water Depth

Data presented by Rothé (1969; 1970), Carder (1970), Gupta and others (1972), Guha and others (1974), Gupta and Rastogi (1976),Stuart-Alexander and Mark (1976), Packer, Lovegreen, and Born (1977) and Packer and others, (1979) suggest that water depth is a significant parameter associated with RIS. The relationship of RIS to water depth is plotted in Figure 10-1. These data indicate that as water depth increases, the ratio of incidents of RIS to the number of reservoirs increases. Water depth is important because, as water depth increases, the load (and shear stress) imposed by a reservoir increases, and the pore pressure would be expected to increase. These increases in stress would, in certain tectonic settings, increase the likelihood of RIS.

Reservoir Volume

Data presented by Rothé (1970), Gupta and Rastogi (1976), and Packer, Lovegreen, and Born, (1977) and Packer and others (1979), suggest that reservoir volume is important to RIS. The relationship of RIS to reservoir volume is plotted in Figure 10-1. These data indicate that as reservoir volume increases, the ratio of incidents of RIS to the number of reservoirs increases. Reservoir volume is important because, as volume increases, the total load (and shear stress) imposed by the reservoir increases, and the pore pressure would be expected to increase. The additional stresses imposed as reservoir volume increases would differ in some instances from those imposed by increasing water depth because, increasing reservoir volume typically results in a total load increase over a large area (such as at Kariba), whereas increasing water depth results in a load increase over a small area (such as at Vajont). The increase in stress associated with increasing reservoir volume would, in certain tectonic settings, increase the likelihood of RIS.

Geologic Setting

Previous studies (Packer, Lovegreen, and Born, 1977; Packer and others, 1979) have made assessments of the importance of bedrock type to the occurrence of reservoir-induced seismicity. Bedrock type includes a large number of variable factors (such as rock type, fracture spacing, interconnection of fractures, degree of tightness of fractures, stratification, hardness, strength, and weathering) which influence the permeability of bedrock. Because detailed data for the factors described above generally are not available for most reservoirs worldwide, bedrock type has been used to represent (albeit indirectly) permeability. Permeability in turn is expected to influence pore pressure changes.

Faulting

Faulting is acknowledged by Rothé (1969, 1970), Carder (1970), Gough and Gough (1970), Gupta and Rastogi (1976), and Packer and others (1979) to be an important parameter for the occurrence of RIS. There has been a difference of opinion, however, among investigators familiar with RIS as to whether induced seismicity can occur along inactive faults and fractures. Failure associated with RIS would be expected to occur along faults or zones of weakness (fractures); the difference of opinion is over whether or not impoundment of a reservoir can create a state of stress such that significant seismicity could be triggered on inactive faults and fractures.

Data reviewed previously and during this study suggest that earthquakes larger than approximately magnitude (M_S) 5 have occurred at reservoirs with faults that have recent displacement (Packer and others, 1979) and that microearthquake activity and possibly events in the magnitude (M_S) 4 to 4-1/2 size range have been associated with fractures. Therefore, as discussed in more detail in Section 10.2.2, it is considered unlikely that reservoir impoundment can trigger large, potentially damaging earthquakes on inactive faults. Microearthquakes and possibly events in the magnitude (M_S) 4 to 4-1/2 size range may occur along fractures.

Stress

Regional tectonic stress (and the associated type of faults with recent displacement) is considered by many investigators to be an important parameter associated with RIS (Snow, 1972; Gupta and Rastogi, 1976; Gough, in press). As shown in Figure 10-2, theoretical considerations suggest that RIS would be more likely at extensional stress environments associated with normal faulting, somewhat less likely at shear stress environments, and least likely at compressional environments associated primarily with reverse or thrust faults.

Observations compiled by Packer and others (1979) suggest that RIS is more likely to occur in shear stress environments, somewhat less likely in extensional environments, and least likely in compressional environments. Confidence in this relationship is tempered by uncertainties associated with defining a stress environment and by the statistically small number of reservoirs available for evaluation.

In addition to the regional stress characteristics discussed above, the state of stress can be a factor in RIS (Carder, 1970; Gough and Gough, 1970; Adams and others, 1973; Gupta and Rastogi, 1976). According to this concept, a reservoir located in a region that is in a state of "critical stress" is more likely to be subject to RIS than is a reservoir in a region that is not in a state of critical stress.

The state of regional stress is difficult to describe, measure, or evaluate, and its effect on RIS cannot be quantified. However, faults with recent displacement can be used indirectly to assess whether a region is in a state of critical stress. While critical stress is not formally included in this study in evaluation of the potential for RIS, it is used as a qualitative indicator that can be factored into the judgment of the likelihood of RIS, taking into consideration the presence or absence of faults with recent displacement within the hydrologic regime of a reservoir.

10.2.1 - Temporal and Spatial Relationships

Temporal

A large variation has been observed in the time between commencement of reservoir filling and the occurrence of induced seismic events. Considering all accepted cases of RIS (45), approximately two-thirds (29) had the first occurrence of a suspected RIS event during the first year after commencement of filling (Figure 10-3). For 19 of these cases, the largest event also occurred in the first year after filling (Figure 10-4). Considering only deep, very deep, and/or very large reservoirs with accepted RIS (27), approximately three-fifths (17) had the first occurrence of a suspected RIS event during the first year (Figure 10-3), and of these 17, 11 had the largest event during the first year (three of the remaining six occurred in the second year, the other three within five years of impoundment).

The relationship between magnitude of the largest RIS event and time to occurrence of that event is shown in Figure 10-5. The trend in Figure 10-5 indicates that, for deep, very deep, and/or very large reservoirs, when the maximum magnitude event is $M_S < 5$, the largest event has occurred within two years of start of impoundment for 84% (16 of 19) of the cases. On the other hand, when the maximum event is $M_S \geq 5$, the largest event has occurred within two years of impoundment for only 50% (4 of 8) of the cases (Figure 10-5). Thus, the larger (and potentially damaging) RIS events tend to occur several years after start of impoundment. Evaluation of the time of the first RIS event and the time of the largest RIS event show no clear correlation. As shown in Figure 10-6, there does not appear to be a relationship or trend between these two occurrences.

The data in Figures 10-5 and 10-6 provide a means to obtain a probabilistic distribution of magnitudes of the largest RIS events. Of the 199 reservoirs with maximum water depth of 300 feet (92m) or greater, 26, or 13%, are accepted cases of RIS. Thus, the likelihood that any deep or very deep reservoir will experience RIS is estimated to be 0.13. Figure 10-7 shows how this probability decreases with increasing magnitude of the RIS event. The probability of occurrence of RIS at a deep or very deep reservoir with maximum magnitude (M_S) of 3 or greater is estimated to be 0.12, while the probability that it will occur with maximum magnitude (M_S) of 6 or greater is estimated to be 0.015.

The probability of occurrence of later RIS decreases further if no events occur during the first year after start of impoundment (Figure 10-8). For example, the probability of RIS with magnitude (M_S) greater than 3 decreases to 0.045, while the probability of RIS with magnitude (M_S) greater than 6 decreases to

0.008. If no events occur during the first two years after impoundment, the probability of RIS decreases still further for small events.

Spatial

Seismicity associated with reservoir impoundment occurs within that portion of the crust under the reservoir's stress or hydrologic influence. The size of the region of influence depends on the size of the reservoir and existing stress and hydrologic conditions. Theoretical studies, such as those of Withers (1977) and Bell and Nur (1978) and a study of the reported locations of earthquakes at cases of RIS (Packer and others, 1979), show that the events are most likely to occur close to the reservoir.

Typically, RIS events occur within an area defined by a circle about the center of the reservoir, whose radius is equal to the longest dimension of the reservoir. Theoretically, the hydrologic influence of a reservoir could extend across an area with a radius three times as large (Withers, 1977). However, for long, thin reservoirs such as the proposed Project reservoir, the hydrologic influence of a reservoir theoretically can be considered to extend across an area with a radius 3 times the maximum width of the reservoir (Withers, 1977), rather than 3 times the longest dimension.

10.2.2 - Relationship to Fault Reactivation

If a fault has not had displacement during the current stress regime, it is very unlikely that impoundment of a reservoir can induce large-magnitude seismic events along the fault. Theoretical analyses of stresses caused by reservoir impoundment indicate that insufficient stresses are concentrated to create any extensive new fractures in rock (Withers, 1977; Packer and others, 1979). The stress increase or pore pressure change imposed by a reservoir generally is very small and typically must act in coordination with existing high tectonic stresses to induce failure along a fault. It is unlikely that a fault which has not had displacement in the current stress regime would be at a stress level close to failure. Thus, it is unlikely that impoundment of a reservoir, with its small effects, will trigger significant failure on such a fault. In particular, the likelihood of inducing surface faulting, and associated moderate-to-large earthquakes on such a fault, is considered to be extremely low.

At least ten reservoirs have had induced seismicity with magnitudes (M_S) of 5 or greater (Table 10-2). Because induced seismic events generally are very shallow (focal depths are typically less than 6 miles (10 km)), it is likely that the larger induced events might be accompanied by surface fault rupture. Field reconnaissance and information available in the literature indicates Quaternary or late Cenozoic surface fault rupture within the hydrologic influence regime of eight of these ten reservoirs (Packer and others, 1979). Insufficient information is available to evaluate the recency of fault displacement at the other two reservoirs, although on the basis of tectonic environments at those two sites, the presence of faults with recent displacement is considered to be likely (Packer and others, 1979).

Microearthquakes have been triggered by many reservoirs in areas where faults with recent displacement had not been recognized. One of the best-documented occurrences of this phenomenon is at Monticello reservoir in South Carolina. In situ stress measurements made after reservoir impoundment suggest that the pore-pressure changes imposed by impoundment of Monticello reservoir could trigger failure on favorably-oriented joints or fractures

(Zoback and others, 1979; Talwani, 1980). Thus, the stresses and pore-pressure changes imposed by reservoir impoundment may be sufficient to trigger microearthquake activity on some faults and fractures that apparently have not had measurable displacement in the current tectonic regime.

10.2.3 - Characteristics of a RIS Event

Several investigators, including Gupta and Rastogi (1976), have suggested that "b" values from frequency-magnitude distributions for RIS sequences may be different from those of naturally occurring earthquakes, and Long and Marion (1978) have suggested that RIS events may have certain unique spectral characteristics. These variations have been recognized for only a limited number of cases, and their significance has not been demonstrated. Thus, on the basis of available data, there appears to be little substantive difference between the nature of induced seismic events and naturally occurring earthquakes.

10.3 - Potential For Reservoir-Induced Seismicity (RIS) at the Project Reservoirs

10.3.1 - Comparison with Worldwide Data Base

Water Depth

The proposed Devil Canyon-Watana reservoir will be among the deepest in the world (Figure 10-1). Its currently proposed depth will be the fourth deepest behind Nurek, Grand Dixence, and Vajont. Among the very deep reservoirs in the world (of which there are currently 37), 10, or 27%, have experienced RIS. Among the reservoirs that are more than 656 feet (200 m) deep (of which there are currently 7), 3, or 42%, have experienced RIS. All three of the reservoirs that are deeper than the proposed combined reservoir have had induced events.

If the occurrence of reservoir-induced events is evaluated for a set of reservoirs for which data are readily available, the frequency of very deep reservoirs among reported cases of RIS can be estimated. Among the deep and very deep reservoirs, there are 28 reported cases of RIS. Of these, 10 are very deep, giving a frequency of 0.36 among reservoirs having accepted RIS.

These data suggest that the deep water depth for the proposed combined reservoir should have a pronounced effect on the likelihood of RIS. Depending on how the population of very deep reservoirs is assessed, the likelihood of an induced event of any size at the proposed combined reservoir ranges from 0.27 to 1.00. Thus, the potential for RIS is high for this very deep reservoir when water depth is considered as an independent parameter.

Volume

In addition to being among the world's deepest reservoirs, the proposed Devil Canyon-Watana reservoir will be among the world's largest (in terms of volume). There are 59 reservoirs currently with volumes greater than that for the proposed reservoir. Of these, 8, or 13%, have been subject to RIS.

If the occurrence of reservoir-induced events is evaluated for a set of reservoirs for which data are readily vailable, the frequency of very large reservoirs among reported cases of RIS can be evaluated. Among the deep, very deep, and/or very large reservoirs, there are 29 reported cases of RIS. Of these, seven are very large, giving a frequency of 0.24 among reservoirs having accepted RIS. Thus, the potential for RIS is high at the proposed very large reservoir when volume is considered as an independent parameter.

Stress Conditions

Theoretical models of RIS suggest that RIS occurrence may be more likely under certain stress conditions than under others. Figure 10-9 indicates the distribution for the strike-slip (shear), normal (extensional), and thrust (compressional) types of stress regime. The compressional stress curve is applicable to the proposed Devil Canyon-Watana reservoir. The likelihood of RIS occurrence at a deep reservoir in a compressional stress regime is 0.14; this estimate is based on a comparison of the number of deep reservoirs with RIS in compressional environments with those without RIS in compressional environments. The likelihood that a RIS event of magnitude (M_S) 5 or greater will occur in a compressional environment is approximately 0.02 (Figure 10-9). In contrast, the likelihood of a magnitude (M_S) 5 RIS event at any deep reservoir, regardless of the stress regime, is 0.015. This reflects a "conditional probability" of RIS given that particular stress environment.

Geologic Conditions

The likelihood of the largest RIS events also varies according to the rock type prevalent at a reservoir. Figure 10-10 is a plot of occurrence of the largest RIS events for sedimentary, igneous, and metamorphic geologic environments. The igneous geology curve, with a likelihood of 0.12 for occurrence of at least one RIS event, is applicable to the proposed Devil Canyon-Watana reservoir. The likelihood that a RIS event of magnitude (M_S) 5 or greater will occur is approximately 0.05.

10.3.2 Evaluation of Potential Occurrence

Likelihood of Occurrence

Twenty-seven percent of all very deep reservoirs have had RIS. Thus, the likelihood that any very deep reservoir will experience RIS is 0.27. However, the tectonic and geologic conditions at any specific reservoir may be more or less conducive to RIS occurrence. Models have been developed by Baecher and Keeney in Packer and others (1979) to estimate the likelihood of RIS at a reservoir, characterized by its depth, volume, faulting, geology, and stress regime.

Two models used here treat depth and volume as dependent variables, while the other variables are assumed to be independent. In one model, depth and volume are treated as discrete variables (i. e., deep, very deep, large, very large), and in the other model, depth and volume are treated as continuously dependent variables (thus a specific depth/volume combination, such as 183m/10,000x$10^6$$m^3$ is assigned). This approach was taken because (chi-squared (x^2)) tests of independence of these variables suggest that water depth and volume may have a weak dependency while other combinations of attributes are not dependent. The relationship of water depth to volume is treated differently in the two models because the degree of dependence between the two variables apparently differs depending on how the variables are considered.

In these models, conditional likelihoods are assigned to each variable on the basis of occurrence of RIS at reservoirs with that attribute. For example, the likelihood of RIS at a very deep reservoir in a compressional stress regime is 0.50. These attribute likelihoods are then combined using established statistical procedures to obtain a composite likelihood of RIS for the particular characteristics of the reservoir of interest. For the combined Devil Canyon-Watana reservoir, the likelihood of occurrence of a RIS event of any size ranges from 0.29 to 0.9. The statistical relationships used to obtain this likelihood are discussed in Packer and others (1979).

The relatively high likelihood reflects the extreme depth and volume of the reservoir. Only nine other reservoirs worldwide out of a population of approximately 11,000 are very deep and very large and only one of these, Nurek, which has had RIS, is both deeper and larger.

Because the Devil Canyon-Watana reservoir is among the deepest of the very deep category, the likelihood of RIS is very high using the continuous dependence model and somewhat lower using the discrete dependence model.

The models from which these likelihoods are derived are preliminary. A sensitivity analysis indicated that the likelihoods are very sensitive to changes in data classification, particularly among those deep reservoirs that are accepted cases of RIS (Packer and others, 1979). Thus, the specific likelihoods obtained from these models must be used with caution. The depth and volume of the proposed reservoir is among the settings most likely to be subject to RIS, so the likelihood of occurrence of RIS (including microearthquakes) at the Devil Canyon-Watana reservoir is considered to be high.

Maximum Size

Reservoirs are believed to be a perturbation on the present stress regime that can trigger an earthquake by means of a small incremental increase in stress or an increase in pore pressure as discussed in Section 10.2. Thus, the reservoir triggers strain release commensurate with that which a region can sustain within the present stress regime. Careful study and evaluation of the maximum credible earthquake for a region provides the upper bound for the size earthquake that a reservoir can trigger. That is, a reservoir cannot trigger an event larger than the maximum credible earthquake because it is a small perturbation added to the existing stress regime, not a major source of stress which would generate earthquakes independent of the existing stress regime.

An RIS event typically will be of lower magnitude than the maximum credible earthquake (e.g., many of the maximum RIS events are microearthquakes that are several orders of magnitude smaller than the maximum credible earthquake for a region). Because of the limited influence of the reservoir on the existing stress regime, the reservoir is unlikely to trigger the maximum earthquake (unless stored stress is nearly sufficient for such a failure), even though it may trigger failure along a fault. Furthermore, a reservoir may trigger an earthquake before the tectonic stress is built up to maximum event levels that would trigger a large "naturally occurring" earthquake. In other words, by reducing the strength of tectonically-stressed materials, the reservoir may trigger an event that is smaller and that occurs earlier than a naturally occurring event.

The reservoir may also have an impact on the location of the "naturally occurring" earthquake. The reservoir may trigger the "naturally occurring" event on a structure closer to (as well as within) the reservoir than would otherwise occur.

The RIS events have exceeded the earthquake that had been used for design in several instances (e.g., Koyna). Review of these cases suggests that thorough geologic and seismologic studies of faults within the hydrologic regime of the reservoir would have resulted in a maximum credible earthquake at least as large as the RIS events occurring in the vicinity of the reservoir (Packer and others, 1979). With these data, an appropriate design earthquake and ground motions can be selected.

Location

As discussed in Section 10.2.2, reservoir-induced seismicity occurs in the region under the influence of the reservoir's hydrologic regime and stress. Because of the configuration of the Devil Canyon-Watana reservoir, it can be modeled as a half-pipe at the top of a half-space as discussed by Withers (1977). A qualitative review of this model indicates that increases in normal stress are essentially localized beneath the reservoir. Shear stresses have their greatest concentration beneath the deepest part of the reservoir; however, their effects can extend to depths and distances up to three times the width of the reservoir (as measured from the center of the reservoir).

The typical width of the proposed Devil Canyon-Watana reservoir is 0.6 to 1.9 miles (1 to 3 km) with a section at Watana Creek that will have a width of approximately 8 miles (13 km). Thus, the maximum width of the combined reservoir will be 8 miles (13 km) at one location. For the purposes of this investigation, we have assumed that the average width of the combined reservoir is somewhat less than the maximum local width and larger than the typical width. The average width of the combined reservoir is assumed to be 6 miles (10 km). Thus, the hydrologic effect of the combined reservoir can be inferred to extend vertically and horizontally a maximum distance of approximately 19 miles (30 km). This volume, which includes the reservoir and an envelope 19 miles (30 km) in radius around the reservoir vertically and horizontally, represents the maximum area of hydrologic influence of the reservoir. It is inferred that reservoir-induced events would occur within this space about the reservoir.

Temporal Relationships

As discussed in Section 10.2.1, most reservoir-induced events occur within the first five years of impoundment. This relationship is applicable primarily to reservoir-induced microearthquakes. For larger events of magnitude greater than 5 (of which there have been 10), 30% have occurred between 5 and 10 years after impoundment, including the Koyna event of magnitude (M_S) 6.3. Consequently, a potentially damaging event (magnitude (M_S) greater than 5) has a relatively high likelihood of occurring up to 10 years after impoundment of the reservoir.

10.4 - Effect of RIS on Earthquake Occurrence Likelihood

The likelihood of RIS occurrence at the proposed Devil Canyon-Watana reservoir can be combined with the frequency-magnitude relationship for naturally occurring seismicity in the Devil Canyon-Watana area to assess the combined likelihood of earthquake occurrence. However, this approach generally assumes that, for earthquakes of magnitude (M_S) > 5 to occur, faults with recent displacement (capable of generating an earthquake of this magnitude) are present within the hydrologic regime of the reservoir (as discussed in Section 10.2.2). To date this investigation has not identified any faults with recent displacement within the hydrologic regime of the Devil Canyon-Watana reservoir, although the results are preliminary. Consequently, it is considered premature to assess the likelihood of RIS events of magnitude (M_S) > 5 until additional data are obtained on the recency of faulting in the hydrologic regime of the reservoir during the 1981 field season (discussed in Section 14).

10.4.1 Implications of RIS for Method of Reservoir Filling

The occurrence of RIS events has most often been correlated with rapid initial filling of a reservoir, especially with irregular filling histories or rapid reservoir refill following major drawdowns (Packer and others, 1979). The precise relationship between irregularities in the filling cycle and the occurrence of RIS events is not well-documented in most cases. Furthermore, no controlled experiments have been performed at reservoirs to vary filling rates and examine the effect on seismicity. However, detailed information is available on the correlation between seismicity and filling rates for at least one reservoir--Nurek, U.S.S.R.

Although impoundment at Nurek began in 1968, the first significant impoundment (to 328 feet (100 m)) took place between late August and early November 1972. A step was made in the filling curve late in September; following this step, seismicity increased. Upon completion of the first stage filling cycle, seismicity reached a peak with maximum magnitudes (M_S) of 4.6 and 4.3. Seismicity between November 1972 and June 1976 broadly paralleled changes in water level (Simpson and Negmatullaeu, 1978).

On the basis of this experience, it was recommended that second-stage filling resulting in a water depth of 656 feet (200m), be accomplished by a smooth filling cycle with no abrupt slowdowns in filling rate. Seismicity remained low during this filling until a minor but rapid fluctuation in filling rate occurred in August

1976. Following this fluctuation, there was a pronounced increase in seismicity, along with the occurrence of the largest event reported to that time, a magnitude (M_S) 4.1 earthquake. It has been implied that the increase in seismicity during this second filling cycle may have been directly related to the sudden change in rate of filling (Simpson and Negmatullaev, 1978; Keith and others, 1979).

From this experience at Nurek, and from consideration of the correlations between filling curves and seismicity for other cases of RIS, it appears that sudden changes in water level and sudden deviations in rate of water level change are common triggers of induced seismicity. A controlled, smooth filling curve, with no sudden changes in filling rate, should be less likely to be accompanied by induced seismicity than rapid, highly fluctuating filling rates.

10.4.2 Potential for Landslides Resulting from Reservoir-Induced Seismicity

Any assessment of the potential landslides resulting from RIS should be considered within the context of the overall potential for landslides and rockfalls in the reservoir area. That is, the potential for landslides which can be triggered by impoundment of the reservoir by natural processes (such as freeze-thaw conditions) as well as by RIS should be considered. Within this context, we have considered the potential for landslides triggered by RIS by making a preliminary assessment of whether in-situ conditions suitable for landslides exist in a proposed reservoir area, and whether earthquakes will release enough energy to trigger landslides.

During this investigation, a very preliminary assessment of landslide potential has been made from remotely sensed data interpretation, review of previous studies conducted for the project, and aerial and ground reconnaissance studies. On this basis, it is concluded the potential exists for landslides to occur in the reservoir area.

An RIS event occurring within the hydrologic regime of the reservoir could trigger a landslide if the event occurred close enough to a potential slide area and if it released sufficient energy to trigger a slide. At this point in the investigation, the location and size of an RIS event within the hydrologic regime of the combined reservoir cannot be estimated with sufficient precision to provide a meaningful assessment of where in the reservoir a landslide could occur and how large an earthquake would be necessary to trigger a landslide. However, the configuration of the Susitna River valley is such that there appears to be little likelihood that a large landslide (such as occurred at Vajont, Italy) would occur in the proposed reservoir during an RIS event.

TABLE 10-1

REPORTED CASES OF RESERVOIR-INDUCED SEISMICITY (RIS)[1]

No.[2]	Dam Name, Reservoir Name[3]	Country	Classification of RIS	Magnitude of Largest RIS Event[4]
1	Akosombo Main, Lake Volta	Ghana	Accepted, macro	Intensity V
2	Almendra, Tormes Reservoir	Spain	Accepted, micro	Less than 2
3	Bajina Basta	Yugoslavia	Accepted, micro	Less than 3
4	Benmore	New Zealand	Accepted, macro and micro	5 (?)
5	Blowering	Australia	Accepted, macro and micro	3.5
6	Cabin Creek	USA	Not RIS	---
7	Cajuru	Brazil	Questionable	Approx. 4
8	Camarillas	Spain	Accepted, macro	4.1
9	Canelles	Spain	Accepted, macro	4.7
10	Clark Hill	USA	Accepted, micro (macro?)	4.3 (?)
11	Contra, Lake Vogorno	Switzerland	Accepted, micro	Less than 3
12	Coyote Valley, Lake Mendocino	USA	Accepted, macro	5.2
13	El Grado	Spain	Not RIS	---
14	Emosson	Switzerland	Accepted, micro	Less than 3
15	Eucumbene	Australia	Accepted, macro	5 (?)
16	Fairfield, Lake Monticello	USA	Accepted, micro	2.8
17	Ghirni	India	Questionable	---
18	Grancarevo	Yugoslavia	Accepted, micro	Less than 3
19	Grandval	France	Accepted, macro and micro	Intensity V
20	Hendrik Verwoerd	South Africa	Accepted, micro	Less than 2
21	Hoover, Lake Mead	USA	Accepted, macro and micro	5.0
22	Itezhitezhi	Zambia	Accepted, macro	4 or less (?)
23	Jocassee	USA	Accepted, macro and micro	3.2
24	Kamafusa	Japan	Accepted, micro	Less than 3
25	Kariba	Zambia/Rhodesia	Accepted, macro and micro	6.25
26	Kastraki	Greece	Accepted, macro	4.6
27	Keban	Turkey	Accepted, micro	Less than 3
28	Kerr, Flathead Lake	USA	Accepted, macro	4.9
	Kinarsani	India	Questionable	---
29	Koyna, Shivaji Sagar Lake	India	Accepted, macro and micro	6.5
30	Kremasta	Greece	Accepted, macro and micro	6.3
31	Kurobe	Japan	Accepted, macro and micro	4.9
32	La Cohilla	Spain	Questionable	---
33	La Fuensanta	Spain	Questionable	---
34	Mangalam	India	Questionable	---
35	Mangla	Pakistan	Not RIS	---
36	Manicougan 3	Canada	Accepted, macro and micro	4.1
37	Marathon	Greece	Accepted, macro	5.75
38	Mica	Canada	Not RIS	---
39	Monteynard	France	Accepted, macro	Intensity VII
40	Mula	India	Accepted, micro	Less than 1
41	Nurek	USSR	Accepted, macro and micro	4.5
42	Oroville	USA	Accepted, macro	5.7
43	Oued Fodda	Algeria	Accepted, micro	Less than 3
44	Palisades	USA	Accepted, micro	3.7 (?)
45	Parambikulam	India	Questionable	---
46	Piastra	Italy	Accepted, macro and micro	4.4
47	Pieve di Cadore	Italy	Accepted, macro and micro	Intensity V
48	Porto Colombia	Brazil	Accepted, macro	Intensity VI to VII
49	Rocky Reach	USA	Not RIS	---
50	San Luis	USA	Not RIS	---
51	Sanford	USA	Not RIS	---
52	Schlegeis	Austria	Accepted, micro	Less than 2
53	Sefid Rud	Iran	Questionable	4.7
	Sharavathi	India	Questionable	---
54	Shasta	USA	Accepted, micro	Less than 3
55	Sholayar	India	Questionable	---
56	Talbingo	Australia	Accepted, macro and micro	3.5
57	Ukai	India	Questionable	---
58	Vajont	Italy	Accepted, micro	Less than 3
59	Volta Grande	Brazil	Accepted, macro	Less than 4
60	Vouglans	France	Accepted, macro	4.4
61	Warragamba, Lake Burragorang	Australia	Questionable	5.4
62	Xinfengjiang	China	Accepted, macro and micro	6

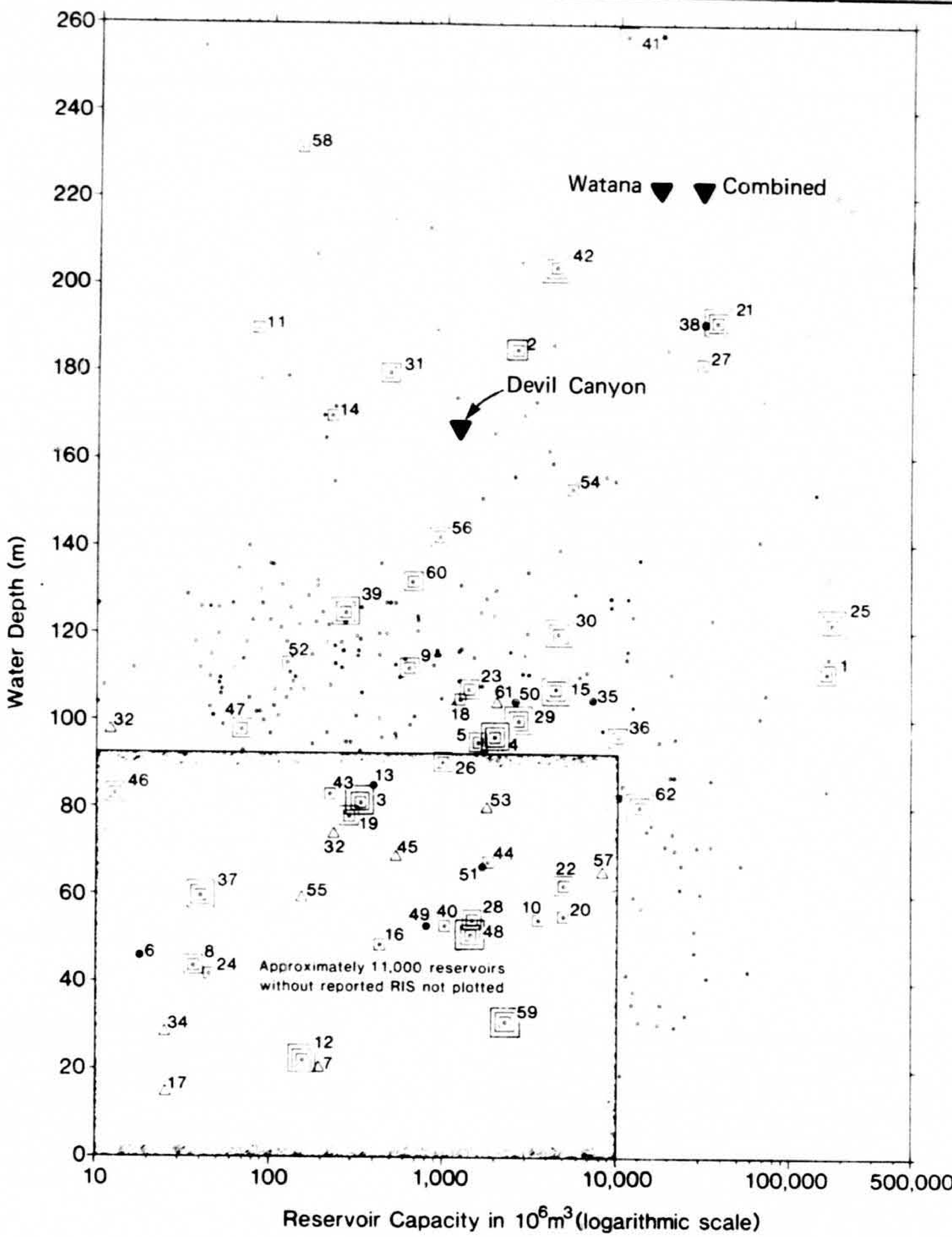
Notes: 1. Data source: Packer and others (1979).
2. Numbers correspond to numbers in Figure 10-1; Kin sani and Sharavathi are unplotted because of insufficient data.
3. Where only one name is given, either the reservoir name is the same as the dam name or only the dam name is known.
4. A dash indicates the magntiude was not obtained. Intensities are given in Modified Mercalli Scale.

TABLE 10-2

RESERVOIR-INDUCED SEISMIC EVENTS WITH MAXIMUM MAGNITUDE OF 5 OR GREATER[1]

Dam	Reservoir	Magnitude	Active Fault Present[2]
Koyna	Shivaji Sagar Lake	6.5	Yes[3]
Kariba	Lake Kariba	6.25	Not obtained[4]
Kremasta	Lake Kremasta	6.3	Yes[3]
Xinfengjiang	Xinfengjiang	6.0	Yes
Marathon	Lake Marathon	5.75	Not obtained[4]
Oroville	Oroville Reservoir	5.7	Yes
Coyote Valley	Lake Mendocino	5.3	Yes
Benmore	Lake Benmore	5.0	Yes[3]
Eucembene	Lake Eucembene	5.0	Yes[3]
Hoover	Lake Mead	5.0	Yes[3]

Notes:
1. Data Source: Packer and others (1979).
2. Active faults are those defined as having displacement in the present tectonic stress regime.
3. Determination is based on field reconnaissance studies.
4. The presence of an active fault has not been obtained but is considered probable because of the tectonic setting.



Note: The following reservoirs were not plotted because of insufficient data: Kinarsani, Sharavathi.

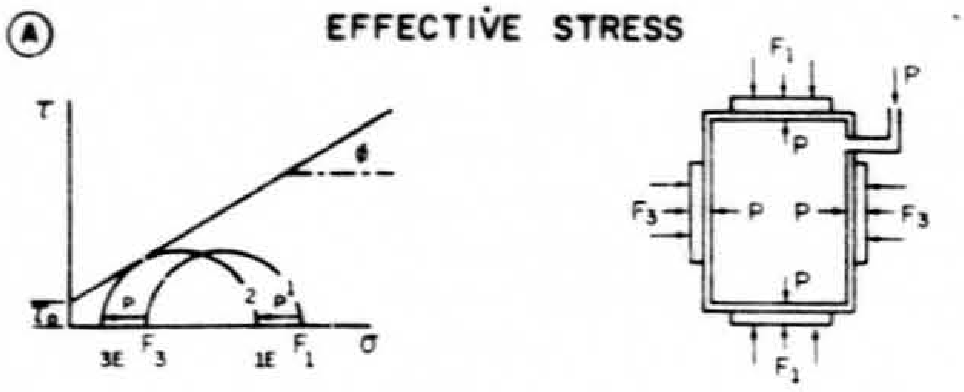
*41 - Nurek (USSR) depth is in excess of 285 m.

LEGEND

- Deep and/or very large reservoir
- Accepted case of RIS, maximum magnitude ≥ 5
- Accepted case of RIS, maximum magnitude 3-5
- Accepted case of RIS, maximum magnitude ≤ 3
- Questionable case of RIS
- Not RIS

PLOT OF WATER DEPTH AND VOLUME FOR WORLDWIDE RESERVOIRS AND REPORTED CASES OF RIS

(A) EFFECTIVE STRESS



A jacketed sample of fluid-filled rock is in compression by forces of F_1 and F_3. The fluid is maintained at constant pressure P from an external reservoir. Slippage occurs when the Mohr circle touches the frictional sliding envelope given by:

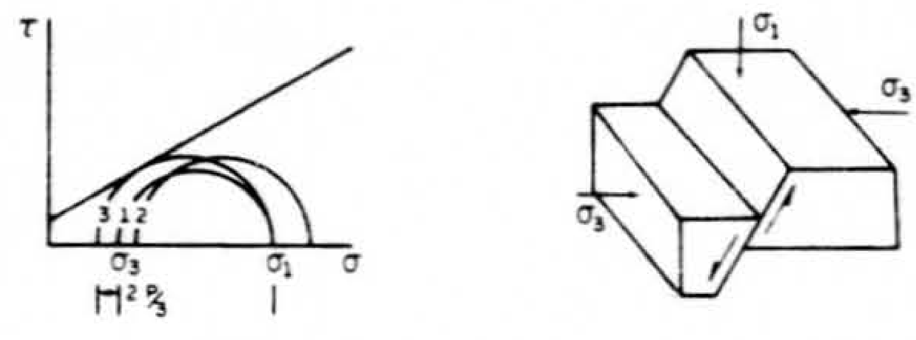
$$\tau = \tau_0 + \mu \sigma$$

where $\mu = \tan\phi$ is the coefficient of friction of the rock. In a sample with fluid pressure P, the Mohr circle is moved to the left to position 2, while F_1 and F_3 are kept constant. Circle 2 defines the "effective stress" σ_{3E}, σ_{1E} where:

$$\sigma_{1E} = F_1 - P$$

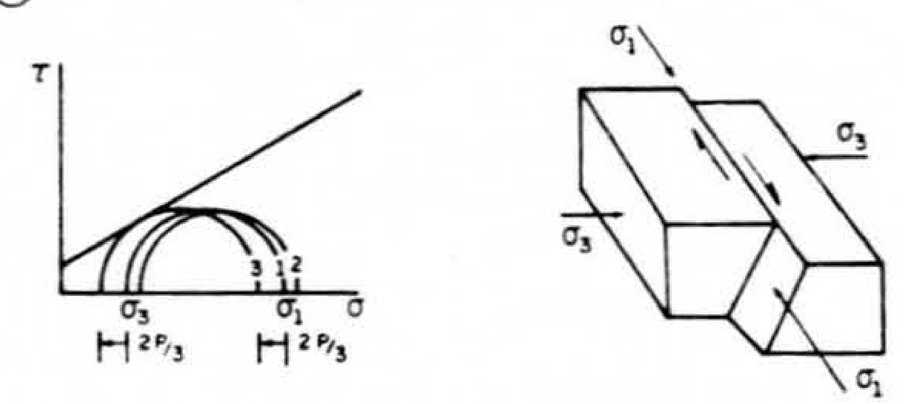
$$\sigma_{3E} = F_3 - P$$

(B) NORMAL (DIP-SLIP) FAULT



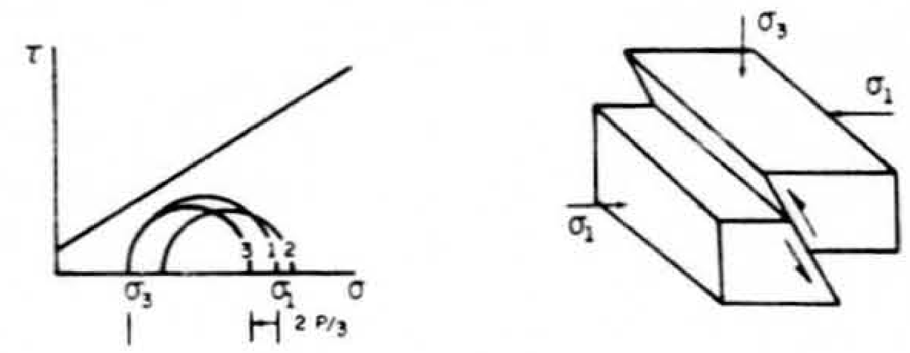
In an extensional stress regime, represented by normal faulting, the largest stress (σ_1) is vertical and the smallest stress (σ_3) is horizontal. Application of a vertical load increases σ_1 by P and σ_3 by P/3 (in material with Poisson's ratio $\gamma = 0.25$). The Mohr circle moves to position 2, and has a larger radius than at position 1. When fluid is introduced into the fault, Mohr circle 2 moves to the left by the amount of fluid pressure P to position 3. Relative to the preloading condition (1), the final condition (3) is less stable, and subject to failure.

(C) STRIKE-SLIP FAULT



In a shear stress regime, represented by strike-slip faulting, the largest stress (σ_1) and the smallest stress (σ_3) are horizontal. Application of a vertical load increases σ_1 and σ_3 by P/3 (in material with Poisson's ratio $\gamma = 0.25$) and shifts the Mohr circle to the right by P/3 to position 2. When fluid is introduced into the fault, the Mohr circle moves to the left by the amount of the fluid pressure P to position 3. The final Mohr circle (3) is of the same radius as the initial condition (1), but is offset towards instability and subject to failure.

(D) THRUST FAULT

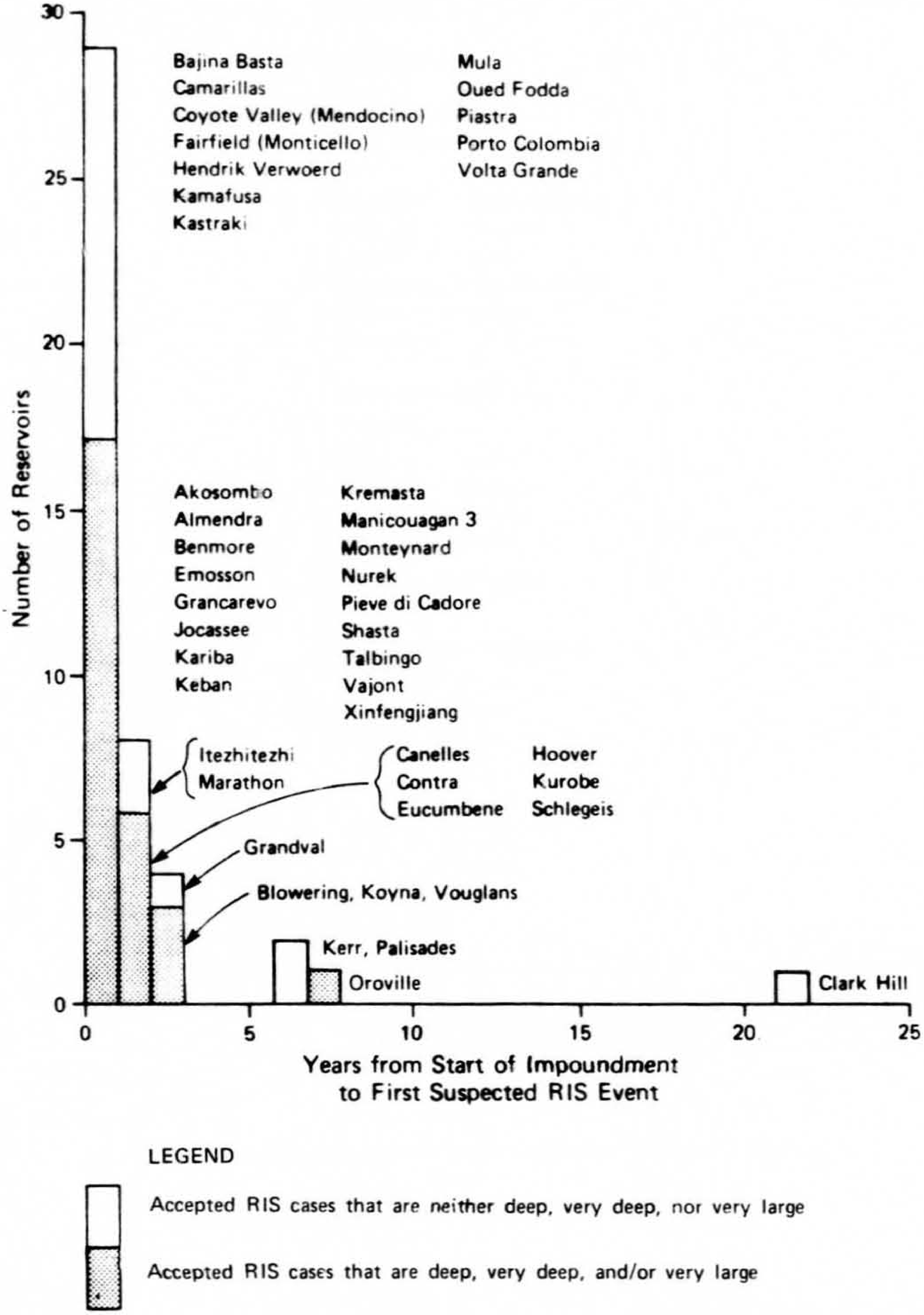


In a compressional stress regime, represented by thrust faulting, the smallest stress (σ_3) is vertical and the largest stress (σ_1) is horizontal. Application of a vertical load increases σ_3 by P and σ_1 by P/3 (in material of Poisson's ratio $\gamma = 0.25$). The Mohr circle moves to position 2, has a smaller radius than at position 1, and represents a more stable condition relative to the initial condition. When fluid is introduced into the fault, Mohr circle 2 moves to the left by the amount of fluid pressure P to position 3. This condition is also more stable than the initial condition. In a compressional stress regime, loading the reservoir may lead to stabilization of the area.

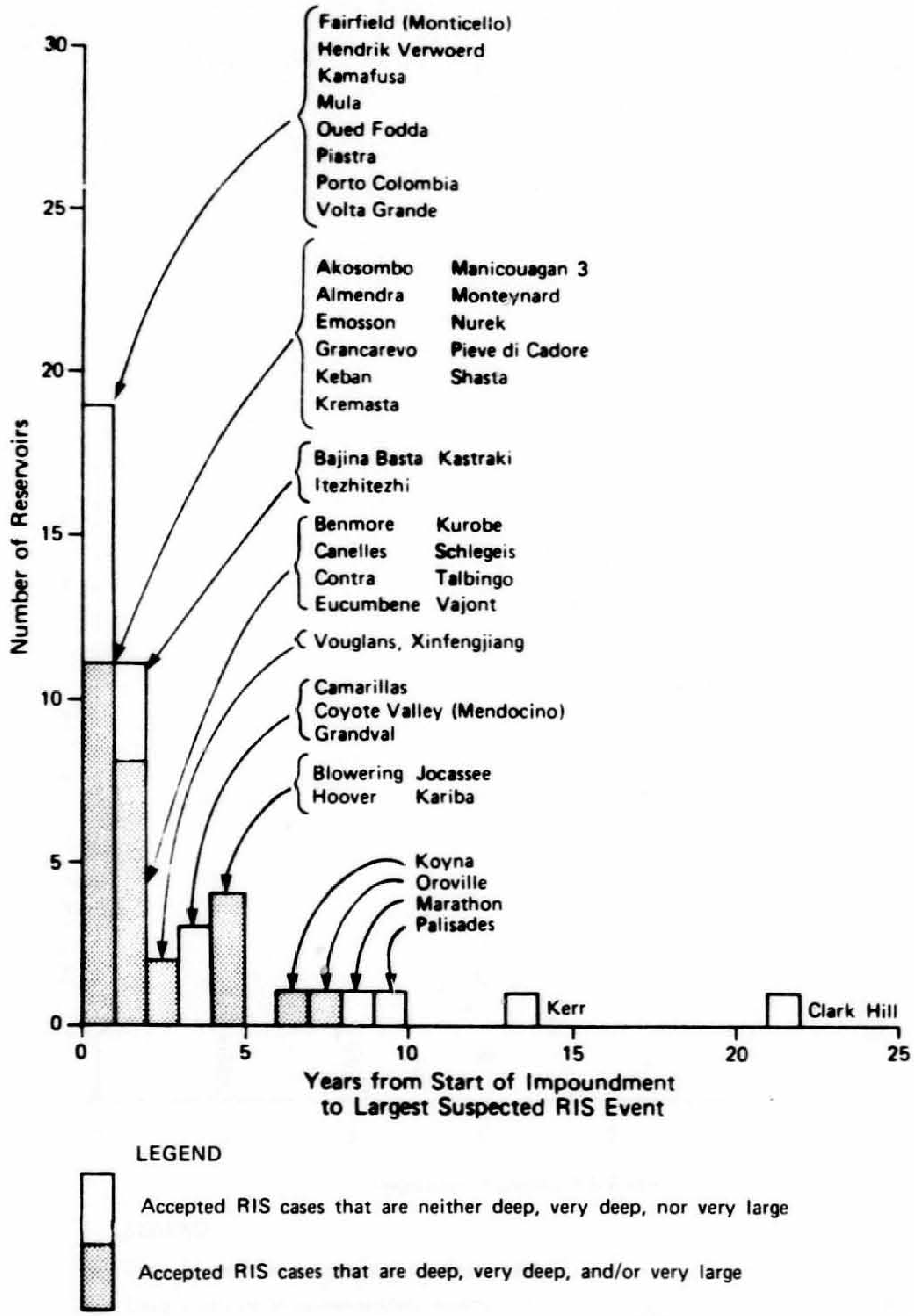
NOTE

1. Modified after Gough (in press) and Withers (1977).

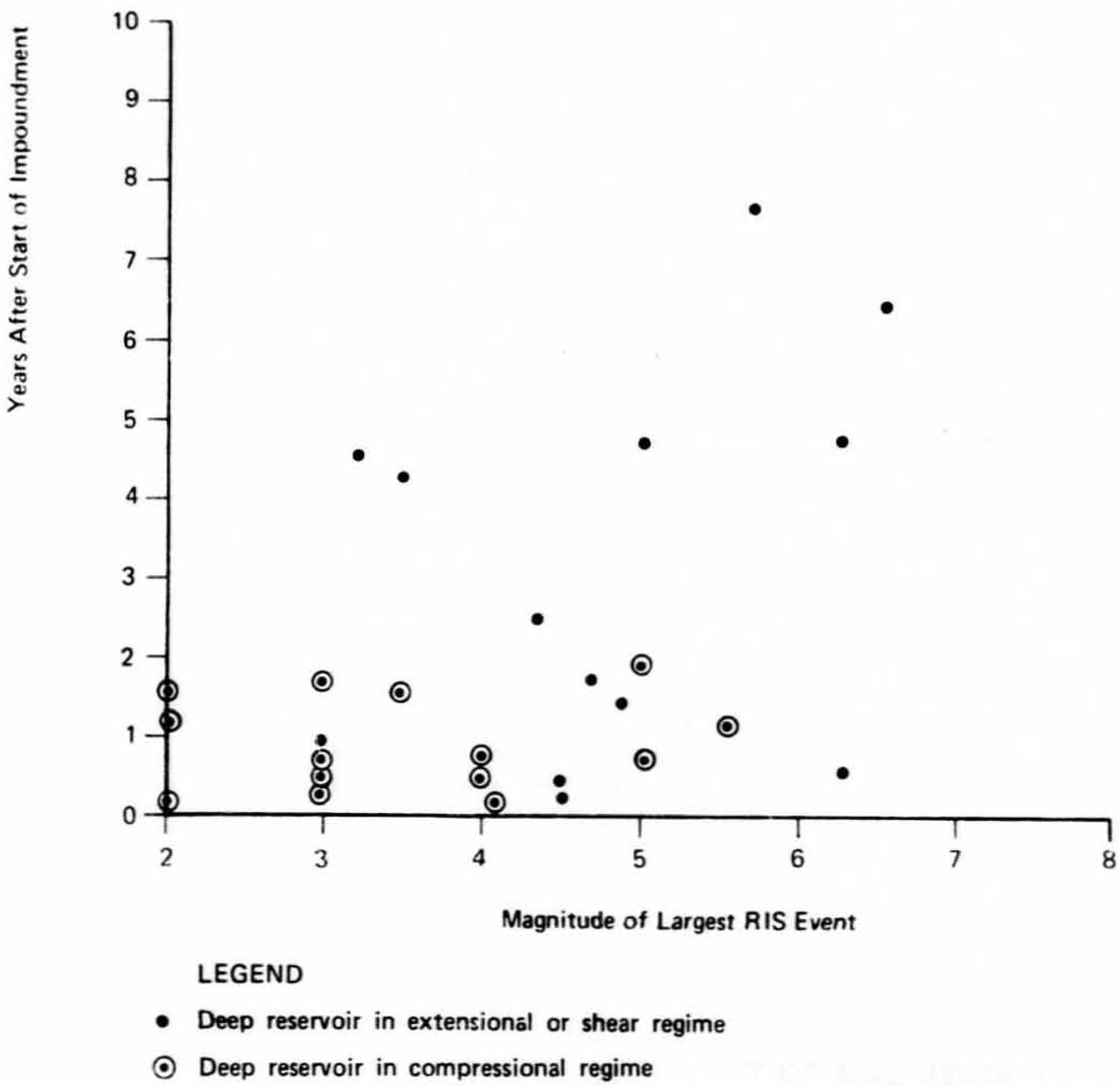
DIAGRAMS SHOWING EFFECTIVE STRESS RELATIONSHIPS



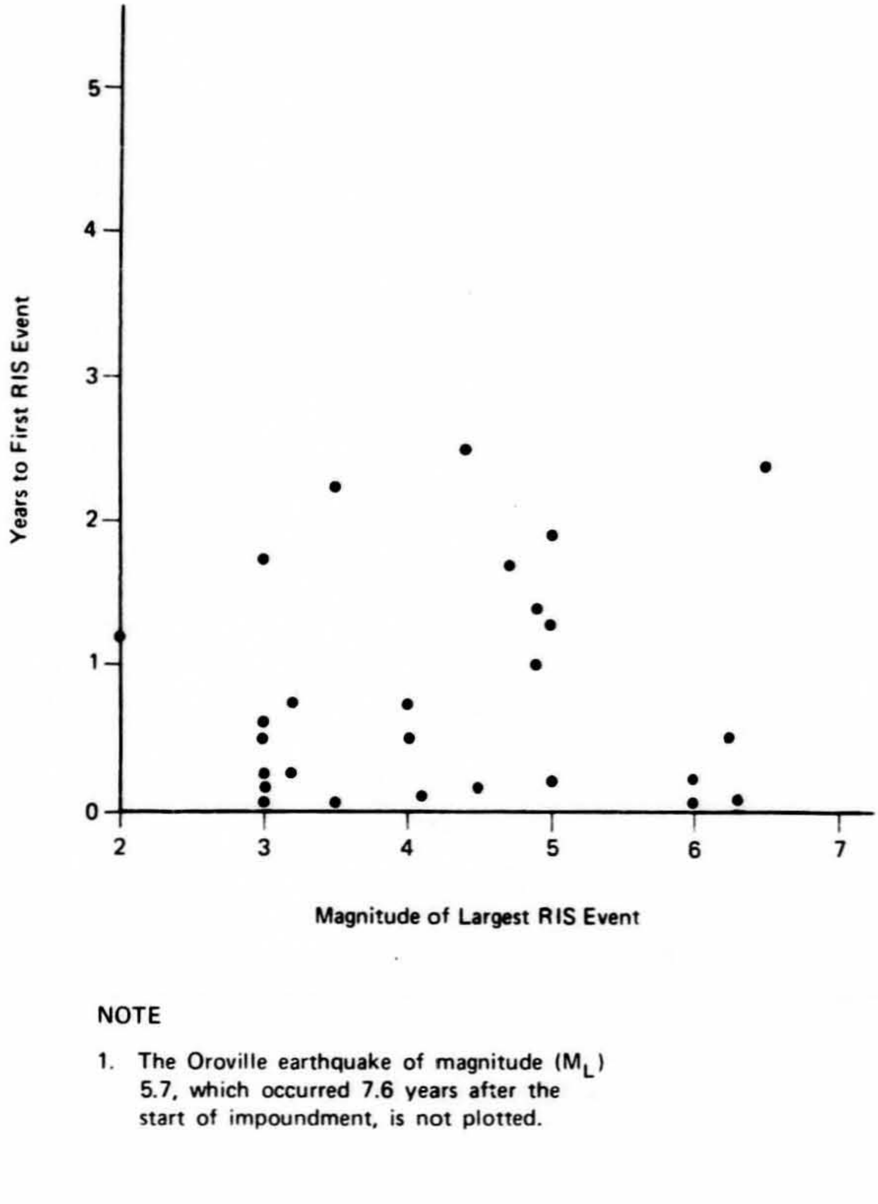
PLOT OF TIME BETWEEN IMPOUNDMENT AND FIRST SUSPECTED RIS EVENT



PLOT OF TIME BETWEEN IMPOUNDMENT AND LARGEST SUSPECTED RIS EVENT



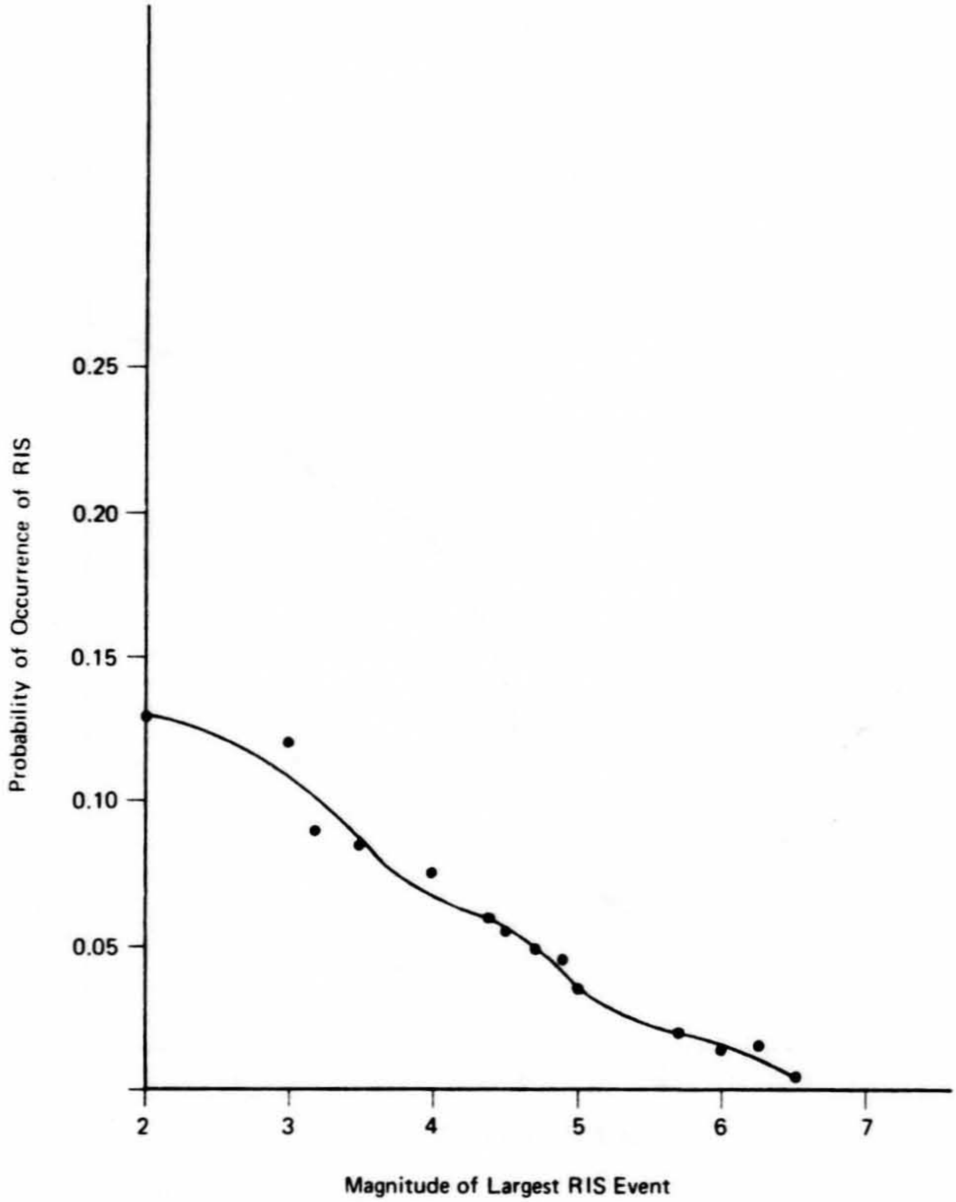
PLOT OF MAGNITUDE OF LARGEST RIS EVENT VERSUS TIME AFTER IMPOUNDMENT FOR ACCEPTED RIS AT DEEP, VERY DEEP, AND/OR VERY LARGE RESERVOIRS



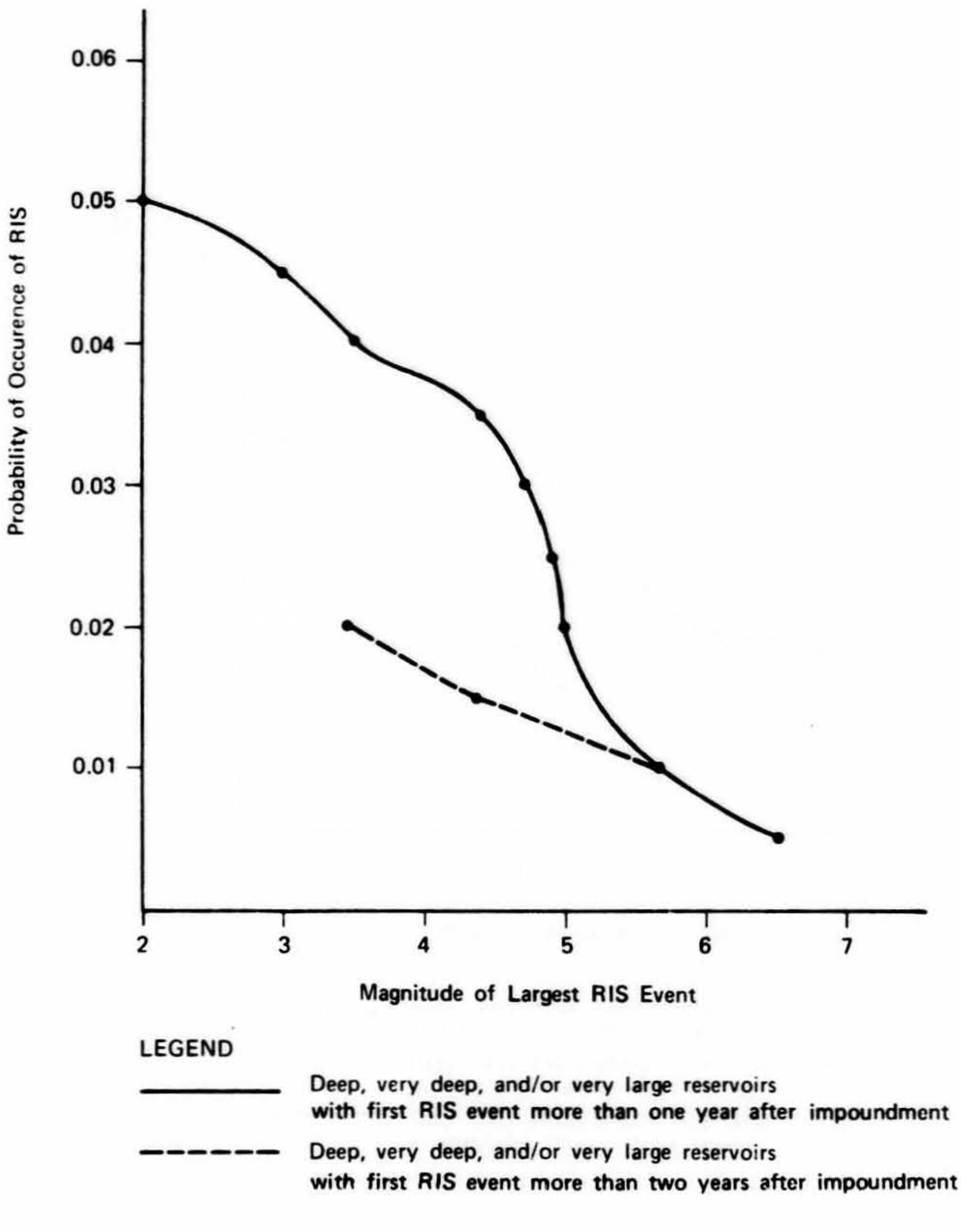
NOTE

1. The Oroville earthquake of magnitude (M_L) 5.7, which occurred 7.6 years after the start of impoundment, is not plotted.

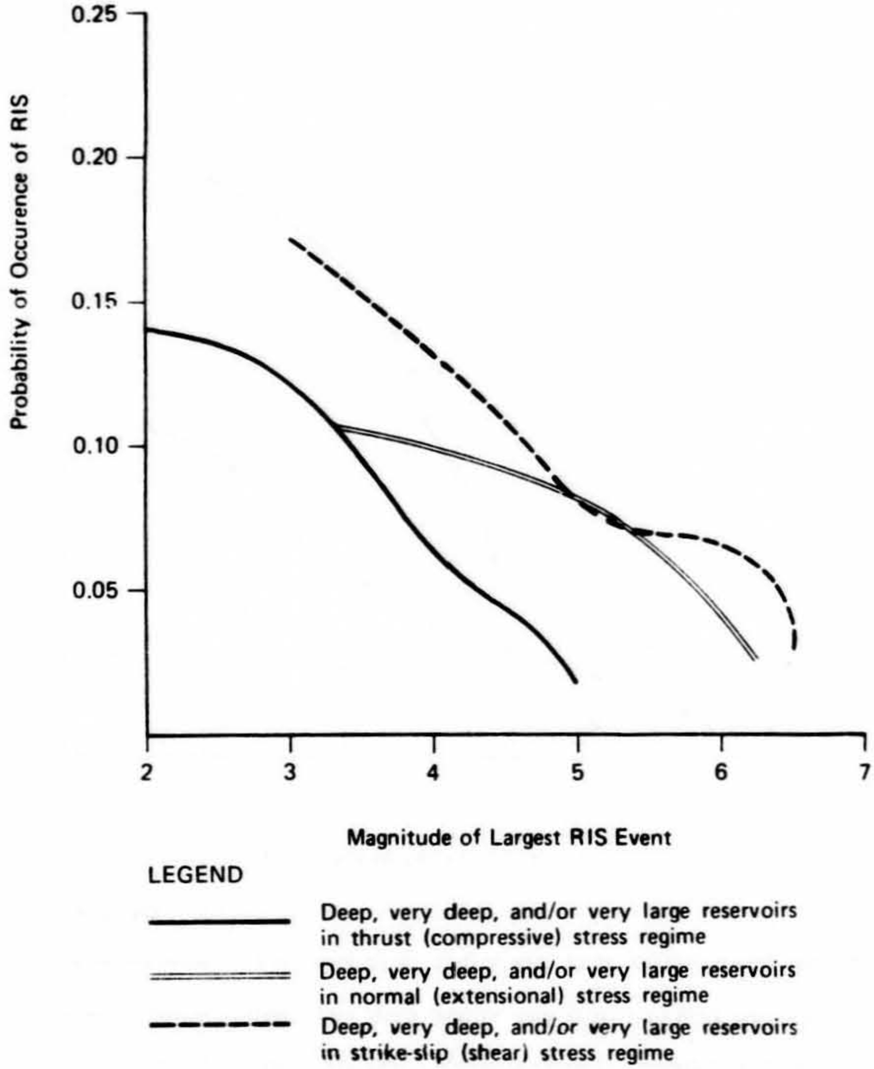
PLOT OF MAGNITUDE OF LARGEST RIS EVENT VERSUS TIME TO FIRST RIS EVENT AT DEEP, VERY DEEP, AND/OR VERY LARGE RESERVOIRS



PROBABILITY OF RIS OCCURENCE WITH MAXIMUM MAGNITUDE ≥M FOR DEEP, VERY DEEP, AND/OR VERY LARGE RESERVOIRS

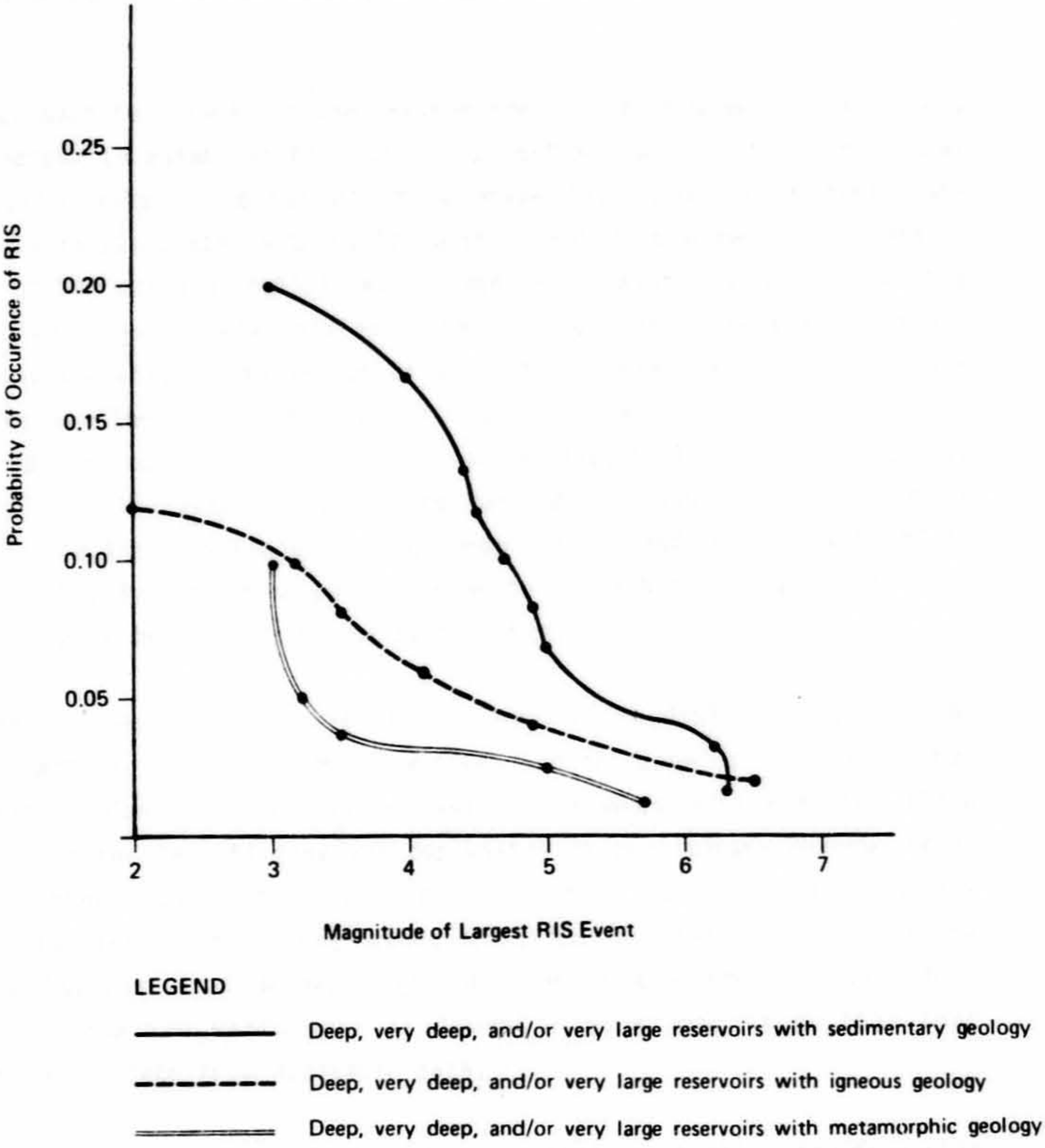


PLOT OF VARIATION OF RIS PROBABILITY WITH DELAY TO FIRST EVENT



PLOT OF VARIATION OF RIS PROBABILITY WITH DIFFERENT STRESS REGIMES FOR DEEP, VERY DEEP, AND/OR VERY LARGE RESERVOIRS

FIGURE 10-9



PLOT OF VARIATION OF RIS PROBABILITY WITH DIFFERENT GEOLOGIC SETTINGS FOR DEEP, VERY DEEP, AND/OR VERY LARGE RESERVOIRS

11 - PRELIMINARY MAXIMUM CREDIBLE EARTHQUAKES (PMCEs)

The approach to estimating the maximum credible earthquakes in a region, and thereby to establishing a basis for estimating the ground motion at a specific site, is based on the premise that significant earthquake activity is associated with faults with recent displacement. The evaluation of the maximum credible earthquake, which may be associated with a given fault, is closely related to the geologic and seismologic setting of fault activity in the region of the site. Therefore, it is necessary to identify the characteristics of the faults with recent displacement in order to assess their seismic source potential. For this study, the only faults accepted as having had recent displacement within or adjacent to the site region are the Denali fault and the Castle Mountain fault. The Benioff zone passes at depth beneath the site and is also considered to be a potential seismic source.

For this investigation, selection of maximum credible earthquakes for faults with recent displacement and the Benioff zone is considered preliminary. Consequently, the maximum earthquakes estimated for these faults and the Benioff zone are designated as preliminary maximum credible earthquakes (PCMEs) and are subject to revision during additional studies. Because the method of estimating these PCMEs is conservative (as discussed below), any revisions is expected to result in a maximum credible earthquake of lower or equal magnitude than that estimated to date from available data.

The results of the investigation to date indicate that no faults within the Talkeetna Terrain have had recent displacement. Consequently, it is inappropriate at present to consider formally PMCEs for faults within the Talkeetna Terrain. The methods used to estimate PMCEs are briefly summarized below and the fault rupture length methodology used for the Denali and Castle Mountain faults is discussed in more detail in Appendix E. It is recognized that these methods may lead to excessively large earthquakes being hypothesized as PMCEs. However, for purposes of evaluating project feasibility, the methods are considered to provide a reasonably conservative estimate of PMCEs for a given source.

11.1 - Distant Sources outside the Talkeetna Terrain

11.1.1 - Sources Outside the Talkeetna Terrain

The PMCEs for sources outside the Talkeetna Terrain, such as the Aleutian Trench or the Fairweather fault, are not of significance to the Project because of the distance of these faults from the Project and because of the presence of seismic sources such as the Denali-Totschunda fault system and Benioff zone which are closer to the Project. Even if it is assumed that a magnitude (M_s) 8.5 event could occur on a known seismic source outside the Talkeetna Terrain, the resultant ground motions would be significantly less than those for the Denali fault. Consequently, PMCEs associated with seismic sources outside of Talkeetna Terrain have not been considered further for this investigation.

11.1.2 - Talkeetna Terrain Boundary Sources

Estimates of PMCEs have been made for three of the boundaries of the Talkeetna Terrain. These boundary sources are the Denali-Totschunda fault system to the north and east, the Castle Mountain fault to the south, and the Benioff zone at depth. Because no single brittle deformation feature forms the boundary to the west (as discussed in Section 5), no PMCE has been estimated for that boundary.

The PMCE for the Denali-Totschunda fault system is estimated to be a magnitude (M_s) 8.5 event. This estimate is based on the

Woodward-Clyde Consultants

assumptions that: as much as one third of the 1,250-mile (2,000-km) length of the fault system could undergo displacement during a single event (as discussed in Appendix E.2) and, the style of movement on the Denali fault during the earthquake would be one of strike-slip displacement.

The PMCE for the Castle Mountain fault is estimated to be a magnitude (M_S) 7.4 event. This estimate is based on the assumptions that: the entire observed length of the fault system could undergo displacement during a single event; and, movement on the fault during the earthquake would be one of oblique-reverse slip.

The PMCE for the Benioff zone is estimated to be a magnitude (M_S) 8.5 event. This estimate is based on the assumptions that: the 1964 Prince William event of magnitude (M_S) 8.4 represents approximately the largest event that can occur on the Benioff zone; and, a magnitude (M_S) 8.5 accommodates uncertainties in magnitude (M_S) for this size event.

The PMCE for the Denali-Totschunda fault system, should it occur at the closest approach of the fault system to the Project sites would occur at least 40 miles (64 km) from the sites. The PMCEs for the Castle Mountain fault and the Benioff zone would occur at least 65 miles (105 km) and 34 miles (50 km) from the sites, respectively. These are the closest seismic sources considered to have the potential of generating a PMCE of greater than magnitude (M_S) 5.

assumptions that: as much as one third of the 1,250-mile (2,000-km) length of the fault system could undergo displacement during a single event (as discussed in Appendix E.2) and, the style of movement on the Denali fault during the earthquake would be one of strike-slip displacement.

The PMCE for the Castle Mountain fault is estimated to be a magnitude (M_S) 7.4 event. This estimate is based on the assumptions that: the entire observed length of the fault system could undergo displacement during a single event; and, movement on the fault during the earthquake would be one of oblique-reverse slip.

The PMCE for the Benioff zone is estimated to be a magnitude (M_S) 8.5 event. This estimate is based on the assumptions that: the 1964 Prince William event of magnitude (M_S) 8.4 represents approximately the largest event that can occur on the Benioff zone; and, a magnitude (M_S) 8.5 accommodates uncertainties in magnitude (M_S) for this size event.

The PMCE for the Denali-Totschunda fault system, should it occur at the closest approach of the fault system to the Project sites would occur at least 40 miles (64 km) from the sites. The PMCEs for the Castle Mountain fault and the Benioff zone would occur at least 65 miles (105 km) and 34 miles (50 km) from the sites, respectively. These are the closest seismic sources considered to have the potential of generating a PMCE of greater than magnitude (M_S) 5.

11.2 - Effect of Reservoir-Induced Seismicity on the Preliminary Maximum Credible Earthquakes

The hydrologic effects of the impounded reservoirs are postulated to influence an elliptical shaped area that extends 19 miles (30 km) around the perimeter of the proposed Watana-Devil Canyon reservoir as discussed in Section 10. The reservoir will not affect consideration of PMCEs along faults outside the hydrologic regime of the reservoir, including the Denali and the Castle Mountain faults and the Benioff zone.

For faults and possible faults within the hydrologic regime of the reservoir, the influence of a reservoir is believed to be limited to that of a triggering mechanism (as discussed in Section 10). For moderate to large earthquakes (magnitude (M_S) > 5), reservoirs with accepted cases of RIS are not known to have triggered events larger than could have occurred naturally along faults with recent displacement. Therefore, the effect of RIS on faults within the hydrologic regime of the proposed Watana-Devil Canyon reservoir cannot be adequately assessed until additional geologic data are obtained on the significant features (discussed in Section 8-5).

If subsequent studies show one or more of the significant features is a fault with recent displacement (with a defined recurrence interval and displacement), a maximum credible earthquake can be estimated for that fault. The effect of RIS is expected to be limited to decreasing the recurrence interval of such an earthquake. The location of the earthquake is also expected to be constrained to the section of the fault lying within the hydrologic influence of the reservoir. RIS would not be expected to increase the size of a maximum credible earthquake estimated for a fault with recent displacement.

12 - PRELIMINARY GROUND MOTION STUDIES

The objective of the studies described here is to develop preliminary estimates of the characteristics of ground shaking at the Watana and Devil Canyon sites resulting from preliminary maximum credible earthquakes on the known faults with recent displacement in the site region. The ground-motion characteristics addressed in this section include peak horizontal ground acceleration, response spectra, and duration of strong ground shaking.

The known faults with recent displacement are the boundary faults of the Talkeetna Terrain: the Denali fault, located north of the sites; the Castle Mountain fault, located south of the sites; and the Benioff zone which underlies the site region at depth. The closest distances of these faults from each site and the preliminary maximum credible earthquake magnitudes for the faults are the following.

Fault	Preliminary Maximum Credible Earthquake Magnitude	Closest Distance of Fault to Site (km)	
		Watana	Devil Canyon
Denali	8.5	70	64
Castle Mountain	7.4	105	115
Benioff Zone	8.5	50	60

Lineaments or faults in the Talkeetna Terrain are not addressed in these studies because these features are not currently known to have been subject to recent displacement. If the future seismic geologic studies identify any of these features to be faults with recent displacement, then ground motions associated with such faults should be evaluated.

12.1 - Methodology for Estimating Earthquake Ground Motions

12.1.1 - Peak Ground Acceleration

Woodward-Clyde Consultants (1978), Idriss (1978), Crouse and Turner (1980), and ongoing studies at Woodward-Clyde Consultants indicate that ground motions from Benioff zone (subduction zone) earthquakes have different characteristics than ground motions from shallow focus crustal earthquakes. The estimates of peak acceleration for Benioff zone earthquakes were based primarily on the attenuation relationship developed from statistical analysis of recorded strong motion data from worldwide historic Benioff zone earthquakes; these analyses were conducted primarily during a previous general analysis of ground motions in Alaska (Woodward-Clyde Consultants, 1978). The data used in that study consisted of strong motion recordings from subduction zone earthquakes in Japan and South America, as very few such data are available from Alaska. During the present study, the limited data from Alaska were examined and found to be reasonably consistent with the results of the previous analysis.

For shallow crustal earthquakes, peak accelerations were selected by examining recorded rock-site data for such earthquakes and published attenuation relationships and ongoing ground-motion studies of Woodward-Clyde Consultants. The applicable data examined are primarily from California, with a few data points from Alaska. The limited Alaskan data were found to be reasonably consistent with the other data used. The published attenuation relationships examined in estimating peak accelerations included Schnabel and Seed (1973), Seed and others (1976), Idriss (1978), and Seed (1980).

Peak horizontal ground acceleration values were estimated for the preliminary maximum credible earthquake on each of the faults. The assumption was made that this earthquake would rupture the fault at the point on the fault closest to the sites.

12.1.2 - Acceleration Response Spectra

Acceleration response spectra for the sites were estimated using spectral shapes appropriate for the preliminary maximum credible earthquake magnitudes and distances of the earthquakes from the sites. These spectral shapes were based on considerations and analyses similar to those described above for peak acceleration. The references cited indicate that spectral shapes, as well as peak acceleration, differ for Benioff zone versus shallow focus crustal earthquakes. The selected spectral shapes were scaled with the corresponding peak horizontal ground acceleration described above to develop the acceleration response spectra.

12.1.3 - Duration of Strong Ground Shaking

The duration of strong ground shaking (significant duration) was estimated primarily on the basis of results presented by Dobry and others (1978). In that study, significant duration is defined as the time during which from 5 to 95 percent of the energy of an accelerogram is developed. The significant durations obtained by Dobry and others (1978) using this definition are not much different than durations proposed by other investigators using different definitions of significant duration.

12.2 - Preliminary Estimates of Earthquake Ground Motions

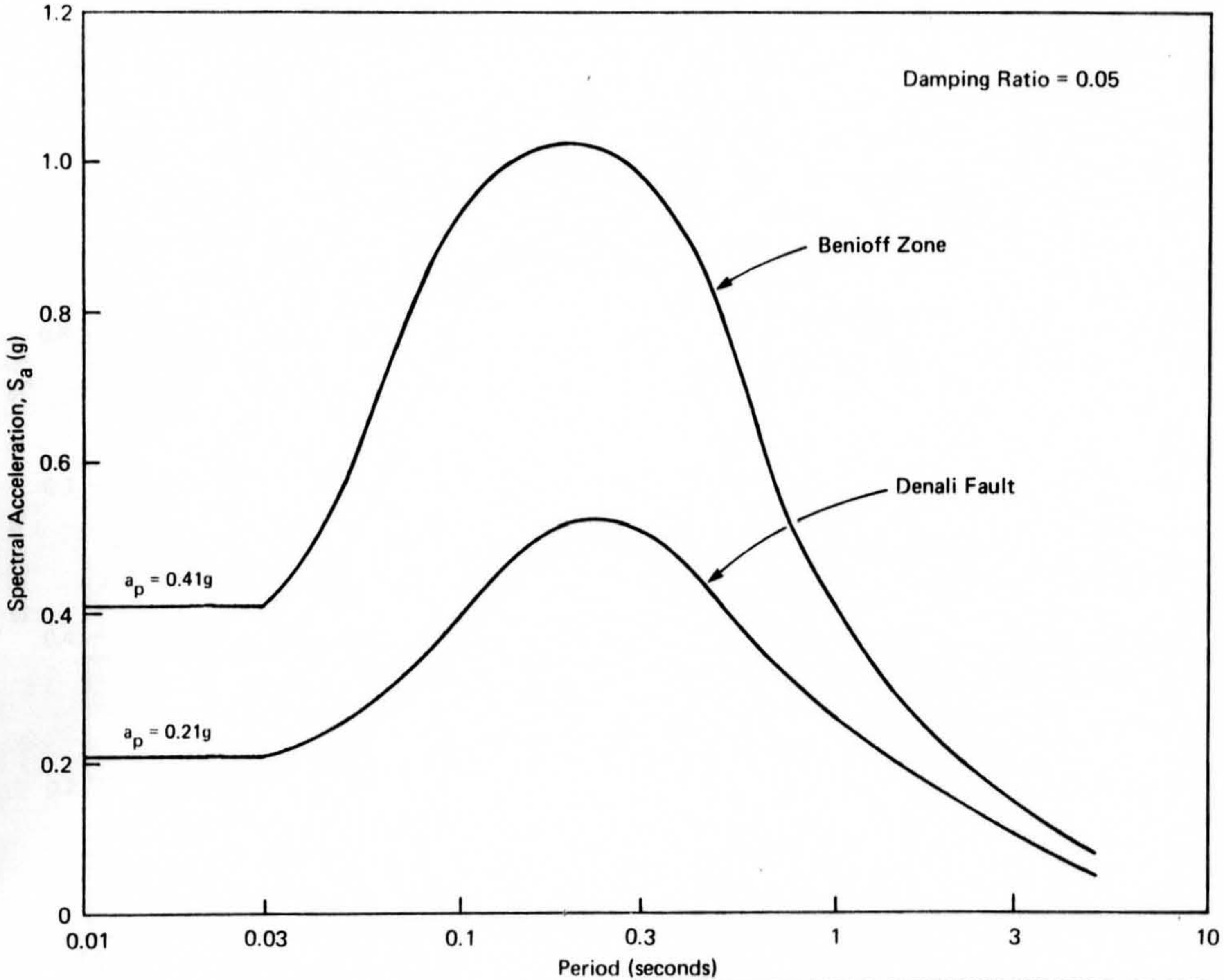
Estimated mean (average) values of peak horizontal ground accelerations at each site resulting from preliminary maximum credible earthquakes are the following:

Earthquake Source	Mean Peak Horizontal Ground Acceleration	
	Watana Site	Devil Canyon Site
Denali Fault	0.21 g	0.21 g
Castle Mountain Fault	0.06 g	0.05 g
Benioff Zone	0.41 g	0.37 g

As may be seen by comparison of these mean peak horizontal acceleration values, the Benioff zone and the Denali fault govern the ground motion levels estimated for the sites; the site ground motions due to the Castle Mountain fault are relatively small. For the Benioff zone and the Denali fault, the estimated mean acceleration response spectra for a damping ratio of 0.05 are illustrated in Figure 12-1 for the Watana site and in Figure 12-2 for the Devil Canyon site.

The duration of strong ground shaking at the sites was estimated to be 45 seconds for preliminary maximum credible earthquakes on both the Benioff zone and the Denali fault.

In summary, the results of these preliminary studies indicate that, of the known faults with recent displacement in the site region, the Benioff zone is expected to govern the levels of peak horizontal ground acceleration, response spectra, and duration of ground shaking.



NOTE

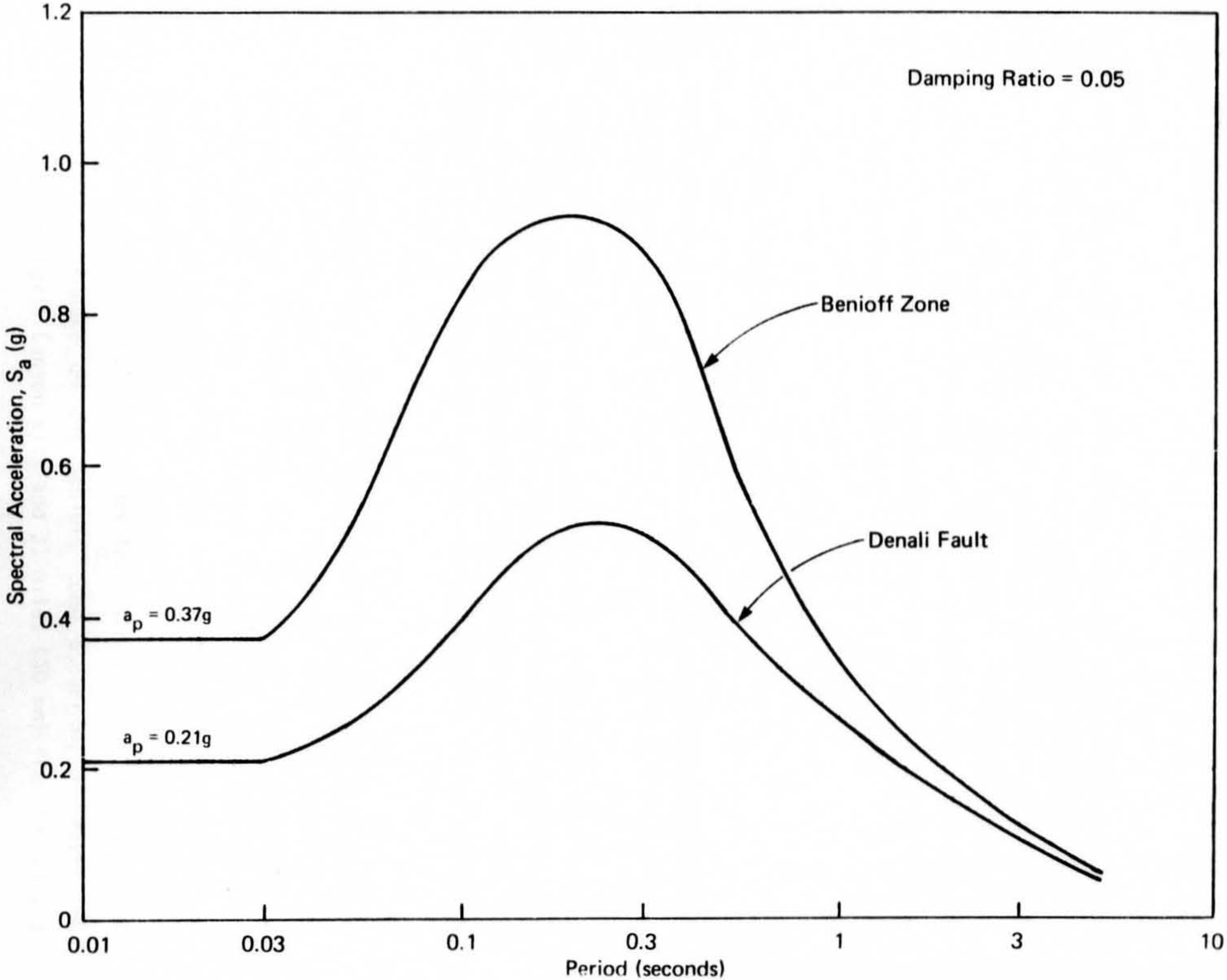
1. a_p is peak horizontal acceleration.

PRELIMINARY MEAN RESPONSE SPECTRA AT THE WATANA SITE FOR PRELIMINARY MAXIMUM CREDIBLE EARTHQUAKES ON KNOWN FAULTS WITH RECENT DISPLACEMENT

WOODWARD-CLYDE CONSULTANTS 14658A December 1980

FIGURE 12.1

WOODWARD-CLYDE CONSULTANTS 14658A December 1980



PRELIMINARY MEAN RESPONSE SPECTRA AT THE DEVIL CANYON SITE FOR PRELIMINARY MAXIMUM CREDIBLE EARTHQUAKES ON KNOWN FAULTS WITH RECENT DISPLACEMENT

FIGURE 12-2

13 - CONCLUSIONS

Two sets of conclusions have been drawn from the results of the investigation conducted to date. One set, designated feasibility conclusions, are those considered important to evaluate the preliminary feasibility of the Project. The second set, designated technical conclusions, are those related to the scientific data collected. Both sets of conclusions are discussed below and form the basis for the proposed 1981 study plan (Section 14).

13.1 Feasibility Conclusions

(a) No faults with known recent displacement (displacement in the last 100,000 years) pass through or adjacent to the Project sites.

(b) The faults with known recent displacement closest to the Project sites are the Denali and Castle Mountain faults. These faults, and the Benioff zone associated with the subducting Pacific Plate (at depth below the Project site), are considered to be accepted seismic sources.

(c) Preliminary maximum credible earthquakes for the Denali and Castle Mountain faults and the Benioff zone have been estimated as a: magnitude (M_S) 8.5 earthquake on the Denali fault occurring 40 miles (64 km) from the Devil Canyon site and 43 miles (70 km) from the Watana site; magnitude (M_S) 7.4 earthquake on the Castle Mountain fault occurring 65 miles (105 km) from the Devil Canyon site and 71 miles (115 km) from the Watana site; and magnitude (M_S) 8.5 earthquake on the Benioff zone occurring 37 miles (60 km) from the Devil Canyon site and 31 miles (50 km) from the Watana site.

(d) Within the site region, 13 faults and lineaments have been judged to need additional investigation to better define their potential affect on Project design considerations. These 13 faults and lineaments (designated significant features) were selected on the basis of their seismic source potential and potential for surface rupture through either site. Four of these features are in the vicinity of the Watana site and nine are in the vicinity of the Devil Canyon site.

(e) At present, the 13 significant features are not known to be faults with recent displacement. If additional seismic geology studies show that any of these features is a fault with recent displacement, then the potential for surface rupture through either site and the ground motions associated with earthquakes on such a fault will need to be evaluated.

(f) Preliminary estimates of ground motions at the sites were made for the Denali and Castle Mountain faults and the Benioff zone. Of these sources, the Benioff zone is expected to govern the levels of peak horizontal ground acceleration, response spectra, and duration of strong shaking. The ground-motion estimates are preliminary in nature and do not constitute criteria for design of project facilities. The site ground-motion estimates will be made final and the design criteria will be developed as part of the next phase of study.

13.2 Technical Conclusions

(a) The site is located with the Talkeetna Terrain. This tectonic unit has the following boundaries: the Denali fault to the north and northeast; the Totschunda fault to the east; the Castle Mountain fault to the south; a broad zone of deformation and volcanoes to the west; and the Benioff zone at depth.

(b) The northern, eastern, and southern boundaries of the Talkeetna Terrain are major fault systems along which displacement has occurred in Quaternary time. The Benioff zone beneath the Talkeetna Terrain represents the upper margin of the Pacific Plate which is being subducted beneath the North American Plate. The western boundary is a broad zone of deformation and volcanoes which does not appear to have brittle deformation occurring along a major fault.

(c) The Talkeetna Terrain appears to be acting as a coherent tectonic unit within the present stress regime. Major strain release occurs along the fault systems bounding the Terrain. Within the Terrain, strain release appears to be randomly occurring at depth within the crust. This strain release is possibly the result of crustal adjustments resulting from perturbation imposed by the Benioff zone and by stress (associated with plate motion) imposed along the Terrain margin through the Terrain.

(d) The only fault system within the site region (within 62 miles (100 km) of either Project site) which is known to have had displacement in Quaternary time (the last two million years) is the Denali fault. This fault is approximately 40 miles (64 km) north of the sites at its closest approach. The Castle Mountain fault system is immediately south of the site region. This fault system has had displacement in Quaternary time.

(e) Within the site region, 48 candidate significant features have been identified. These features are faults and lineaments for which no evidence of recent displacement was observed, but for which evidence of precluding recent displacement has not been demonstrated.

(f) Of the 48 candidate significant features, there are 13 significant features which the results of this study suggest need additional investigation. These 13 features were selected on the basis of their seismic source potential and potential for surface rupture through either Project site. Four of these features are in the vicinity of the Watana site and include the Talkeeetna thrust fault (KC4-1), the Susitna feature (KD3-3), the Fins feature (KD4-27), and lineament KD3-7. Nine of the features are in the vicinity of the Devil Canyon site and include fault KD5-2 and lineaments KC5-5, KD5-3, KD5-9, KD5-12, KD5-42, KD5-43, KD5-44, and KD5-45.

(g) No evidence of the Susitna feature has been developed to date during this study. Reconnaissance level aerial and ground checking has produced no evidence of a fault in bedrock and no evidence of deformation in overlying surficial units.

Review of aerial gravity and magnetics data shows no evidence of a major tectonic dislocation. Earthquakes correlated with the southern portion of the feature by Gedney and Shapiro (1975) occurred at depths greater than 43 miles (70 km). These focal depths suggest that the earthquakes occurred on the Benioff zone well below the crust and well below the extent of the Susitna feature, if the latter is a fault. The feature may be the result of glaciation of stream drainages whose alignment reflects structural control such as joints or perhaps folding.

(h) The Talkeetna thrust fault is a northeast-southwest trending fault which may dip either to the northwest or the southeast. The northeastern continuation of the fault is the Broxson Gulch thrust fault resulting in a 167-mile (270-km) long fault that passes approximately 3.5 miles (5.4 km) upstream of the proposed Watana site. No evidence of displacement younger than Tertiary in age (approximately two to several tens of millions of years old) has been reported for either the Talkeetna or Broxson Gulch thrust faults. However, anomalous relationships in deposits of Tertiary (?) age on the north side of the Susitna river were observed during this investigation and may be related to faulting.

(i) Seismicity within the Talkeetna Terrain can be clearly delineated as crustal events occurring at depths to approximately 5 to 12 miles (8 to 20 km) and as Benioff zone events which occur at greater depths. The depth to the Benioff zone increases from approximately 25 miles (40 km) in the southeastern part of the site region to more than 50 miles (80 km) in the northwestern part of the microearthquake study area and more than 78 miles (125 km) in the northwestern site region.

(j) The largest reported historical earthquake within the site region is the magnitude (M_S) 6-1/4 event of 1929 which occurred approximately 25 and 31 miles (40 and 50 km) south of the Devil Canyon and Watana sites, respectively. Four earthquakes greater than magnitude (M_S) 5 have occurred during the period 1904 through August 1980.

(k) Earthquakes as large as magnitude (M_S) 5 to 5-1/2 may possibly occur in the site region without direct association with surface fault rupture. Such events would probably be constrained to rupture planes deeper than 6 miles (10 km).

(l) The largest crustal event recorded within the microearthquake study area during 3 months of monitoring was magnitude (M_L) 2.8. It occurred 6.8 miles (11 km) northeast of the Watana site at a depth of 9.3 miles (15 km) on 2 July 1980.

(m) Two clusters of microearthquake activity were observed within the microearthquake network during the three-month monitoring period. These two clusters occurred in the same general vicinity east of the southern portion of the Talkeetna Thrust fault. These clusters of seismicity occurred at depths of 6 to 12 miles (10 to 20 km). One of the clusters gives a composite focal plane mechanism of N23°E, dipping 50°NW, consistent with local geologic trends. The sense of movement is reverse (toward the southeast) with a dextral component of slip.

(n) The clusters of microearthquake activity described in (m) above appear to be related to a small subsurface rupture plane that does not extend to the surface. These clusters do not appear to be related to the Talkeetna thrust fault.

(o) Seismicity in the vicinity of the site, including the clusters described above, appears to reflect relatively small-scale crustal adjustments at depth in the crust. These adjustments may be related to stresses imposed by the Benioff zone and/or by plate motion.

(p) No association of microearthquake activity with candidate significant or significant features is apparent on the basis of information obtained to date.

(q) The two reservoirs are considered as one reservoir hydrologically. This combined Watana-Devil Canyon reservoir would be among the deepest and largest in the world. It is concluded that the likelihood of a reservoir-induced earthquake of any size within the hydrologic regime of the proposed reservoir is high (0.9 on a scale of 0 to 1); this is primarily because water depth has a major apparent theoretical and empirical correlation with the occurrence of reservoir-induced seismicity.

(r) Preliminary maximum credible earthquakes (PMCEs) have been estimated for crustal faults with recent displacement in and adjacent to the site region and for the Benioff zone. The PMCE for the Denali fault is estimated to be a magnitude (M_S) 8.5 event occurring 40 miles (64 km) from the Devil Canyon site and 43 miles (70 km) from the Watana site. The PMCE for the Castle Mountain fault is estimated to be a magnitude (M_S) 7.4 event occurring 65 miles (105 km) from the Devil Canyon site and 71 miles (115 km) from the Watana site. The PMCE for the Benioff zone is estimated to be a magnitude (M_S) 8.5 event occurring 31 miles (50 km) beneath the Watana site and 37 miles (60 km) beneath the Devil Canyon site.

14 - Proposed 1981 Study Plan

The proposed study plan is designed to provide additional information for Project design in accordance with the Plan of Study (Acres American Inc., 1980). This information will include data on the characteristics of the 13 significant features and a subsequent refined assessment of the potential for moderate to large (magnitude (M_L) > 5) reservoir-induced earthquakes. From these studies, a refined estimate of earthquake ground motions at the sites can be made and earthquake ground motion design criteria can be developed for the Project.

The proposed study plan is expected to be evolutionary in nature. Therefore, the details of the plan can change during the course of the 1981 studies. The plan is to:

(a) Conduct a detailed Quaternary geologic investigation. This investigation will include research of available information of recent geologic deposits, weathering rates, and glacial history; interpretation of large-scale aerial photographs; mapping of Quaternary deposits; and age dating. The purpose of this investigation will be to identify and obtain ages for Quaternary deposits. These deposits can then be used to evaluate the recency of displacement along faults.

(b) Obtain and analyze low-sun-angle photography around both sites and along the Talkeetna thrust fault and Susitna feature. The purpose of these studies will be to look for evidence suggestive of recent fault displacement. If such evidence is observed, the locations identified on the low-sun-angle photographs will be examined during the geologic field studies.

(c) Conduct field geologic studies of the 13 significant features. These studies will include additional air photo analysis and field mapping in appropriate locations. They can also include test pits, trenches, geophysical surveying, borings, and age dating.

(d) Conduct calibration studies along either the Denali or Castle Mountain faults. The calibration can include field mapping, air photo analysis, and trenching as appropriate. The purpose of these studies will be to provide detailed information on the style, amount, and rate of deformation on faults with recent displacement. Thus, during the field studies of the significant features, the characteristics of the significant features will be calibrated against the degree of confidence in judgments made about recent fault displacement.

(e) Design a program manual for future seismologic network monitoring. The manual will summarize data recording, interpretation, and documentation procedures. The purpose of the manual will be to provide guidelines for obtaining additional high quality seismologic data for the project.

(f) Re-evaluate the estimated potential for reservoir-induced seismicity by incorporating the results of the geologic field studies. The presence or absence of faults with recent displacement within the hydrologic regime of the proposed Watana-Devil Canyon reservoir will affect the potential for moderate to large magnitude (M_s) > 5 reservoir-induced earthquakes. After the field studies are completed, theoretical modeling and additional statistical analyses can be conducted to assess this potential.

(g) Finalize the estimates of earthquake ground motion at the Project sites. This will be done after the seismic geology studies are performed to assess the seismic activity of significant features.

(h) Develop Project earthquake ground motion design criteria based on the results of the ground motion evaluations.

APPENDIX A - ANNOTATION AND DOCUMENTATION PROCEDURES FOR THE GEOLOGIC INVESTIGATION

A.1 - Introduction

This appendix describes the procedures used to annotate and document candidate features during the geologic investigation. The geologic investigation included literature acquisition and analysis, acquisition and interpretation of existing remotely sensed imagery and photography, and field reconnaissance studies. The procedures used during the investigation can be considered as two sets--one set used prior to and the other used during the field reconnaissance studies.

The two sets of procedures were developed prior to initiation of the geologic investigation. Revisions were made during the course of the investigation to accommodate changes in conditions which developed. The purpose of the procedures was to provide a systematic method of annotation and documentation to be used during the review of data sources for the recording of pertinent information, for the transferral of that information to appropriate base maps, and for the recording of field observations. This method of annotation and documentation was designed to provide repeatable and accurate results which could be reviewed by an independent reviewer.

A summary of the annotation and documentation procedures is shown in Figure A-1. Examples of the documentation forms are included in this appendix. Completed forms for each candidate feature are filed in the project master file; they are not reproduced in this report.

A.2 - Fault and Lineament Annotation and Documentation Procedures

A.2.1 - Literature Review (Form SHP-2)

Purpose

The purpose of this procedure was to outline the steps necessary for documentation of the literature review. Form SHP-2 (Figure A-2), used for the documentation, was designed to meet the following goals:

(a) To provide documentation for each reference;

(b) To provide an easily retrievable, brief summary of the data contained in the reference;

(c) To provide a quick reference for faults or lineaments which were identified or discussed in the reference;

(d) To provide a full reference citation for the report bibliography.

Procedure

The following is a summary of the procedures used to complete selected portions of the form.

At the top of the sheet, an (X) is placed by the field of study emphasized in the reference; a check (✓) is placed by the fields of study that are considered to be of secondary emphasis in the reference. The project reference file is divided into the same fields of study as those listed at the top of the page.

The original reference documentation sheet is filed alphabetically by the lead author's last name in the project master file. The reference and a copy of the reference documentation sheet is filed under the field of study emphasized in the reference, i. e., the field marked with an (X). A copy of the reference documentation sheet is also filed under the heading of the secondary fields of emphasis marked with a check (√).

This procedure provides a cross reference system for references. If, for example, information on age dating is needed, a review of the file under the heading of age dating provides all references (and reference documentation forms) which emphasize age dating. In addition, reference documentation sheets are present for other references that don't emphasize age dating but which nevertheless contain usable age dating data.

The name of the person who reviewed the reference is entered, along with the date of the review. If a copy of the reference is not in the project file, the "no" is circled on the form and the location of the reference (e. g., Woodward-Clyde Consultants Library, UCLA Library) is written at the end of the Full Citation section.

A complete and accurate citation is included, using the format given in Bishop and others (1978). Illustrations such as maps and cross sections which are pertinent to fault studies are listed. The title and scale of the illustration are also included.

The geographic area covered in the reference is described using physiographic feature names and/or geographic names. If appropriate, more specific locations are described by citing 15 minute quadrangle sheets, township and range, or longitude and latitude.

The summary provides a brief synopsis of the reference contents. Data that may be useful in the seismic geology study are noted, and the quality of those data with respect to the purposes of the project is indicated.

For references marked "not useful," a brief explanation of why the reference is not useful is provided.

Structural elements (faults and lineaments) identified in the reference that occur within a 62-mile (100-km) radius of both dam sites are transferred to the base map and are assigned a map code number using the procedures discussed below in Section A.2.5. The map code number and names, if applicable, of all structural elements cited in the reference are listed on Form SHP-2.

A.2.2 - Remotely Sensed Data (Form SHP-4)

Purpose

The procedures described below include the documentation methods that were used during the interpretation of lineaments on remotely sensed data. The key sections of the procedures are the annotation of mylar overlays and the completion of the remote sensing lineament worksheet (Form SHP-4). An example of the form is shown in Figure A-3. The coverage of remotely sensed data used for this investigation is shown in Figures A-4 and A-5.

Procedure

All interpretation of remotely sensed data was annotated on mylar overlays. The overlay includes registration marks, image type and scene identification number, the project number, the interpreter's initials, and the date of interpretation.

All lineaments interpreted to be possible faults or possible faults with potential recent displacement were delineated on the overlay. Lineaments meeting the length-distance screening criteria (described in Section 3.2) were assigned a remote sensing code number by using procedures described below in Section A.2.3. This interim remote sensing code number was written on the mylar overlay adjacent to the lineament. Lineaments which did not meet length-distance screening criteria were annotated with an X. After all lineaments were annotated with either an interim remote sensing code number or an X, overlays were filed in the project master file.

Lineaments which met length-distance screening criteria were described on the remote sensing lineament worksheet (Form SHP-4). The intent of these descriptions was to provide a concise list and summary of geomorphic expressions which could possibly suggest that a feature may be a fault and may have recent displacement. Key locations from which to examine the feature were recorded to facilitate examination during the field reconnaissance studies.

A.2.3 - Assignment of Remote Sensing Code Numbers

After lineaments were identified on remotely sensed data, recorded on mylar overlays, and screened using the length-distance criteria described in Section 3.2, they were assigned a 3-element remote sensing code number.

The first element of the remote sensing code number is a letter which designates the type of remote sensing imagery on which the lineament is expressed. The letter symbols used were:

A - LANDSAT IMAGE, MSS BAND 7, 1:500,000 scale print;

B - LANDSAT IMAGE, MSS BAND 7, 1:1,000,000 scale negative;

C - LANDSAT IMAGE, MSS BAND 5, 1:1,000,000 scale negative;

D - High-altitude near-infrared (IR) color print, approximately 1:125,000 scale;

E - Low-altitude black-and-white panchromatic print, approximately 1:20,000 to 1:50,000 scale.

The second element of the remote sensing code number consists of the flight line and frame identification number, for aerial photography, and the scene identification number, for LANDSAT imagery.

The third element of the remote sensing code number is a number from 1 to "n," for "n" number of lineaments which have centerpoints located on that particular photo or image. A small letter (e. g., 1a, 1b, 1c) can be used to identify splays, lineament segments, etc. that are considered to be part of a larger, through-going lineament.

Two examples of remote sensing map code numbers for a lineament are:

D13700-3 and D13700-3a

The first remote sensing code number identifies the lineament as lineament number 3 that has been interpreted on high-altitude, near-IR color photograph 700 taken on flightline 13. The second remote sensing code number identifies a lineament that is a splay off lineament D13700-3.

Only the third element of the remote sensing code number was marked on the photo or image overlay. The complete remote sensing code number was recorded in the space provided on the remote sensing lineament worksheet (Form SHP-4).

After the interpretation of the various types of remote sensing imagery was completed, all worksheets for a given lineament were reviewed. All geomorphic expressions and the corresponding key locations to be examined in the field were summarized in Items A.2 (Geomorphic) and A.4 respectively on the fault and lineament data summary sheet (Form SHP-3, shown in Figure A-6). The remote sensing code number was cited as the data source for these entries on Form SHP-3.

A.2.4 - Transfer of Lineaments Identified on Remotely Sensed Data to Base Maps

If a lineament interpreted during the remote sensing analysis did not duplicate the plotted location of a lineament or fault identified from the literature review, then the lineament was plotted on the map and assigned the next available map code number using procedures described in Section A.2.5 below. The map code number was recorded on Forms SHP-3 and SHP-4.

If a lineament or fault (identified from the literature review) had already been plotted in approximately the same location as a lineament identified during the remote sensing analysis, then the lineament was not added to the base map. Instead, the map code number for the feature already on the base map was assigned to the lineament and recorded on Form SHP-4. In addition, the remote sensing code number was listed in the Data Sources/References Section of Form SHP-3, and the geomorphic expression of the lineament was summarized on Form SHP-3.

If a lineament was longer than a lineament or fault which had already been plotted at the same location and if the center point of the longer lineament fell within a different 15 minute quadrangle, then a map code number was assigned to the longer lineament (using the procedure described in Section A.2.5 below) and the map code number for the longer lineament was assigned to replace the map code number for the shorter fault or lineament. This replacement involved immediate correction of forms filled out for the previously plotted shorter fault or lineament.

If a lineament was discovered to be a splay of, or closely parallel to, a previously plotted fault or lineament, then either a new map code number was assigned to the lineament or the existing map code number was modified (using the 1a, 1b designation described in Section A.2.3) and assigned to the lineament. If the latter procedure was used, Forms SHP-3 and SHP-4 were annotated to document the presence of subsidiary lineaments to the previously identified fault or lineament.

A.2.5 - Assignment of Map Code Numbers to Faults and Lineaments

Purpose

The purpose of this procedure was to provide the basis by which faults and lineaments evaluated during this study would be labeled. The alpha-numeric code (termed map code number) was assigned and used to identify faults and lineaments shown on project base maps, remote sensing overlays, and documentation forms.

Procedure

During the literature review and remotely sensed data interpretation, a map code number was used for each lineament or fault that was entered on the base maps and various documentation forms. The method of constructing the map code number for (a) faults and lineaments identified in the literature and (b) lineaments identified on remotely sensed data is described below.

All faults and lineaments (including those from published geophysical data) obtained from the literature review and located within the 62-mile (100-km) radius of both sites were plotted on base maps and assigned a 3-element map code number. In addition, the Castle Mountain fault and associated branches and splays which lie outside the 62-mile (100-km) radius were also assigned map code numbers because the fault is a boundary fault which was included in the scope of this investigation.

The first element of the map code number is a one letter symbol which designates the 2° quadrangle map on which the approximate center point of the fault or lineament is located. The letter symbols for the appropriate 2° quadrangle maps are as follows:

A - Anchorage
G - Gulkana
H - Healy
M - McKinley
T - Talkeetna
K - Talkeetna Mountains
V - Tyonek
X - Mt. Hayes

The second element of the map code number is a two-unit alphanumeric symbol which describes the 15 minute quadrangle map on which the approximate center point of the fault or lineament is located. This alpha-numeric symbol is based on the U. S. Geological Survey's letter/number matrix that identifies the 15 minute quadrangle maps within each 2° quadrangle map, as indicated below.

6	5	4	3	2	1	
						D
						C
			X			B
						A

For example, within the Talkeetna 2° quadrangle map, B3 would denote the location of the 15-minute quadrangle map in the south-central portion of the 2° quadrangle map as indicated by the X in the above illustration.

The third element of the map code number is a number from 1 to "n" for "n" number of faults or lineaments which have center-points located on the 15-minute quadrangle map just described. A small letter (e. g., 1a, 1b, 1c) is used to identify fault splays, fault segments, etc. that are considered to be part of a larger through-going fault or lineament.

Two examples of a map code number for a fault or lineament are:

TB3-3 and TB3-3a

The first map code number identifies the feature as fault or lineament number 3 having a centerpoint in the B3 15-minute quadrangle of the Talkeetna 2° quadrangle. The second map code number identifies a fault or lineament that is a splay off the fault or lineament TB3-3.

A.2.6 - Completion of the Fault and Lineament Data Summary Sheet (Form SHP-3)

Purpose

The fault and lineament data summary sheet (Form SHP-3, Figure A-6) is the key form of the project. Its purpose is: (1) to summarize the information used to identify and characterize (a) faults or lineaments described in the literature or (b) lineaments identified by remotely sensed data interpretation which meet the length-distance screening criteria; and (2) to track the progress of the field work for each feature and to verify that work has been completed or that additional field studies are considered necessary.

Procedures

The fault and lineament data summary sheet (Form SHP-3) has been completed as described below for every fault or lineament identified in the literature and for all lineaments identified on remotely sensed data meeting the project screening criteria.

Faults and Lineaments Identified in the Literature

Section A.1 was completed for all faults and lineaments identified in the literature including those inferred from geophysical data by Woodward-Clyde Consultants or by others.

If the fault or lineament was judged not to be a candidate significant feature on the basis of the length-distance screening criteria (described in Section 3.2), "No" was written after "Significant Feature?" The person making the evaluation then initialed and dated the decision on the back of Form SHP-3. No other data were entered on the form and it was filed in the project master file.

If the fault or lineament was judged to be a significant feature on the basis of the length-distance screening criteria, "Yes" was written after "Significant Feature?" The person making the evaluation then initialed and dated that decision on the back of form SHP-3. The remainder of the form was completed with all applicable data as described in the following paragraphs.

Sections A.2 through A.4 were completed prior to the field reconnaissance studies. Applicable data were summarized and keyed to the appropriate data source or reference cited on the back of the form. Section A.4 was of particular importance to facilitate field checking of the feature.

Section B was completed during the field reconnaissance studies. Section B.1 was completed after the initial examination of the feature during the field reconnaissance studies. If additional work was judged to be necessary, Items B.2 and B.3 were completed as appropriate.

Lineaments Identified on Remotely Sensed Data

Sections A and B were completed for all lineaments that met length-distance screening criteria. The procedures for completing the form were the same as those discussed above for faults and lineaments.

References and Data Sources

All references and data sources were entered on the back of the form. Reference citations include the author(s) and date. Each data source or reference was assigned a number. This number is listed in Section A following pertinent data from the references or data source.

A.3 - Field Reconnaissance Study Documentation Procedures

Purpose

During the field reconnaissance studies, the procedures described below were used to observe candidate features and to document the observations. As a part of these procedures, Forms SHP-6, SHP-7, and SHP-8 were used to maintain the uniformity of the data collected and recorded by the project team members.

Procedures

For maximum effectiveness, the field geologists ordinarily worked in two-person teams. During aerial reconnaissance, the geologist seated in the front of the aircraft had primary responsibility for navigation, as well as responsibility for observations of morphologic features visible from his or her side of the aircraft. The second geologist, who occupied a rear seat on the same side of the aircraft, had primary responsibility for documentation of information relating both to his or her own observations and that of the other team member and had a secondary responsibility for verifying the locations of the observations. Photography of the features observed was a shared responsibility. In order to gain the fullest benefit of the experience of each member of the field team and to ensure a common basis for arriving at an informed opinion about the origin of the observed features, each previously identified lineament was flown in both directions.

For some long faults or lineaments, it was necessary to examine the feature in detail at a number of different locations. Aircraft landings were made, where possible, to study fault-related features and features that could possibly have been related to recent fault displacement. Each location which was studied in detail along a given feature was given a separate site number, and a copy of Form SHP-6 was completed for these locations. Each landing site was marked on the appropriate 15-minute quadrangle map with a given symbol. Where appropriate, measurements were made of: the strike and dip of features; slopes of the ground surface; length and height of scarps; and the amount of displacement or diversion of streams. Measurements were taken by Brunton compass, by estimation, or by pacing. Where appropriate, samples of bedrock were collected and labeled, and bedrock geology was mapped in selected areas.

Color 35-millimeter photographs were taken of all faults and lineaments. Photographic data recorded in the field on the photo log (Form SHP-7 shown in Figure A-8) included the map code number of the fault or lineament, the site number, the photograph look direction, the orientation of the lineament in the photograph, and significant observations.

A.3.1 - Completion of Field Observation Documentation Sheet (Form SHP-6)

Purpose

The purpose of Form SHP-6 (shown in Figure A-7) was to document observations made for candidate features during field reconnaissance studies. The form was designed to facilitate the distinction between observations and interpretations.

Procedures

The field observation documentation sheet (Form SHP-6) was completed during aerial and ground reconnaissance for each candidate feature. All observations in the vicinity of the candidate feature were noted by checking the appropriate entries on Form SHP-6. The only interpretations recorded on the form were entered in Sections 3e and 3f for which interpretations of the origin of the feature and estimates of the age of the youngest unit displaced by the feature were made.

The study of a fault or lineament was considered complete when the field crew agreed that adequate data had been gathered. Whenever there was uncertainty or disagreement about the interpretation of the origin of a lineament that could have had recent or potentially recent displacement, a blue symbol was marked on the map and on Forms SHP-3 and SHP-6. This symbol indicated that the feature should be considered further by the principal investigator or by a senior reviewer. A copy of each form was given to the Project Geologist for evaluation by the appropriate personnel.

A.3.2 - Photography Documentation (Forms SHP-7 and SHP-8)

Purpose

The purpose of the photographic documentation forms (Forms SHP-7 and SHP-8) was to record all photographs taken for each roll of film and ultimately to record all photographs taken of a specific candidate feature. Figures A-8 and A-9 provide examples of these forms.

Procedures

Prior to the field reconnaissance study, each roll of film was assigned a project roll number (e. g., S-1, S-2). For each roll of film, the same project roll number was assigned to a copy of Form SHP-7. All photographs taken on a roll of film during the field reconnaissance study were recorded on the corresponding copy of Form SHP-7. During field reconnaissance studies, photographic data were recorded as discussed at the end of Section A.3 (immediately prior to Section A.3.1). When a roll of film was finished, the date of mailing for processing was recorded at the top of Form SHP-7, and the corresponding mailer stub was stapled to the form.

After the film was developed, all prints or slides were marked with the project roll number, frame number, and map code number. The photographs or slides applicable to the various faults or lineaments were recorded on the fault and lineament photo log (Form SHP-8) and were filed with the other data for that fault or lineament.

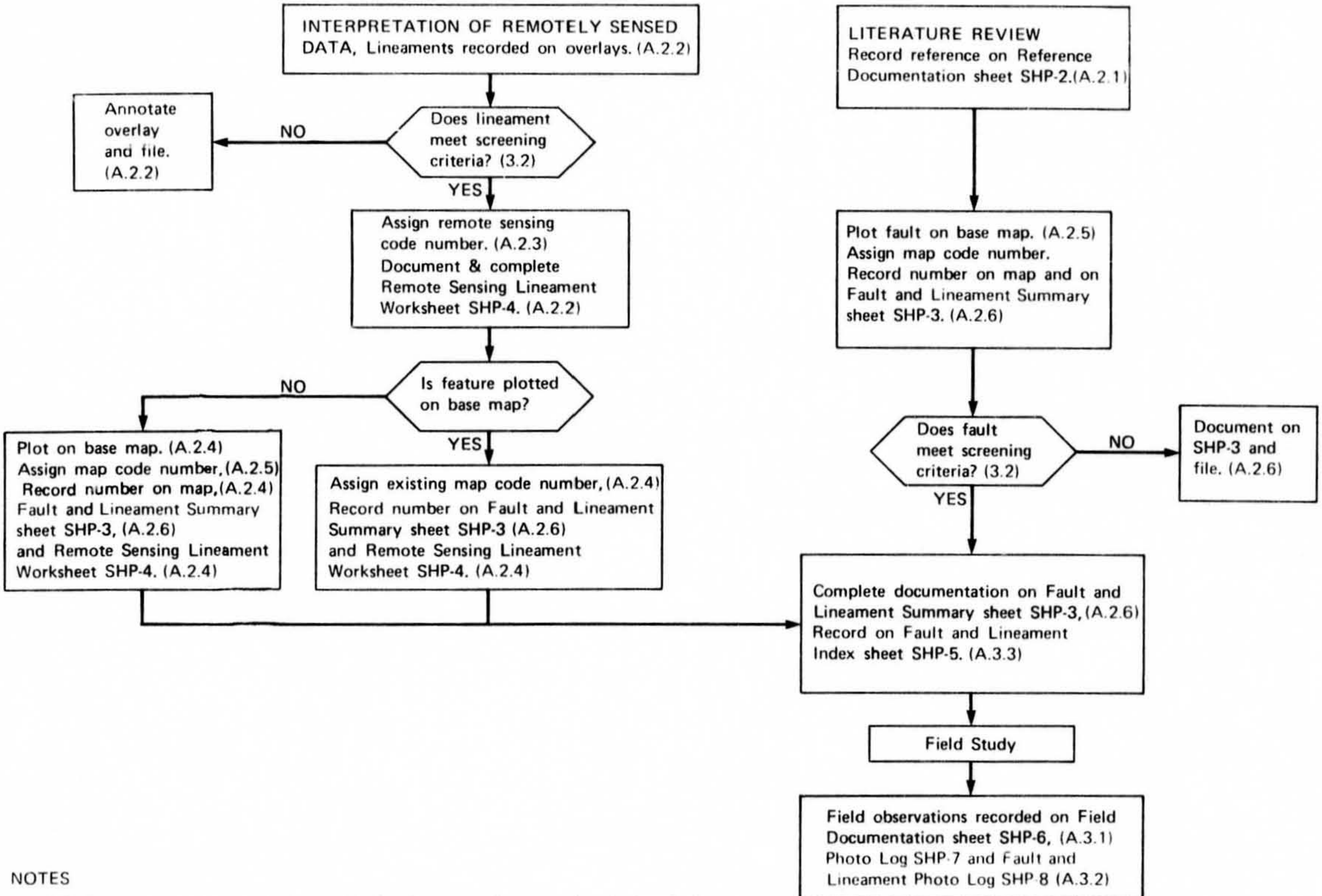
A.3.3 - Completion of Fault and Lineament Index Sheet (Form SHP-5)

Purpose

The purpose of this form (Form SHP-5, shown in Figure A-10) was to maintain a summary of the field examination of candidate features during the 1980 field reconnaissance studies. In addition, the evaluation of these features was monitored with this form.

Procedures

The information for the first three columns was obtained from the fault and lineament data summary sheet (Form SHP-3). Plotting of the features on the 1:250,000 scale base map and on 15-minute quadrangle maps was recorded in the appropriate column when completed. Examination and review in the field, and decisions regarding whether additional work was considered to be necessary were recorded in the appropriate columns during the field investigation. The last two columns were completed by the end of the 1980 field season.



NOTES

1. (A.2.1) is report section in which a particular documentation procedure is described.
2. SHP-4 is form number on which the documentation is recorded.

FLOW DIAGRAM OF DOCUMENTATION PROCEDURES

FIGURE A-1

GEOMORPHOLOGY/QUAT. GEOLOGY ( ) STRUCTURAL ( ) GEN. GEOLOGY ( ) RESOURCES ( )
HYDROLOGY ( ) REMOTE SENSING ( ) TECTONICS ( ) SEISMICITY ( ) AGE DATING ( )

REFERENCE DOCUMENTATION SHEET
SUSITNA HYDROELECTRIC PROJECT
Project No. 14658A

NAME: ______________________
DATE: ______________________
Copy in File: (yes) (no)

FULL CITATION: ______________________

USEFUL ILLUSTRATIONS, TITLES AND SCALES: ______________________

GEOGRAPHIC AREA COVERED: ______________________

SUMMARY OF CONTENT AND QUALITY OF REPORT WITH RESPECT TO PROJECT: ______________________

DATA USEFUL ( ) Not Useful ( ) Explain: ______________________

STRUCTURAL ELEMENTS IDENTIFIED (ASSIGN IDENT. NUMBER, FILL OUT DATA SHEET, FOR EACH LOCATE ON BASE MAP).

FAULTS	LINEAMENTS

(continue listing on back of page)

REFERENCE DOCUMENTATION SHEET (FORM SHP-2)

FIGURE A-2

SUSITNA HYDROELECTRIC PROJECT
14658A - Task 4

IMAGE/PHOTO TYPE: ____________ REMOTE SENSING CODE NO. ____________________

IMAGE/PHOTO NO. ____________ FLIGHTLINE NO. ____________ MAP CODE NO. ________

SCALE ____________ DATE FLOWN ____________ IMAGE QUALITY: Good Fair Poor

WAVELENGTH SENSITIVITY ____________________ QUAD MAP ____________________

LINEAMENT DESCRIPTION By ____________ DATE ____________

LENGTH ____________________ ORIENTATION ____________________

GEOMORPHIC EXPRESSION:

KEY LOCATIONS TO EXAMINE:

SECOND INTERPRETER'S COMMENTS BY ____________________ DATE ____________

SHP-4 Page 1 of 1 Revision #1 10 April 1980

REMOTE SENSING LINEAMENT WORKSHEET (FORM SHP-4)

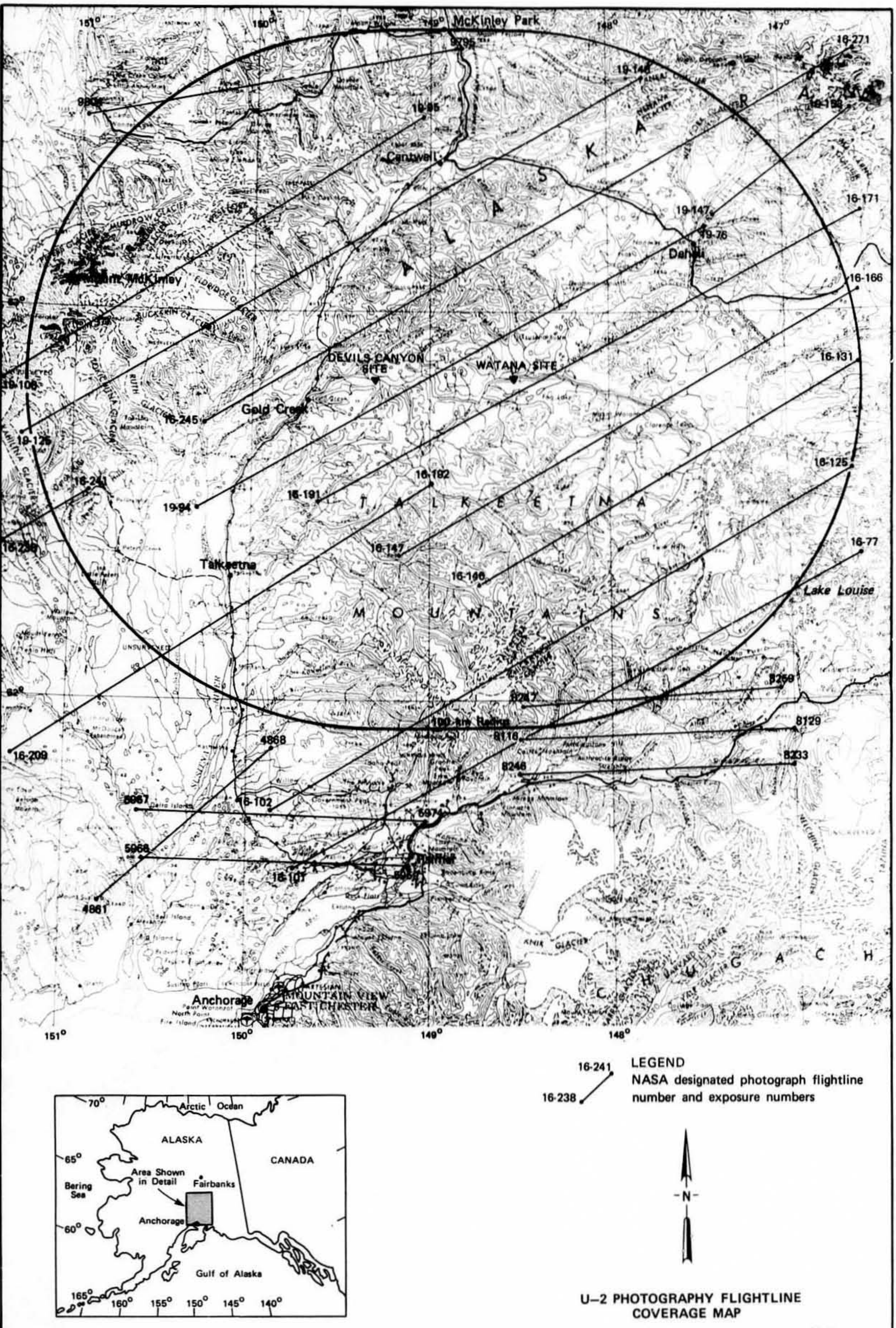
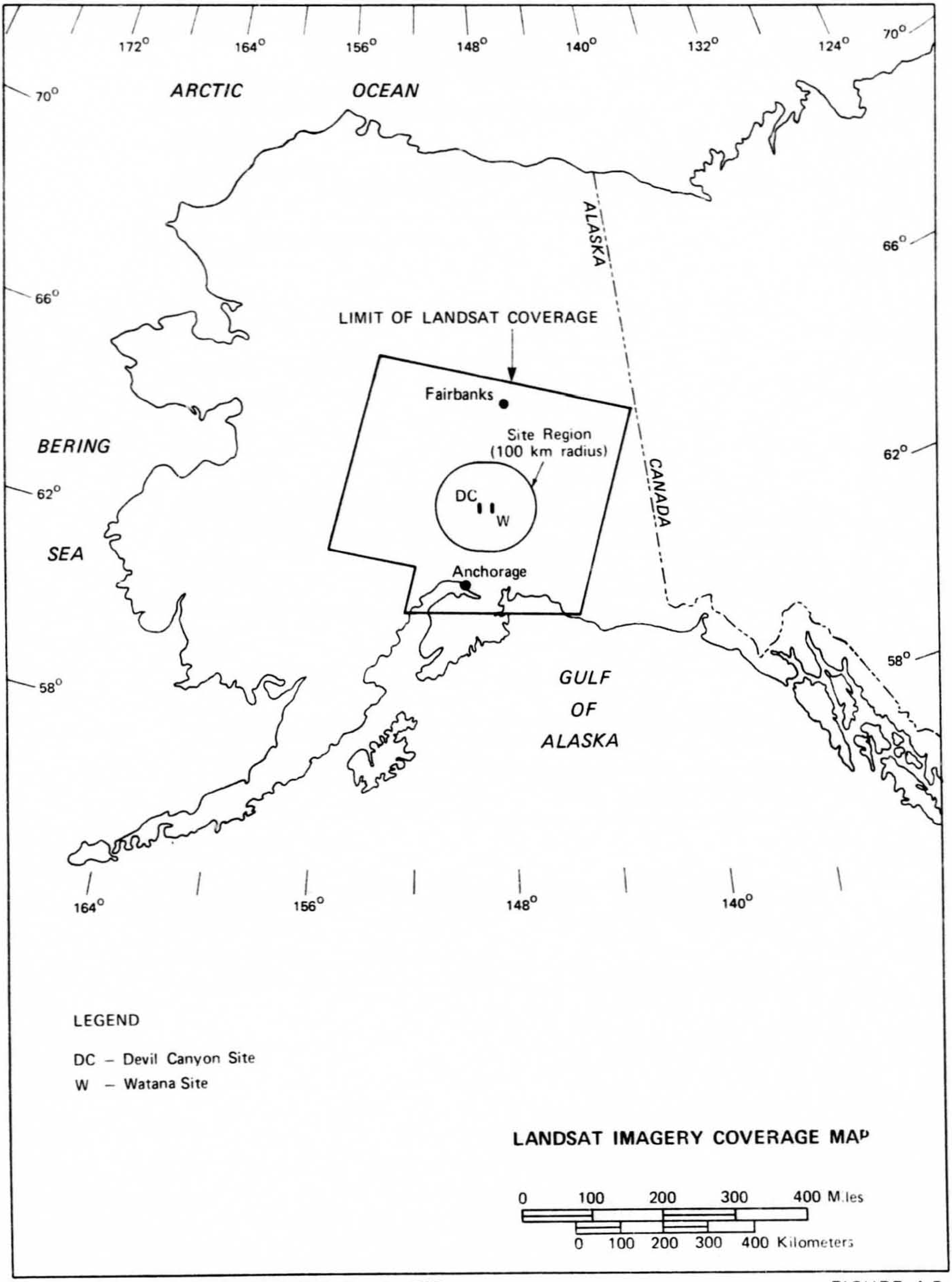
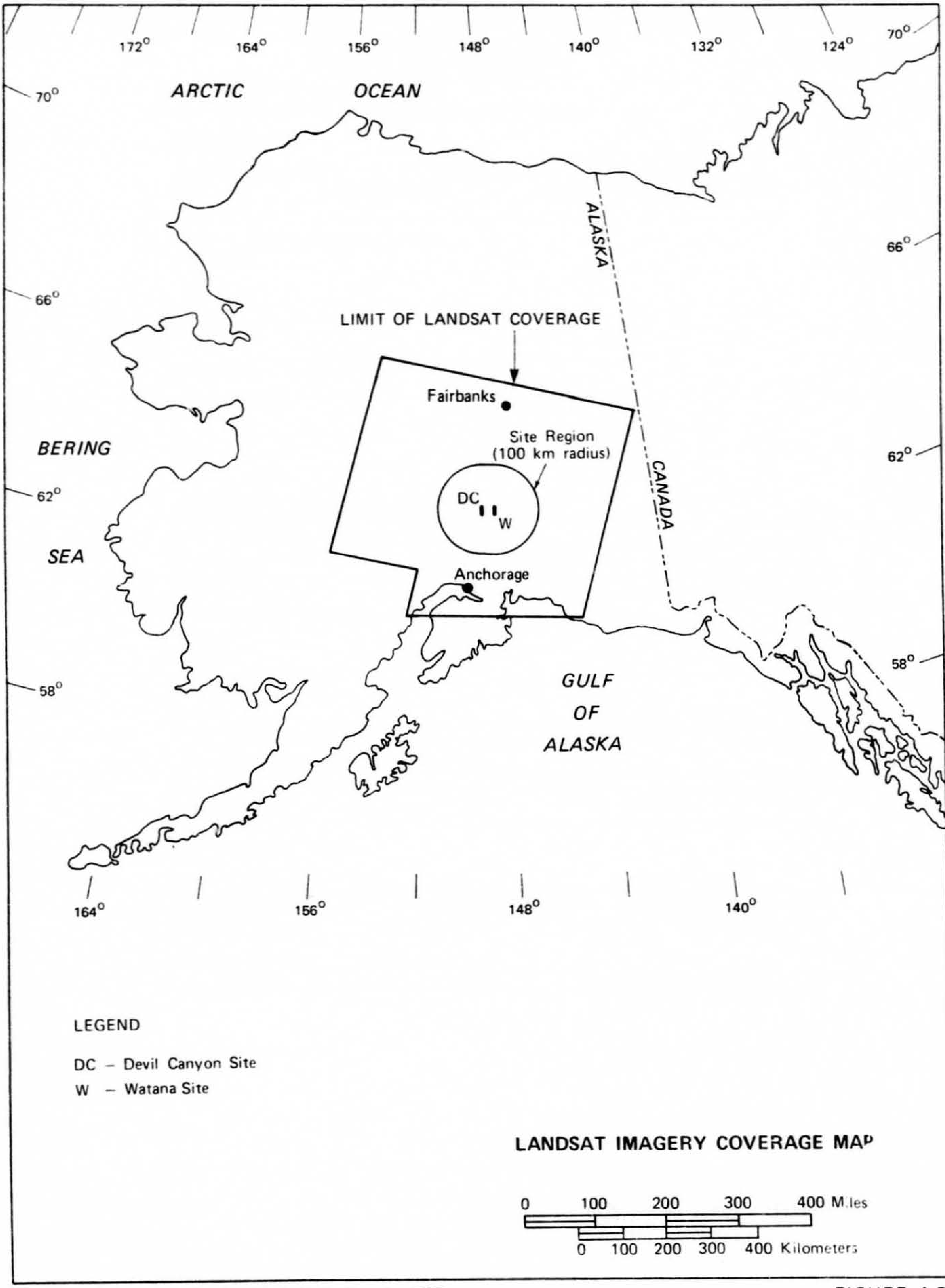

McKinley Park
Cantwell
Denali
Mount McKinley
DEVILS CANYON SITE
WATANA SITE
Gold Creek
Talkeetna
Lake Louise
Anchorage
MOUNTAIN VIEW
A L A S K A R A N G E
T A L K E E T N A M O U N T A I N S
C H U G A C H
RUTH GLACIER
ELDRIDGE GLACIER
BUCKSKIN GLACIER
KNIK GLACIER
151°
150°
149°
148°
147°
16-271
16-171
16-166
16-131
16-125
16-77
19-147
19-76
19-146
16-95
16-108
19-126
16-245
16-241
16-238
19-94
16-191
16-192
16-147
16-166
16-209
16-102
16-101
4868
4861
5968
5967
8129
8233
8247
8246
8116
LEGEND
16-241
16-238
NASA designated photograph flightline number and exposure numbers
N
Arctic Ocean
ALASKA
CANADA
Bering Sea
Area Shown in Detail
Fairbanks
Anchorage
Gulf of Alaska
70°
65°
60°
165°
160°
155°
150°
145°
140°
U–2 PHOTOGRAPHY FLIGHTLINE COVERAGE MAP
0 10 20 30 40 50 Miles
0 10 20 30 40 50 60 70 Kilometers

FIGURE A-4



LANDSAT IMAGERY COVERAGE MAP



LANDSAT IMAGERY COVERAGE MAP

FAULT AND LINEAMENT DATA SUMMARY SHEET
SUSITNA HYDROELECTRIC PROJECT
14658A - Task 4

A. DATA FROM LITERATURE OR REMOTE SENSING INTERPRETATION

1. CHARACTERISTICS:
FEATURE NAME ______ FAULT ( ) LINEAMENT ( ) MAP CODE NO. ______
DIST. FROM SITE (MI) ______ LENGTH (MI) ______ SIGNIFICANT FEATURE? ______
WIDTH (FT) ______ ORIENTATION ______ LOCATION RELATIVE TO DAM/RESERVOIRS ______

2. EVIDENCE USED TO IDENTIFY FEATURE:
GEOMORPHIC

GEOLOGIC

GEOPHYSICAL

SEISMOLOGICAL

OTHER

3. CHARACTERISTICS OF FEATURE IDENTIFIED AS A FAULT:
FAULT TYPE: NORMAL ( ) THRUST ( ) REVERSE ( ) STRIKE-SLIP ( ) OBLIQUE-SLIP ( )
UNITS OR FEATURES DISPLACED, AGE, AMOUNT: ______

EVIDENCE FOR ACTIVE OR INACTIVE FAULT:

GEOLOGIC

SEISMOLOGIC

GEODETIC ______ SLIP RATE ______
MAX. ASSOCIATED EARTHQUAKE ______ FAULT PLANE SOLUTION(S) ______

4. LOCATIONS TO EXAMINE FEATURE: ______

B. FIELD INVESTIGATION SUMMARY

1. INITIAL FIELD RECON: DATE ______ BY ______
2. ADD. AERIAL RECON. NEEDED? ______ DATE CONDUCTED ______ BY ______
3. GROUND STUDIES NEEDED? ______ DATE CONDUCTED ______ BY ______
4. ORIGIN OF FEATURE

5. CONSIDER TRENCHING ____ LOCATION ______

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FAULT AND LINEAMENT DATA SUMMARY SHEET (FORM SHP-3)

FIELD OBSERVATION DOCUMENTATION SHEET

SUSITNA HYDROELECTRIC PROJECT

14658A - Task 4

Map Code No.________________ (Fault) (Lineament): Site No.________________

Location of field observation: ____

____

Quadrangle map ____________ Date ______________ Participants ________________

Documentation: Tape No.________________ Side ______________

Photographs: Roll ______ Numbers _______ Other ________________________________

1. FEATURE TYPE

A. Morphologic:

___ Break in slope; ___ Linear streams; ___ Ridge; ___ Trench; ___ Saddles; ___ Lithologic contrast

B. Nonmorphologic: ___ Vegetation line of ______________;

___ Vegetation contrast between ____

___ Cultural feature ________________; ___ Other ________________________

2. FEATURE MORPHOLOGY

A. Descriptive Classification: ___ Slope; ___ Ridge; ___ Terrace; ___ Plateau; ___ Tundra; ___ Plain;

___ Rolling hills; ___ Hummocks; ___ Fan or cone; ___ Valley; ___ Canyon; ___ Other ________________

B. Genetic Classification: ___ Floodplain; ___ Bar, meander scar; ___ Shoreline; ___ Sand Dunes; ___ Loess;

___ Solifluction

C. Features of Special Interest: Displaced features along lineament (yes) (no);

Type of offset feature: ___ Terrace; ___ Moraine; ___ Stream; ___ Fan; ___ Other ________________

Sense of offset ___________; Amount of offset __________; Age of offset ________________

Alluvial fans along lineament (yes) (no); Terraces crossing lineament (yes) (no);

Scarp along lineament (yes) (no); Description ________________________________

____

D. Geomorphic Fault Features: ___ Folded or warped deposits; ___ Open fissure; ___ Triangular facets;

___ Sag pond or sag; ___ Graben; ___ Other ________________________________

Feature in ____

3. FEATURE GEOLOGY

A. Feature In: ___ Bedrock; ___ Unconsolidated sediment; ___ both

B. Bedrock Type: ___ Igneous; ___ Volcanic; ___ Sedimentary; ___ Metamorphic;

C. Unconsolidated Sediment Origin: ___ Fluvial; ___ Colluvial; ___ Aeolian; ___ Lacustrine; ___ Glacial; ___ Volcanic;

___ Mass Wasting

D. Unconsolidated Sediment Character: ___ Bedded; ___ Unbedded; ___ Sorted; ___ Unsorted; ___ Clay; ___ Silt; ___ Sand;

___ Gravel

E. Youngest Unit Crossed by Lineament: ________________________ Age ________________

F. Origin of Lineament: ____

4. HYDROLOGIC CHARACTERISTICS

A. Surface: ___ Lakeshore; ___ Ponds or marsh; ___ Stream diversion; ___ Stream entrenchment; ___ Snow banks

B. Subsurface: ___ Groundwater barrier; ___ Cold springs; ___ Hot springs; ___ Pingo; ___ Solifluction lobes

5. SCARP DESCRIPTION

A. Dimensions: Slope (Max.) ____; Slope (Avg.) ____; Height (Max.) ____ Height (Avg.) ____

B. Linearity: ___ Linear; ___ Curvilinear; ___ Sinuous; Strike ________________

C. Scarp Character: ___ Continuous; ___ Discontinuous; ___ En echelon; ___ Ramps; ___ Parallel; ___ Branching

D. Scarp Modification: ___ Rilled; ___ Gullied; ___ Breached; ___ Rounded; ___ Beveled; ___ Buried; ___ Landslides;

___ Exposed bedrock

6. COMMENTS: (Use back of form for additional space)

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FIELD OBSERVATION DOCUMENTATION SHEET (FORM SHP-6)

SUSITNA HYDROELECTRIC PROJECT
14658A - Task 4
PHOTO LOG

Role No. _______ Name _______________________ Date _______________
Film Type _______________ No. of Frames _______ ASA _______________
Film sent for processing: To _______________ By _________ Date _________
Film received from processor: Date _________
Photos sorted by fault/lineament; by _______________________ Date _________

Photo No.	Map Code No.	Site No.	15 Minute Quad.	Look Direction	Orientation of Feature on Photo	Subject Description/ Significant Features
1						
2						
3						
4						
5						
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PHOTO LOG
(FORM SHP-7)

FAULT AND LINEAMENT PHOTO LOG
SUSITNA HYDROELECTRIC PROJECT
14658A - Task 4

Fault or Lineament's Map Code No. ______________________

Roll- No.	Photo No.	Site No.	15 Minute Quad.	Look Direction	Orientation of Feature on Photo	Subject Description/ Significant Features

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FAULT AND LINEAMENT PHOTO LOG (FORM SHP-8)

FAULT AND LINEAMENT
INDEX SHEET
SUSITNA HYDROELECTRIC PROJECT
14658A - Task 4

Map Code No.	Quad	Feature Name	Plotted on 15' map By Date	Examined in Field By Date	Add. Examination Needed Yes/No		Add. Examination Completed By Date	Ground Exam. Needed Yes/No		Ground Exam. Completed By Date	Reviewed By Date	Active Fault Yes/No		Candidate Significant Fault Yes/No

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FAULT AND LINEAMENT INDEX SHEET (FORM SHP-5)

APPENDIX B - 1980 MICROEARTHQUAKE NETWORK INSTALLATION, OPERATION, AND MAINTENANCE PROCEDURES

B.1 - Site Selection

Preliminary site selections based on available photos and maps were made before the fieldwork began. When helicopter access became available in the last two weeks of June, 1980, these selections were refined on the basis of the following requirements:

- The sites must be within 30 miles (48 km) of the Project sites;
- The network must provide good geometrical coverage around the sites;
- The sites must be easily accessible by helicopter;
- The sites must be on or near competent bedrock;
- The sites must provide good telemetry paths to the Watana Base Camp recording site; and
- To allow for high signal amplification, the sites must be relatively free of background noise created by wind, water, and cultural activities.

Table B-1 lists the locations, elevations, and operating periods of all stations used in the study. Three stations (DPC, DCR, GRB) were moved during the study to provide better location control around a cluster of small earthquakes. The new locations, TKR, SBL, and UPG were selected on the basis of the same criteria. The network configuration, as shown in Figure B-1, allowed for earthquake location in the study area even if one or two stations were inoperable at the time of an event.

B.2 - Instrumentation

Two types of microearthquake recording instruments were used for the field monitoring program. The first instrument, the Sprengnether MEQ-800 seismographic recorder, is a battery-powered drum recorder which provides a continuous analog paper record. Voltage signals from the seismometer are amplified and drive a galvanometer, which traces the amplified signals onto a rotating smoked-paper drum with a sapphire stylus. The instrument is equipped with selectable frequency filters to reduce background seismic noise that may obscure earthquake data. Recording is continuous until space on the drum is exhausted, at which time the smoked paper must be changed. An accurately adjusted quartz oscillator clock provides precise timing marks that are superimposed on the record. The internal clock is synchronized to an external reference clock when the records are changed.

Eight MEQ-800 recorders were operated at Watana Base Camp using telemetered signals from the remote seismograph station sites. These eight stations that telemetered the data to the base camp were equipped with a Mark Products L-4C vertical component, short period (1 Hz) seismometer and an electronics package containing a Sprengnether AS-110 amplifier, Sprengnether TC-10 Voltage Controlled Oscillator (VCO), and a Monitrom 100 mw radio transmitter. The voltage signal from the seismometer was amplified and converted to a varying-frequency audio tone that was then transmitted by FM radio. The various tones were received by a FM radio receiver at the base camp, demodulated using a Sprengnether TC-20 discriminator, and recorded on the MEQ-800 recorders. In some cases, several VCO tones were multiplexed. Both transmitter and receiver employed Scala antennas. The transmitter station was powered by two 2.5 volt Edison Carbonaire batteries with a DC-DC converter which stepped up the voltage to 12 volts. Watana Base Camp recorders were powered by four 12-volt lead acid batteries that were recharged using the camp generator.

The second type of instrument used in this study was a Sprengnether DR-100 three-component digital event recorder. The DR-100 is designed to record intermittently only when a signal is identified as an earthquake according to programmed criteria. When an earthquake is detected, the recorder is triggered and the signal is recorded on a magnetic tape cassette. The frequency of tape-changes on a DR-100 instrument depends upon the level of seismic activity in the area and upon the success with which the instrument was adjusted to discriminate between noise signals and earthquakes. The three sensors for the DR-100 are also Mark Products L-4C seismometers--one is vertically and two are horizontally oriented (north-south and east-west). The vertical seismometer acts as the signal source for the detection algorithm.

The operation of the DR-100 is much more complex than that of the MEQ-800. Signals from the seismometers are amplified and converted from analog to digital form before being processed. A logic circuit monitors the incoming vertical-component digital signal and determines if it is an earthquake signal. When the trigger criteria are satisfied, the data from all three components are retrieved from digital memory and are recorded on cassette tape. The DR-100 provides an accurate time record in a manner similar to that of the MEQ-800.

The triggering criteria are programmed in the field and depend upon the level and nature of the background noise present at each site. At sites having a low and constant background noise level, it is possible to set the triggering criteria to permit the detection of very small earthquakes and still to have a tape last for long periods. To prevent the tape from running out too quickly, sites that are subject to large, occasional noise signals, such as those generated by passing vehicles, must have the triggering criteria adjusted so the instrument is less sensitive to small signals, including small earthquakes.

For time corrections, the internal clock of the DR-100 is synchronized to an external reference clock. For this study, the synchronization was achieved during field operations by using a Sprengnether TS-400 time reference; this is a portable quartz oscillator clock similar in design to the integral clock of the MEQ-800 seismograph. The reference clock was calibrated to the international radio time standard, station WWV, using a radio time receiver and an oscilloscope. This allowed timing accuracy to within several hundredths of a second.

Two DR-100 three-component stations were installed, one at the Watana dam site (WAT) and the other at the Devil Canyon dam site (DEV). Each station was powered by three 12-volt lead acid batteries. The seismometer signals were first amplified with Sprengnether AS-110 amplifiers before being sent to the DR-100 recorders.

B.3 - Installation, Operation, and Record Changing

The microearthquake network (Figure B-1) was installed during late June and the first week in July, 1980, and operation began on the dates listed in Table B-1 and shown in Figure B-2. Once the stations were installed, a program of maintenance and record changing was established. The frequency of visits to the stations WAT and DEV depended upon the rate of triggering on the DR-100's (that is, on the level of seismic activity). On the average, 15 to 20 triggered events could be written on a 15-minute magnetic tape. An average of 4 to 10 events per day triggered the DR-100's during the monitoring period, so the magnetic tape lasted 2 to 3 days. Thus, record changing was performed every other day, except in bad weather. Even if the two digital stations were not operating, coverage was provided by the continuous telemetry system. The DR-100 stations required further adjustment of their trigger settings during the initial monitoring. All transportation from Watana Base Camp to the network stations was accomplished by helicopter. Routine maintenance of the DR-100's consisted of checking and synchronizing the internal clocks with the TS-400 reference clock, checking the voltage level of the batteries, and verifying the proper operation of the recorder.

The eight MEQ-800 smoked paper records required changing every 24 hours. A total of sixteen drums were kept at the base camp so that one set of eight could be papered and smoked with carbon-black while the other eight were recording data. Records were fixed (made permanent) with a shellac/alcohol solution to prevent the carbon from rubbing off. Time corrections were made daily using an oscilloscope and the WWV radio time standard. The TS-400 reference clock was corrected daily in the same manner. Gain settings were adjusted to be as high as possible (66 to 78 db electronic amplification) but were reduced during periods of excessive noise, such as during high wind and heavy rain. Information that was noted on the back of each smoked paper record is shown in Figure B-3. Routine maintenance of the MEQ-800 recorders in the central recording station included changing low batteries, checking the telemetered center frequencies, and making sure the drums rotated properly. The routine maintenance checks and any changes in the status of the recording equipment in the central recording station were recorded daily in the central recording station log book. The MEQ-800 recorders were calibrated to give a pen deflection of 14 mm at a gain setting of 72 db with both filters out when a current of 120 micro amps at 6.2 volts was applied with a handcalibrator.

Figure B-2 shows the period of successful operation for each station during the three-month period. For some stations, malfunctions of the recorders or delays in changing records caused missed recording time. For the three-month period, 95% of all the possible recording time was successfully recorded with continuous coverage provided by seven or more stations. Table B-1 gives the removal dates for each station at the completion of the field season.

B.4 - Record Reading Procedures

Smoked paper records from the MEQ-800's and digital tapes from the DR-100's collected from the field were brought to Watana Base Camp for data reduction and analysis. Station information was recorded in the central recording station log book. Identification information for each of the magnetic tapes was listed in the DR-100 tape log book. Magnetic tapes were reproduced on a paper chart recorder, and every triggering event was identified by its "ON" and "OFF" time which was entered on a list of trigger events. The lists of triggered events for stations DEV and WAT were then compared to the MEQ preliminary reading sheets to identify any event that appeared on two or more station records. The paper analog records of these events were produced from the digital tapes using a Sprengnether DP-100 Digital Playback Unit and a strip-chart recorder.

All recorded events were then identified as being local, regional, or teleseismic earthquakes and were recorded on the MEQ-800 preliminary reading sheets (Figure B-4). A local earthquake was defined as an event that occurred within or near the boundaries of the network configuration (shown on Figure B-1). The distance of an event from a particular station can be quickly calculated by measuring the time difference between the shear (S) wave and the compressional (P) wave arrival times. Any earthquake having an S-P time of 10 seconds or less at all stations (which time corresponds to a distance of approximately 56 miles (90 km) was defined as a local event. Ten seconds was used as the cutoff for local status since the P-wave travel time between the two most distant stations in the net was approximately nine seconds. An event having an S-P time of 10 to 40 seconds was considered to be a regional earthquake; an event having an S-P time of greater than 40 seconds was classified as a teleseismic earthquake.

The P- and S-wave arrival times of the earthquakes were read from the records as precisely as possible. Arrival times could be measured with a precision of 0.025 second on the MEQ-800 records and 0.05 second on the DR-100 records. The P- and S-wave arrival times were entered on computer coding sheets in the format required for computer analysis.

The maximum amplitude of the waveform and the total signal duratic of the earthquakes recorded at each station were measured for use in magnitude calculations.

An important factor influencing the accuracy of locating earthquake epicenters is the accuracy with which arrival times are determined. Particular care was taken to time the seismic-wave arrivals with respect to an accurate common time base and to maintain the quality of timing for the many steps of the data reduction. The internal clock drift measured during each record change was also accounted for. Time corrections were calculated for the arrival times of events that were to be located and entered into the computer location program. The coding sheets were checked before entry into the computer by verifying the internal consistency of the entries and re-examining the preliminary reading sheets to verify timing information and number of stations recording the event.

Of equal importance to locating earthquake epicenters is the accuracy of the geographic locations of the seismograph stations. The stations were located on 1:63,360 maps from which the latitudes, longitudes, and elevations of the stations were measured. These data were also entered into the computer program.

Using the procedures described above, the epicenter and hypocenter uncertainty within the microearthquake network is estimated to be approximately 1.2 miles (2 km) with the uncertainty in hypocenter depth slightly greater than that for the epicenter location.

B.5 - Velocity Model

In addition to the arrival times and station locations, earthquake location computations require a crustal velocity model. On the basis of this model, the seismic ray travel times from hypocenter to each station are calculated.

Velocity models are best derived from the results of large scale seismic refraction and reflection studies. Alternatively, because approximate characteristic velocities of most rock types are known, models can be estimated on the basis of regional geologic data. This latter method is inferior to the former because regional geology models have not been verified beyond depths of a few hundred meters and because the seismic velocity can vary considerably in the various tectonic areas of the earth.

The velocity model used in this study (Table B-2) is a regional model developed by the University of Alaska Geophysical Institute (UAGI) (Biswas, 1980). It is the model presently employed by the UAGI for locating earthquakes in central Alaska. Few detailed crustal studies have been conducted in central Alaska, and little is known of the actual crustal velocity structure. However, the regional velocity model is probably representative of the actual velocity structure in the Talkeetna Terrain and is judged acceptable for use in the location of earthquakes in this study.

B.6 - Location of Microearthquakes

All local events (S-P wave arrivals of approximately 10 seconds or less) located during this study are listed in Appendix D. An event was located by computer if there were arrivals recorded at four or more stations. For this investigation, earthquakes of magnitude (M_L) approximately 0.5 to 1.0 or greater were large enough to be recorded at a sufficient number of stations and to be located by computer. Most earthquakes of magnitude less than 0.5 were noted but not located. Figure 9-4 shows the number of earthquakes per day which were located within the microearthquake study area.

Final earthquake hypocentral locations determined by computer were calculated using the program HYPOELLIPSE (Lee and Lahr, 1979). The inputs to the program are the station locations, velocity model, and the arrival times of P- and S-waves from an earthquake recorded by the station network. The origin time, latitude, longitude, and focal depth of an earthquake are calculated from these data. The calculation basically involves the solution of a time versus distance problem; the computer program calculates the four parameters by mathematically minimizing the difference between the observed and computed travel times by the iterative application of a least-squares process. Each observed S or P wave travel time is obtained from the observed station arrival time by subtracting the origin time obtained in the preceding iteration. Each computed travel time is obtained using the crustal velocity model and the epicentral distance based on the station location and the hypocentral location from the preceding iteration. The origin time and hypocentral location of the earthquake are initially fixed to correspond to the P-wave arrival time and to the location of the station having the earliest arrival time.

The program compares the residuals of all the stations in the least-square process and adjusts the trial hypocenter and origin time to new values that will reduce the size of the residuals. The calculation of residuals and the adjustment are then repeated until the program computes the solution that results in the statistically smallest set of residuals, and this solution is adopted as the origin time and hypocentral location of the earthquake. HYPOELLIPSE also performs a statistical analysis of how well the final solution fits the data; this "fit" gives an indication of the quality of the solution. Horizontal and vertical standard errors, in kilometers, of the solution are calculated.

B.7 - Earthquake Magnitude Determination Procedure

A common and accepted parameter for describing the size of earthquakes is local magnitude (M_L), which is based upon Richter's definition using amplitudes of earthquakes recorded on Wood-Anderson seismographs (Richter, 1958). As originally developed and as it has been applied, the magnitude scale gives a measure of the seismic energy released during the earthquake. Earthquakes having magnitudes larger than 5 are often damaging or destructive. Microearthquakes are considered to be earthquakes of magnitudes (M_L) less than 3.

Several methods for determining equivalent Richter magnitudes based on signal duration have been devised, including one that is based on a method used for earthquakes in central California (Lee and others, 1972). The method by Lee and others defines signal duration (coda) as the time from the P-wave arrival to the point where the signal-to-noise ratio is about 5. The equation used to calculate the magnitudes, with coefficients as used in Alaska by Lahr (1979) is:

$$M_L = -1.15 + 2 \log T + 0.0035D + 0.007H$$

where T is the coda duration (in seconds) measured from the time of the P-arrival to the time when the coda becomes less than 1.0 mm in peak-to-peak amplitude (about five times background noise level), D is the epicentral distance to the station in kilometers, and H is focal depth in kilometers. The duration magnitudes have an estimated accuracy of $\pm$ 1/4 magnitude units. One magnitude value is computed for each station in the network and these are averaged for a final value.

Magnitude values are also routinely computed at the UAGI. Their procedure uses amplitude and frequency measurements of the seismic records to determine equivalent Richter magnitudes. The formula used is as follows:

$$M_L = \log_{10} \left[A \cdot \frac{WA(f)}{G(f)} \right] - \log_{10} A_o$$

where

A is 1/2 the maximum peak-to-peak amplitude on the seismometer trace, in millimeters;

f is the frequency of the peak amplitude wave;

WA(f) is the gain at frequency f of a Wood-Anderson horizontal torsion seismometer;

G(f) is the gain at frequency f of a vertical-component seismometer (non Wood-Anderson) used by UAGI; and

A_o is the trace amplitude, in millimeters, for a standard earthquake as a function of the distance from the epicenter.

Magnitude estimates for UAGI data are generally considered accurate to within 1/2 (one-half) magnitude unit (Agnew, 1980).

B.8 - Focal Mechanisms

The pattern of the first ground motions produced by the P-waves of an earthquake recorded at seismograph stations distributed around an epicenter can reveal the orientation of the fault surface upon which the event occurred. Small earthquakes can indicate the same stress field as that of the less frequent large earthquakes. Thus, source mechanisms estimated from small earthquakes can be very important for understanding the regional geologic and tectonic environment.

To prepare a fault plane solution, the first motions for a particular earthquake are plotted on an equal-area stereographic net. The point representing the angle of emergence of the P-wave as it leaves the earthquake focus is plotted at the azimuth from the epicenter to the recording station. All rays are plotted on a lower hemisphere projection.

The possible fault planes and principle stress axes are interpreted from the first motion plots using the double-couple model of faulting. In this model, the maximum and minimum compressive stresses are orthogonal and produce orthogonal, conjugate nodal planes. The first motion quadrants formed by the conjugate nodal planes are characterized by alternating areas of compression and dilation, which correspond to up and down ground motion, respectively. The principal stress axes (maximum and minimum) lie midway between the orthogonal planes and are perpendicular at their line of intersection.

First motion plots are usually prepared for single earthquakes. However, to produce a well-defined focal mechanism, enough stations must have recorded the earthquake to show a clear pattern. The first motions from several earthquakes can be combined to form a composite first motion plot. The technique of forming composite first motion and interpreting focal mechanisms depends upon the assumption that the fault orientation and causative stress field remain the same for all the combined earthquakes.

B.9 - Blasting Identification

Individual explosions, such as quarry and mine blasts, can be significant sources of seismic energy (as large as magnitude M_L 3 ano, at the present state of the art, cannot be positively discriminated from earthquakes by simple inspection of the signal on the seismogram. However, repetitive blasts at the same location do produce very similar seismograms. If done regularly at about the same time, repeated blasting operations can be identified. No blasting sources were identified within the seismograph network for the Susitna Project.

TABLE B-1

MICROEARTHQUAKE STATION LOCATION AND OPERATION SUMMARY[1]

Station Code	Name	Latitude[2]	Longitude[2]	Elevation Meters[2]	Installation Date[3]	Removal Date[3]
WAC[4]	Watana Camp	62°50.2'N	148°30.9'W	822	20 June	4 July
WAT	Watana Dam Site	62°49.8'N	148°33.2'W	868	25 June	27 Sept.
Dev	Devil Canyon Dam Site	62°49.8'N	149°19.1'W	650	26 June	27 Sept.
DED	Deadman Mt.	63°03.7'N	148°13.6'W	1649	27 June	28 Sept.
JAY	Jay Creek	62°50.0'N	147°56.9'W	1203	27 June	28 Sept.
KOS	Kosina Creek	62°33.3'N	148°06.6'W	1250	28 June	27 Sept.
GRB	Grebe Mt.	62°36.9'N	148°51.9'W	1119	30 June	25 Aug.
DCR	Devil Creek	62°56.9'N	148°54.5'W	1356	1 July	25 Aug.
CNL	Chunilna Mt.	62°41.6'N	149°36.8'W	1192	2 July	26 Sept.
DPC	Disappointment Creek	62°32.9'N	149°27.6'W	1158	4 July	22 Aug.
HUR	Hurricane	62°57.5'N	149°33.5'W	1173	4 July	26 Sept.
TKR	Talkeetna River	62°27.45'N	148°45.26'W	1370	22 August	27 Sept.
UPG	Upper Grebe	62°34.95'N	148°52.89'W	1310	25 August	28 Sept.
SBL	Swimming Bear Lake	62°52.78'N	148°54.60'W	1155	30 August	28 Sept.

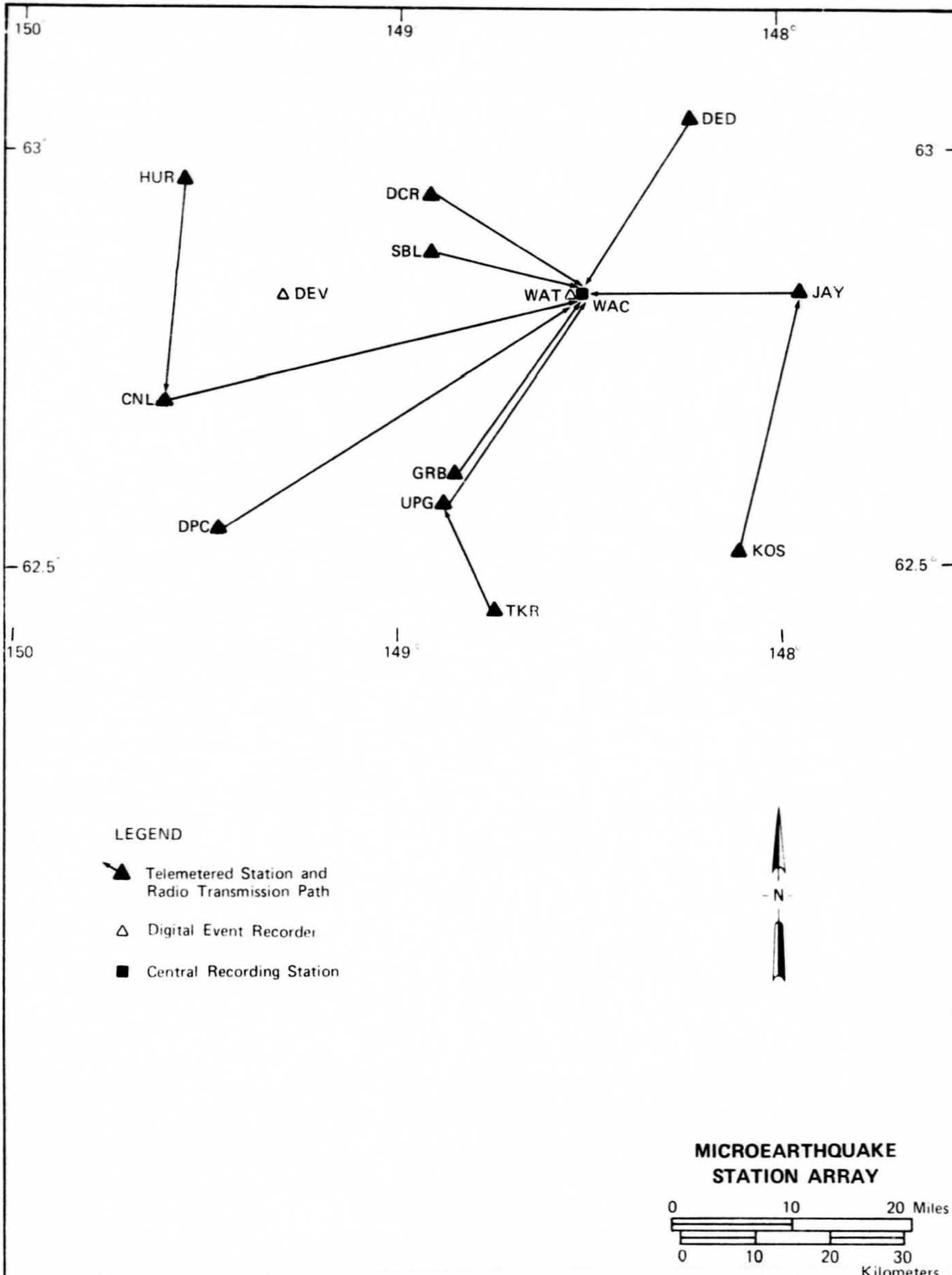
Notes:
1. Station locations are shown in Figure B-1.
2. Station location and elevation were scaled from 1:63,360 scale base maps on which stations were plotted during installation of the network.
3. Installation and removal dates are for 1980.
4. This was a temporary station installed for calibration purposes.

TABLE B-2

VELOCITY MODEL USED FOR 1980
MICROEARTHQUAKE DATA ANALYSIS

Depth (km)	Velocity of P-Wave (km/sec)
0.0 - 24.3	5.90
24.4 - 40.1	7.40
40.2 - 75.9	7.90
76.0 - 300.9	8.29
301.0 - 544.9	10.40
545.0 - deeper	12.60

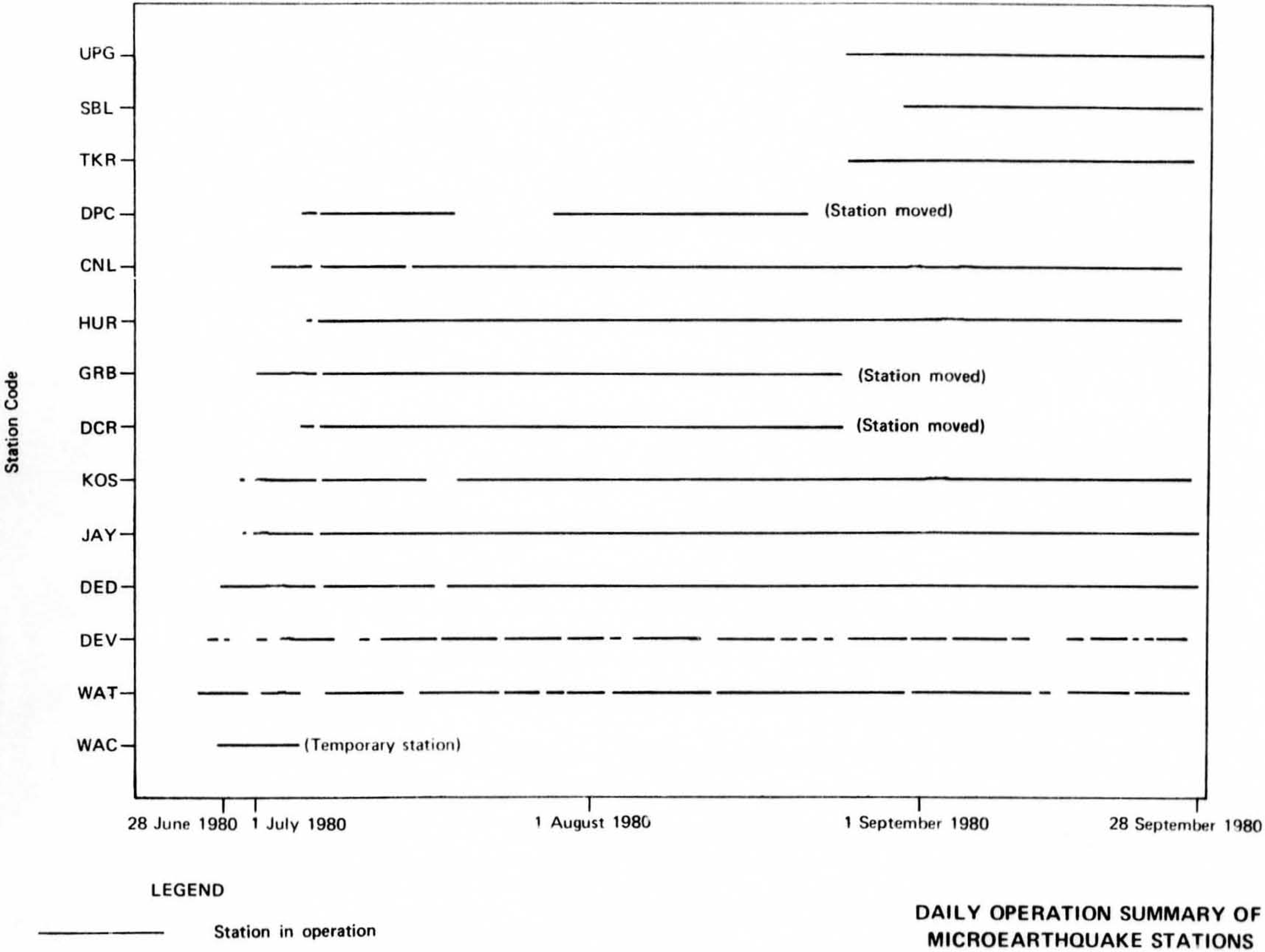
Note: 1. Data source is Biswas (1980).
2. S-wave velocity was determined from P-wave velocity for each layer by assuming Vp/Vs = 1.78.



MICROEARTHQUAKE STATION ARRAY

WOODWARD-CLYDE CONSULTANTS 14658A December 1980

FIGURE B-1



DAILY OPERATION SUMMARY OF MICROEARTHQUAKE STATIONS

FIGURE B-2

WOODWARD-CLYDE CONSULTANTS 14658A December 1980

PORTABLE MICROEARTHQUAKE SYSTEM
STATION DOCUMENTATION FORM
FOR MEQ-800

Station:______________________________ Project:____________________

ON: time_______ date _______ TC=__________ msec advanced @ __________
retarded
(circle)

OFF: time _______ date ______ TC=__________ msec advanced @ __________
retarded
(circle)

GAIN: ______________db FILTERS: high__________Hz low __________Hz

RECORD LENGTH:_______________hours MAX DEFLECTION _______________ mm

INTERNAL
BATTERIES: A _________________ B____________ OPERATOR ON __________
OPERATOR OFF __________

CAL PULSE: ____________mA @ ____________ db RECORDER #_______________

COMMENTS ____

____

____

____

____

Woodward-Clyde Consultants

SMOKED PAPER DATA SHEET

FIGURE B-3

PRELIMINARY READING SHEET

COMMENTS:
L - Local (S-P ≤ 10 sec.)
R - Regional (S-P > 10 sec.)
T - Teleseism
B - Blast
TR - Trace
? - Questionable event

CARD: yes
no

STATION READINGS:
I - readable, impulsive
E - readable, emergent
X - not readable

DATE ______ year month day Julian

READ BY ______ date: ______

REVIEWED BY ______ date: ______

PROJECT: ______

Time Hr-Min	Card	Remarks-Location	Comments	STATIONS												

FORM 21 REV. 1-9/24/79

Woodward-Clyde Consultants

MICROEARTHQUAKE PRELIMINARY READING SHEET

FIGURE B-4

APPENDIX C - HISTORICAL EARTHQUAKE CATALOG

This appendix lists instrumentally recorded earthquakes of (a) magnitude 4.0 or greater (includes all magnitude scales) or (b) intensity V or greater; the earthquakes are taken from the National Oceanic and Atmospheric Administration (NOAA) earthquake catalog within the following boundaries:

North boundary - 64°N Latitude
South boundary - 61°N Latitude
East boundary - 146.5°W Longitude
West boundary - 152°W Longitude

The earthquakes in the catalog are shown in Figures 4-4, 4-5, and 4-6. The explanation for the catalog headings in Table C-1 is as follows:

DATE - Date the earthquake occurred, in day, month, year, according to the origin time in Universal Coordinated Time (UCT).

TIME - Origin time of the earthquake, in hours, minutes, and seconds in Universal Coordinated Time (UCT).

LAT, LONG - North latitude and west longitude of epicenter in degrees.

INTEN - Modified Mercalli Intensity of the event from felt reports.

MAG - Magnitude of the earthquake.

SM - Type of magnitude determination.

N' - Magnitude is obtained from the source given in comments

MB - Body-wave magnitude (M_b)

MS - Surface-wave magnitude (M_s)

DIS - Not used.

H - Depth of earthquake (focal depth) in kilometers.

S - Source of location and magnitude values.

TABLE C-1

HISTORICAL EARTHQUAKE CATALOG

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL INTEN (MM)	MAG SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
1	27 AUG 1904	21:56:06.0	64.000N	151.000W	VI	8.30N'	25			N	REPORTED DAMAGE HYPOCENTER DEPTH ASSIGNED ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=8.30, AUTHORITY-PAS
2	31 JAN 1912	20:11:48.0	61.000N	147.500W		7.25N'	80			N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = G R MAGNITUDE(FRACTIONAL NOTATION,AVE)=7.25, AUTHORITY-DAS
3	7 JUL 1912	07:57:42.0	64.000N	147.000W		7.40N'				N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = G R MAGNITUDE(FRACTIONAL NOTATION,AVE)=7.40, AUTHORITY-DAS
4	17 JUL 1923	01:02:11.0	63.000N	147.000W		5.60N'				N	ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=5.60, AUTHORITY-PAS
5	24 FEB 1925	13:45:00.0	61.500N	149.000W	V				Z	N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = EQH NON-INSTRUMENTAL
6	21 JAN 1929	10:30:53.0	64.000N	148.000W		6.25N'				N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=6.25, AUTHORITY-PAS
7	3 JUL 1929	00:53:00.0	62.500N	149.000W		6.25N'				N	ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=6.25, AUTHORITY-PAS
8	4 JUL 1929	04:28:35.0	64.000N	148.000W		6.50N'				N	ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=6.50, AUTHORITY-PAS
9	29 MAY 1931	05:16:32.0	63.000N	149.000W		5.60N'				N	ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=5.60, AUTHORITY-PAS
10	17 OCT 1931	12:34:50.0	63.000N	147.000W	V	5.60N'				N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=5.60, AUTHORITY-PAS
11	14 SEP 1932	08:43:23.0	61.000N	148.000W	V	6.25N'	50			N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=6.25, AUTHORITY-PAS
12	4 JAN 1933	03:59:28.0	61.000N	148.000W	VI	6.25N'				N	REPORTED DAMAGE ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=6.25, AUTHORITY-PAS
13	4 JAN 1933	04:00:00.0	61.000N	147.000W	VI					N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = USE
14	27 APR 1933	02:36:00.0	62.000N	151.000W	VI					N	REPORTED DAMAGE ORIGINAL DATA SOURCE = USE

'AT. O.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL INTEN (MM)	MAG SM	H (KM)	DIS (KM)	Q	S	L O C A T I O N A N D C O M M E N T S
5	27 APR 1933	02:36:04.0	61.250N	150.750W	VII	7.00N'				N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=7.00, AUTHORITY-PAS
6	12 JUN 1933	15:23:38.0	61.500N	150.500W		5.60N'				N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=5.60, AUTHORITY-PAS
7	13 JUN 1933	22:19:47.0	61.000N	151.000W		6.25N'				N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=6.25, AUTHORITY-PAS
8	19 JUN 1933	18:47:43.0	61.250N	150.500W		6.00N'				N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=6.00, AUTHORITY-PAS
9	26 JUL 1933	04:57:26.0	63.000N	147.000W		5.60N'				N	ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=5.60, AUTHORITY-PAS
0	4 MAY 1934	04:36:00.0	61.000N	148.000W	VI					N	REPORTED DAMAGE ORIGINAL DATA SOURCE = USE
1	4 MAY 1934	04:36:07.0	61.250N	147.500W	VI	7.20N'	80			N	REPORTED DAMAGE ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=7.20, AUTHORITY-PAS
2	2 JUN 1934	16:45:29.0	61.250N	147.000W		6.25N'				N	ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=6.25, AUTHORITY-PAS
:3	2 AUG 1934	07:13:00.0	62.000N	148.000W	V					N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = USE
:4	2 AUG 1934	07:13:08.0	61.500N	147.500W	V	6.00N'				N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=6.00, AUTHORITY-PAS
5	18 JAN 1936	01:20:00.0	62.000N	152.000W		5.60N'				N	ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=5.60, AUTHORITY-PAS
6	23 OCT 1936	06:24:24.0	61.400N	149.700W	VI					N	REPORTED DAMAGE ORIGINAL DATA SOURCE = CGS
7	24 OCT 1937	11:36:12.0	61.000N	147.000W	V					N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = CGS
:8	30 JUL 1941	01:51:21.0	61.000N	151.000W	VI	6.25N'				N	REPORTED DAMAGE ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=6.25, AUTHORITY-PAS
'9	3 NOV 1943	14:32:17.0	61.750N	151.000W	V	7.30N'				N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = GUT

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
													MAGNITUDE(FRACTIONAL NOTATION,AVE)=7.30, AUTHORITY-PAS
30	3 NOV 1943	14:32:30.0	62.000N	151.000W		V						N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = USE
31	19 AUG 1948	13:50:46.0	63.000N	150.500W			6.25N'		100			N	QUALITBBB ORIGINAL DATA SOURCE = GUT MAGNITUDE(FRACTIONAL NOTATION,AVE)=6.25, AUTHORITY-PAS
32	25 JUN 1951	16:12:37.0	61.100N	150.100W		V	6.25N'		128			N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = ISS MAGNITUDE(FRACTIONAL NOTATION,AVE)=6.25, AUTHORITY-PAS
33	3 MAR 1954	20:46:07.0	61.500N	146.500W		V			60			N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = USE
34	23 AUG 1954	14:57:34.0	61.000N	148.500W		V						N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = USE
35	9 JUN 1956	02:26:57.0	64.000N	148.000W		V						N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = USE
36	3 JAN 1960	11:38:30.0	61.000N	152.000W		V						N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = CGS
37	10 MAR 1960	00:24:20.0	64.000N	149.000W		V						N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = CGS
38	10 MAY 1962	00:03:40.2	62.000N	150.100W		V	6.00N'		72			N	REPORTED FELT INFORMATION 020 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS MAGNITUDE(FRACTIONAL NOTATION,AVE)=6.00, AUTHORITY-BRK
39	29 JUN 1962	16:28:07.1	62.400N	152.000W		IV	4.75N'		50			N	REPORTED FELT INFORMATION ORIGINAL DATA SOURCE = CGS MAGNITUDE(FRACTIONAL NOTATION,AVE)=4.75, AUTHORITY-BRK
40	21 OCT 1962	02:05:22.7	61.100N	149.700W		VI			80			N	REPORTED DAMAGE 037 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
41	13 DEC 1962	14:57:27.9	61.400N	147.200W		V			69			N	REPORTED FELT INFORMATION 013 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
42	6 APR 1963	11:19:23.2	63.400N	149.600W			5.30MB		42			N	077 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
43	6 APR 1963	12:07:08.2	63.600N	149.700W			5.00MB		49			N	038 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS

TABLE C-1 (CONTINUED)

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
44	2 MAY 1963	23:13:09.4	63.100N	149.900W			6.10MB		79			N	019 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
45	11 JUN 1963	13:08:31.5	63.200N	151.400W			5.10MB		36			N	054 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
46	2 JUL 1963	02:52:55.8	64.000N	148.400W			4.00MB		33			N	005 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
47	22 AUG 1963	03:58:43.2	63.200N	148.500W			4.60MB		101			N	014 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
48	3 SEP 1963	12:59:52.3	61.900N	150.400W			4.00MB		116			N	007 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
49	22 SEP 1963	20:33:47.7	62.900N	148.800W			4.00MB		53			N	006 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
50	18 OCT 1963	08:05:22.1	62.600N	146.600W			4.20MB		51			N	REPORTED FELT INFORMATION 011 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
51	19 OCT 1963	11:19:31.8	62.400N	149.600W			4.30MB		96			N	009 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
52	22 NOV 1963	20:10:40.1	63.400N	150.000W			4.10MB		156			N	006 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
53	24 NOV 1963	17:48:47.0	61.800N	149.500W			4.30MB		36			N	009 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
54	14 DEC 1963	07:51:07.9	62.700N	149.500W			5.10MB		95			N	025 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
55	5 JAN 1964	01:31:27.0	61.900N	149.500W			4.60MB		72			N	011 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
56	28 JAN 1964	18:30:43.9	61.200N	147.800W			4.00MB		172			N	007 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
57	31 JAN 1964	04:17:12.4	61.500N	151.900W			4.90MB		33			N	038 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
58	7 MAR 1964	23:06:27.7	61.600N	151.400W			4.40MB		72			N	008 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
59	22 MAR 1964	06:22:15.1	61.300N	147.800W			4.50MB		62			N	014 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
60	28 MAR 1964	03:36:14.0	61.040N	147.730W		IX	8.50N'		33		S	N	UPLIFT/SUBSIDENCE ASSOCIATED WITH EARTHQUAKE TSUNAMI GENERATED BY EARTHQUAKE

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
													SEICHE ASSOCIATED WITH EARTHQUAKE REPORTED CASUALTIES HYPOCENTER SOLUTION DEPTH RESTRAINED BY GEOPHYSICIST 181 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION MORE ACCURATE SOLUTION BASED ON DETAILED LOCAL DATA ORIGINAL DATA SOURCE = CGS ISOSEISMAL MAP PUBLISHED BY USE MAGNITUDE = 8.3 USING NOAA AVERAGE MS (IASPEI FORMULA) MAGNITUDE(FRACTIONAL NOTATION,AVE)=8.50, AUTHORITY-PAS
61	28 MAR 1964	09:26:16.5	61.300N	148.800W			4.40MB		33			N	013 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
62	28 MAR 1964	13:54:19.9	62.100N	147.100W			4.60MB		15			N	015 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
63	28 MAR 1964	15:27:30.1	61.000N	149.000W			4.70MB		33			N	010 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
64	28 MAR 1964	19:21:38.8	61.600N	146.700W			4.60MB		45			N	019 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
65	29 MAR 1964	23:40:54.8	61.100N	151.000W			4.70MB		25			N	020 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
66	30 MAR 1964	03:35:12.0	61.200N	151.100W			4.40MB		30			N	007 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
67	30 MAR 1964	10:47:05.9	61.500N	146.800W			4.30MB		35			N	009 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
68	30 MAR 1964	11:35:18.8	61.500N	147.900W			4.40MB		25			N	015 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
69	30 MAR 1964	17:41:13.4	61.500N	150.000W			4.30MB		40			N	017 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
70	3 APR 1964	22:33:42.2	61.600N	147.600W		V	5.70MB		40			N	REPORTED DAMAGE 080 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS MAGNITUDE(FRACTIONAL NOTATION,AVE)=6.00, AUTHORITY-PAS
71	7 APR 1964	03:53:57.2	61.100N	148.700W			4.20MB		33			N	011 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
72	12 APR 1964	14:35:39.2	61.200N	151.100W		IV	5.00MB		28			N	REPORTED FELT INFORMATION 041 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
73	13 APR 1964	17:43:26.3	61.100N	147.400W			4.40MB		35			N	011 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
74	13 APR 1964	23:48:52.7	61.000N	149.300W			4.10MB		33			N	009 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
75	14 APR 1964	07:59:25.4	61.400N	147.000W			4.40MB		33			N	018 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
76	14 APR 1964	15:55:10.9	61.300N	147.300W			5.40MB		30			N	051 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
77	14 APR 1964	16:59:30.1	61.400N	150.800W			5.10MB		35			N	036 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
78	14 APR 1964	21:33:37.3	61.000N	147.300W			4.20MB		40			N	014 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
79	16 APR 1964	14:31:16.3	61.400N	149.200W			4.60MB		33			N	015 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
80	17 APR 1964	07:26:39.0	61.100N	149.400W			4.40MB		33			N	007 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
81	20 APR 1964	11:56:41.6	61.400N	147.300W			5.70MB		30			N	REPORTED FELT INFORMATION 087 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS MAGNITUDE(FRACTIONAL NOTATION,AVE)=6.50, AUTHORITY-PAS
82	20 APR 1964	15:40:28.0	61.500N	147.300W			5.00MB		30			N	029 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
83	20 APR 1964	16:49:41.8	61.400N	147.300W			4.20MB		33			N	009 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
84	21 APR 1964	05:01:35.7	61.500N	147.400W			5.40MB		40			N	REPORTED FELT INFORMATION 066 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS MAGNITUDE(FRACTIONAL NOTATION,AVE)=6.00, AUTHORITY-PAS
85	30 APR 1964	11:50:47.4	61.300N	147.000W			4.40MB		33			N	015 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
86	9 MAY 1964	21:06:12.2	61.700N	152.000W			5.00MB		25			N	010 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
87	20 MAY 1964	01:55:23.8	61.300N	148.300W			4.00MB		33			N	006 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
88	5 JUN 1964	11:50:24.9	63.100N	151.100W			4.20MB		94			N	006 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
89	16 JUN 1964	10:23:39.7	61.200N	146.800W			4.50MB		40			N	012 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
90	22 JUN 1964	08:32:02.1	62.100N	148.500W			4.10MB		33			N	009 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
91	26 JUN 1964	05:28:49.0	61.700N	148.300W			4.30MB		33			N	011 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
92	29 JUN 1964	07:21:32.8	62.700N	152.000W			5.60MB		33			N	REPORTED FELT INFORMATION 058 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
93	27 JUL 1964	15:53:23.6	63.400N	148.500W			4.20MB		115			N	008 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
94	16 AUG 1964	02:57:05.6	61.600N	150.200W			4.10MB		63			N	008 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
95	16 AUG 1964	12:38:20.6	62.100N	147.300W			4.10MB		56			N	005 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
96	20 AUG 1964	14:03:34.4	61.400N	147.500W			4.30MB		35			N	008 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
97	24 AUG 1964	01:36:23.7	61.200N	146.800W			4.00MB		47			N	007 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
98	27 AUG 1964	10:31:59.7	63.600N	148.200W			4.20MB		106			N	008 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
99	6 SEP 1964	17:36:44.3	63.100N	147.700W			4.80MB		33			N	013 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
100	23 SEP 1964	16:37:19.1	61.600N	150.000W			4.10MB		33			N	REPORTED FELT INFORMATION 005 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
101	28 SEP 1964	18:30:20.2	61.000N	147.400W			4.50MB		89			N	013 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
102	3 OCT 1964	13:39:39.9	61.400N	147.100W			5.20MB		48			N	039 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
103	20 NOV 1964	21:27:39.5	63.700N	146.500W			4.60MB		80			N	REPORTED FELT INFORMATION 012 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
104	27 NOV 1964	07:47:07.6	62.600N	151.500W		IV	5.40MB		113			N	REPORTED FELT INFORMATION 023 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS MAGNITUDE(FRACTIONAL NOTATION,AVE)=4.63, AUTHORITY-BRK

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
105	21 DEC 1964	18:32:03.0	63.100N	150.300W			4.80MB	111			N	018 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
106	1 JAN 1965	20:02:38.0	61.700N	148.900W			4.30MB	33			N	008 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
107	11 JAN 1965	16:57:27.0	61.100N	151.000W			5.40MB	59			N	022 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
108	8 FEB 1965	03:37:34.8	63.400N	151.700W			4.50MB	31			N	011 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
109	25 FEB 1965	02:02:37.4	61.200N	146.700W			4.50MB	40			N	015 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
110	1 MAR 1965	13:56:07.4	61.700N	147.700W			4.00MB	43			N	010 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
111	8 MAR 1965	12:04:21.0	62.500N	150.400W			4.50MB	104			N	016 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
112	10 MAR 1965	20:29:34.5	62.500N	147.300W			4.80MB	85			N	017 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
113	19 APR 1965	07:15:54.4	62.100N	150.200W			4.10MB	83			N	014 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
114	9 MAY 1965	14:27:18.6	63.200N	149.200W			4.00MB	111			N	010 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
115	11 MAY 1965	17:37:38.3	61.400N	149.600W		IV	5.50MB	58			N	REPORTED FELT INFORMATION 015 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS MAGNITUDE(FRACTIONAL NOTATION,AVE)=5.75, AUTHORITY-PAS
116	2 JUN 1965	00:43:04.3	62.100N	151.400W			4.50MB	24			N	016 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
117	26 JUN 1965	23:13:42.4	62.800N	149.100W			4.80MB	75			N	020 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
118	20 JUL 1965	16:57:00.2	62.000N	147.000W			4.00MB	33			N	010 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
119	7 AUG 1965	21:14:43.6	61.900N	151.000W			4.80MB	80			N	030 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
120	8 AUG 1965	11:28:21.9	61.200N	149.300W			4.10MB	86			N	007 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS

AT. O.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
21	13 AUG 1965	15:19:17.2	61.200N	151.400W			4.20MB		92			N	019 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
22	16 OCT 1965	11:45:25.7	63.100N	150.300W			4.60MB		84			N	014 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
23	27 OCT 1965	12:47:28.3	61.000N	146.500W			4.00MB		7			N	014 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
24	24 NOV 1965	08:22:39.0	63.200N	150.900W			5.00MB		129			N	REPORTED FELT INFORMATION 037 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS MAGNITUDE(FRACTIONAL NOTATION,AVE)=4.40, AUTHORITY-BRK
25	14 DEC 1965	17:54:57.4	63.600N	150.000W			4.00MB		113			N	009 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
26	24 DEC 1965	16:10:01.1	62.400N	149.700W			4.20MB		95			N	008 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
27	18 JAN 1966	21:28:51.5	61.400N	151.900W			4.10MB		80			N	REPORTED FELT INFORMATION 011 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
28	18 JAN 1966	21:46:01.5	61.500N	150.700W			4.10MB		69			N	REPORTED FELT INFORMATION 011 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
29	24 JAN 1966	11:41:25.1	62.600N	151.600W			4.20MB		41			N	010 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
30	3 MAR 1966	17:37:03.7	61.400N	150.600W			4.00MB		53			N	REPORTED FELT INFORMATION 010 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
31	19 MAR 1966	09:33:43.8	62.400N	151.200W			4.30MB		86			N	018 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
32	22 MAR 1966	10:28:59.9	61.200N	151.600W			4.20MB		103			N	019 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
33	25 MAR 1966	01:15:11.8	62.600N	151.000W			4.40MB		106			N	005 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
34	17 APR 1966	18:49:57.3	63.800N	151.400W			4.10MB		47			N	007 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
35	11 MAY 1966	01:26:24.3	62.800N	150.100W			4.60MB		99			N	023 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS

TABLE C-1 (CONTINUED)

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
136	19 JUN 1966	12:56:14.3	63.300N	151.400W			4.30MB		136			N	012 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
137	22 JUN 1966	11:38:50.7	61.300N	147.700W			5.20MB		28			N	REPORTED FELT INFORMATION 073 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS MAGNITUDE(FRACTIONAL NOTATION,AVE)=5.13, AUTHORITY-PAL
138	17 JUL 1966	08:46:27.7	62.000N	151.900W			4.50MB		119			N	041 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
139	30 AUG 1966	20:20:53.9	61.300N	147.500W		V	5.80MB		35			N	REPORTED FELT INFORMATION 143 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS MAGNITUDE(FRACTIONAL NOTATION,AVE)=5.88, AUTHORITY-PAS
140	30 AUG 1966	20:23:18.2	61.500N	147.500W		V	5.50MB		33			N	REPORTED FELT INFORMATION 019 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS MAGNITUDE(FRACTIONAL NOTATION,AVE)=5.00, AUTHORITY-BRK
141	31 AUG 1966	14:10:43.9	64.000N	146.800W			4.10MB		28			N	012 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
142	1 SEP 1966	23:19:08.1	61.700N	149.700W			5.10MB		63			N	REPORTED FELT INFORMATION 079 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
143	9 SEP 1966	12:24:03.3	61.400N	146.900W			4.00MB		33			N	016 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
144	9 SEP 1966	15:36:57.3	61.400N	147.800W			4.40MB		58			N	015 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
145	7 OCT 1966	20:55:56.4	61.700N	150.100W			5.60MB		57			N	REPORTED FELT INFORMATION 115 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
146	11 OCT 1966	16:49:49.2	62.600N	148.800W			4.20MB		54			N	015 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
147	11 DEC 1966	19:22:00.6	62.700N	150.900W			4.10MB		70			N	006 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
148	16 DEC 1966	21:59:46.2	61.400N	149.500W			4.10MB		53			N	REPORTED FELT INFORMATION 012 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
149	13 JAN 1967	09:37:55.9	63.227N	150.893W			4.00MB		120			N	019 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS

CAT. NO.	DATE DAY MO YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
150	19 JAN 1967	19:38:56.7	62.499N	151.766W			4.10MB		82		*	N	007 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION NOAA FEELS THIS IS A LESS RELIABLE SOLUTION ORIGINAL DATA SOURCE = CGS
151	14 FEB 1967	08:12:52.3	63.879N	151.126W			4.00MB		46		*	N	006 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION NOAA FEELS THIS IS A LESS RELIABLE SOLUTION ORIGINAL DATA SOURCE = CGS
152	16 FEB 1967	07:41:38.7	62.381N	151.338W			4.10MB		81			N	REPORTED FELT INFORMATION 011 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
153	1 MAR 1967	11:51:34.7	63.047N	151.264W			4.00MB		127			N	014 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
154	31 MAR 1967	04:18:31.3	63.124N	148.495W			4.50MB		82			N	REPORTED FELT INFORMATION 033 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
155	3 APR 1967	02:53:46.4	62.811N	150.918W			4.20MB		105			N	011 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
156	9 APR 1967	12:52:05.3	61.620N	151.380W			4.20MB		54			N	012 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
157	10 APR 1967	14:44:26.8	63.008N	148.797W			4.00MB		72			N	015 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
158	5 MAY 1967	17:06:15.3	63.713N	148.451W			5.00MB		103			N	REPORTED FELT INFORMATION 087 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
159	14 JUN 1967	20:45:44.7	62.500N	149.200W			4.10MB		86			N	013 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
160	6 JUL 1967	05:06:13.4	62.400N	147.400W		III	5.10MB		59			N	REPORTED FELT INFORMATION 072 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = USE
161	12 JUL 1967	15:15:37.9	62.700N	149.500W			4.10MB		78			N	016 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
162	18 AUG 1967	05:50:29.0	61.500N	151.000W			4.50MB		19			N	REPORTED FELT INFORMATION 043 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = USE
163	11 OCT 1967	07:56:36.1	63.000N	151.100W			4.60MB		115			N	REPORTED FELT INFORMATION 023 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = USE

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
164	10 NOV 1967	18:29:57.3	62.300N	151.400W			4.90MB		90			N	041 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
165	14 NOV 1967	00:22:10.0	61.500N	151.800W			4.00MB		33			N	009 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
166	22 NOV 1967	02:44:26.3	63.600N	147.200W			4.30MB		2			N	029 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
167	4 DEC 1967	08:19:08.5	62.400N	151.800W			4.90MB		96			N	028 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
168	10 DEC 1967	03:13:34.8	61.400N	147.400W			4.20MB		30			N	010 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
169	21 MAR 1968	11:33:24.3	62.400N	150.600W			4.10MB		72			N	021 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
170	8 APR 1968	03:32:48.4	61.500N	147.800W			4.20MB		48			N	025 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
171	30 APR 1968	17:39:40.2	62.000N	151.100W			4.00MB		78			N	016 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
172	18 MAY 1968	06:50:27.4	61.200N	147.600W			4.30MB		33			N	REPORTED FELT INFORMATION HYPOCENTER SOLUTION HELD AT 33 KM (NORMAL DEPTH) 014 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = USE
173	29 MAY 1968	15:25:39.0	62.300N	149.100W			4.00MB		51			N	REPORTED FELT INFORMATION 013 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = USE
174	15 JUN 1968	13:38:06.5	61.000N	146.900W			4.90MB		19			N	REPORTED FELT INFORMATION 038 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = USE
175	7 JUL 1968	01:10:29.5	61.252N	147.289W			4.80MB		14			N	019 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
176	3 AUG 1968	07:51:13.1	61.754N	151.349W			4.10MB		60			N	014 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
177	31 AUG 1968	17:47:06.9	61.734N	150.911W			4.10MB		66			N	013 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
178	22 SEP 1968	06:13:56.6	61.184N	150.729W			4.00MB		51			N	009 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
179	4 OCT 1968	16:27:24.5	61.303N	147.213W			4.50MB		44			N	026 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS

AT. D.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
30	7 OCT 1968	18:54:53.6	61.400N	150.300W		IV	4.20MB		55			N	REPORTED FELT INFORMATION 016 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = USE
31	28 DEC 1968	04:15:55.0	63.000N	148.200W			4.60MB		80			N	REPORTED FELT INFORMATION 021 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = USE
32	29 DEC 1968	20:57:07.9	62.980N	151.014W			4.00MB		139			N	010 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
33	31 MAR 1969	11:44:20.8	63.617N	147.681W			4.10MB		93			N	011 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
34	4 MAY 1969	09:28:00.1	63.549N	148.697W			4.20MB		33			N	HYPOCENTER SOLUTION HELD AT 33 KM (NORMAL DEPTH) 019 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
35	10 MAY 1969	21:16:04.1	62.991N	151.143W			4.00MB		117			N	011 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
36	9 JUN 1969	08:02:17.2	62.400N	149.000W			4.10MB		54			N	REPORTED FELT INFORMATION 022 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = USE
37	17 JUL 1969	22:03:36.7	63.978N	147.480W			4.20MB		12			N	REPORTED FELT INFORMATION 018 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
38	6 AUG 1969	00:38:42.8	61.400N	150.700W		IV	4.80MB		53			N	REPORTED FELT INFORMATION 022 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = USE MAGNITUDE(FRACTIONAL NOTATION,AVE)=4.80, AUTHORITY-
39	18 AUG 1969	13:57:10.0	62.254N	150.426W			4.10MB		60		*	N	009 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION NOAA FEELS THIS IS A LESS RELIABLE SOLUTION ORIGINAL DATA SOURCE = CGS
30	16 OCT 1969	21:00:46.5	62.500N	151.300W			4.00MB		94			N	REPORTED FELT INFORMATION 016 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = USE
31	4 DEC 1969	10:06:21.5	63.085N	151.833W			4.00MB		44			N	013 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
32	30 JAN 1970	09:15:34.9	61.492N	146.624W			3.90MB		33			N	HYPOCENTER SOLUTION HELD AT 33 KM (NORMAL DEPTH) 014 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS LOCAL MAGNITUDE = 4.10 SCALE =ML AUTHORITY= CGS

TABLE C-1 (CONTINUED)

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
193	28 FEB 1970	06:56:49.9	63.073N	150.563W			4.10MB		120			N	017 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
194	15 MAR 1970	12:58:24.9	62.750N	150.839W			4.00MB		100			N	027 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
195	1 MAY 1970	20:58:12.5	63.600N	149.400W		IV	4.00MB		33			N	REPORTED FELT INFORMATION 015 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = USE LOCAL MAGNITUDE = 4.20 SCALE =ML AUTHORITY= CGS
196	2 JUN 1970	02:59:31.3	61.600N	151.700W		IV	5.50MB		95			N	REPORTED FELT INFORMATION HYPOCENTER DEPTH SOLUTION RESTRAINED WITH P-P ARRIVALS 091 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = USE MAGNITUDE(FRACTIONAL NOTATION,AVE)=4.75, AUTHORITY-BRK
197	10 JUN 1970	04:15:16.8	61.311N	151.086W			4.00MB		64			N	025 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS
198	19 JUN 1970	01:42:11.1	63.534N	150.933W			4.20MB		33			N	HYPOCENTER SOLUTION HELD AT 33 KM (NORMAL DEPTH) 013 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS LOCAL MAGNITUDE = 4.10 SCALE =ML AUTHORITY= CGS
199	10 JUL 1970	09:16:44.2	61.467N	146.545W			4.20MB		35			N	036 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = CGS LOCAL MAGNITUDE = 4.70 SCALE =ML AUTHORITY= CGS
200	15 AUG 1970	16:55:51.5	63.581N	146.983W			4.30MB		33		*	N	HYPOCENTER SOLUTION HELD AT 33 KM (NORMAL DEPTH) 008 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION NOAA FEELS THIS IS A LESS RELIABLE SOLUTION ORIGINAL DATA SOURCE = CGS
201	2 OCT 1970	05:55:40.9	62.351N	151.567W			4.10MB		84		*	N	017 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION NOAA FEELS THIS IS A LESS RELIABLE SOLUTION ORIGINAL DATA SOURCE = NOS
202	31 OCT 1970	15:51:38.4	62.187N	148.677W			4.20MB		44			N	REPORTED FELT INFORMATION 014 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = NOS
203	3 NOV 1970	02:30:11.4	62.000N	151.200W		V	5.60MB		70			N	REPORTED FELT INFORMATION 125 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = USE
204	10 DEC 1970	09:46:29.0	63.061N	151.357W			4.30MB		118			N	021 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = NOS
205	20 DEC 1970	06:01:36.1	63.100N	151.400W			5.30MB		130			N	REPORTED FELT INFORMATION HYPOCENTER DEPTH SOLUTION RESTRAINED WITH P-P ARRIVALS

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
													085 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = USE
206	5 JAN 1971	05:55:34.0	61.421N	147.549W			4.50MB		46			N	REPORTED FELT INFORMATION 022 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = NOS
207	20 JAN 1971	02:07:34.3	63.293N	150.966W			4.60MB		131			N	HYPOCENTER DEPTH SOLUTION RESTRAINED WITH P-P ARRIVALS 032 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = NOS
208	23 JAN 1971	15:12:14.7	63.091N	150.750W			4.50MB		112			N	013 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = NOS
209	19 FEB 1971	04:43:43.8	63.206N	150.474W			4.00MB		115			N	016 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = NOS
210	21 FEB 1971	16:08:09.1	62.574N	151.348W			4.20MB		91			N	027 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = NOS
211	21 FEB 1971	18:10:34.6	63.075N	150.346W			4.70MB		115			N	014 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = NOS
212	2 MAR 1971	12:46:36.4	63.394N	149.822W			4.80MB		111			N	020 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = NOS
213	9 MAR 1971	08:08:53.9	63.968N	149.829W			4.30MB		140			N	016 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = NOS
214	9 MAR 1971	10:56:36.0	63.960N	149.823W			4.00MB		138			N	013 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = NOS
215	5 MAY 1971	10:32:44.4	61.733N	151.456W			4.10MB		75			N	014 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = NOS
216	14 MAY 1971	15:00:35.1	62.457N	151.137W			4.30MB		82			N	020 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = NOS
217	16 MAY 1971	16:50:57.4	63.103N	148.316W			4.10MB		77			N	008 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = NOS
218	2 JUN 1971	19:06:32.9	61.030N	151.256W		III	5.00MB		29			N	REPORTED FELT INFORMATION 048 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = NOS LOCAL MAGNITUDE = 5.50 SCALE =ML AUTHORITY= NOS
219	26 JUL 1971	16:17:35.6	63.283N	149.726W			4.10MB		33		*	N	REPORTED FELT INFORMATION HYPOCENTER SOLUTION HELD AT 33 KM (NORMAL DEPTH) 009 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION NOAA FEELS THIS IS A LESS RELIABLE SOLUTION ORIGINAL DATA SOURCE = ERL LOCAL MAGNITUDE = 4.40 SCALE =ML AUTHORITY= ERL

TABLE C-1 (CONTINUED)

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
220	30 JUL 1971	02:07:52.1	62.079N	151.374W			4.20MB		81		*	N	020 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION NOAA FEELS THIS IS A LESS RELIABLE SOLUTION ORIGINAL DATA SOURCE = ERL
221	12 SEP 1971	23:46:10.1	63.593N	150.904W			3.80MB		8			N	011 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL LOCAL MAGNITUDE = 4.10 SCALE =ML AUTHORITY= ERL
222	22 OCT 1971	23:10:59.0	63.140N	151.109W			4.60MB		133			N	027 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL
223	30 DEC 1971	17:56:03.5	61.145N	150.360W		III	4.10MB		41			N	REPORTED FELT INFORMATION 014 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL LOCAL MAGNITUDE = 3.70 SCALE =ML AUTHORITY= ERL
224	15 JAN 1972	09:35:44.8	63.178N	149.997W			4.00MB		91		*	N	009 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION NOAA FEELS THIS IS A LESS RELIABLE SOLUTION ORIGINAL DATA SOURCE = ERL
225	11 APR 1972	18:21:35.5	62.023N	150.418W			4.50MB		18			N	025 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL LOCAL MAGNITUDE = 4.20 SCALE =ML AUTHORITY= ERL
226	16 APR 1972	18:35:39.3	63.527N	147.713W			4.10MB		11			N	REPORTED FELT INFORMATION 026 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL LOCAL MAGNITUDE = 4.60 SCALE =ML AUTHORITY= ERL
227	25 APR 1972	13:35:54.1	61.984N	148.823W			4.60MB		58			N	044 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL
228	28 APR 1972	19:05:15.3	63.613N	149.909W			4.70MB		131			N	025 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL
229	22 JUN 1972	05:57:34.2	61.417N	147.491W		II	4.50MB		48			N	REPORTED FELT INFORMATION 029 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL
230	1 OCT 1972	10:08:49.7	62.743N	149.082W		II	4.70MB		76			N	REPORTED FELT INFORMATION 036 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL
231	21 OCT 1972	19:52:05.4	63.154N	151.063W		IV	5.40MB		132			N	REPORTED FELT INFORMATION HYPOCENTER DEPTH SOLUTION RESTRAINED WITH P-P ARRIVALS 076 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL
232	16 FEB 1973	02:25:23.8	62.997N	150.624W			4.30MB		109			N	021 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
233	5 MAR 1973	08:30:49.2	63.734N	148.442W			4.00MB	106			N	025 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL
234	16 MAR 1973	02:49:19.4	62.218N	151.056W			4.30MB	72			N	035 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL
235	24 MAR 1973	07:51:43.5	63.218N	150.833W			4.20MB	122			N	014 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL
236	4 APR 1973	15:43:26.6	62.974N	150.835W			4.20MB	124			N	021 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL
237	22 APR 1973	03:40:54.1	63.597N	150.946W			4.40MB	14			N	030 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL LOCAL MAGNITUDE = 4.50 SCALE =ML AUTHORITY= ERL
238	18 MAY 1973	18:32:55.7	63.070N	150.951W			4.70MB	128			N	035 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL
239	25 MAY 1973	03:10:15.0	63.205N	150.741W			4.00MB	128			N	023 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL
240	22 JUL 1973	07:33:43.8	63.803N	149.110W			4.10MB	120			N	014 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL
241	19 AUG 1973	17:34:51.3	63.235N	150.426W			4.10MB	130			N	017 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = ERL
242	31 AUG 1973	02:30:57.9	61.096N	147.414W		III	5.10MB	49			N	REPORTED FELT INFORMATION 100 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS MAGNITUDE = 5.0 USING NOAA AVERAGE MS (IASPEI FORMULA)
243	6 SEP 1973	10:59:36.7	61.039N	146.828W		III	5.50MB	29			N	REPORTED FELT INFORMATION HYPOCENTER DEPTH SOLUTION RESTRAINED WITH P-P ARRIVALS 087 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS MAGNITUDE = 5.3 USING NOAA AVERAGE MS (IASPEI FORMULA) LOCAL MAGNITUDE = 5.50 SCALE =ML AUTHORITY= PMR
244	24 JAN 1974	18:43:26.8	61.588N	147.626W		V	4.80MB	40			N	REPORTED FELT INFORMATION 65 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 5.20 SCALE =ML AUTHORITY= PMR
245	2 FEB 1974	15:55:28.3	61.602N	147.603W			5.10MB	48			N	REPORTED FELT INFORMATION 81 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS MAGNITUDE = 4.7 USING NOAA AVERAGE MS (IASPEI FORMULA)

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SI. INTEN (MM)	MAG SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
246	5 FEB 1974	02:25:22.0	62.703N	148.854W	V	5.00MB	75			N	REPORTED FELT INFORMATION 61 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
247	15 FEB 1974	06:06:28.5	63.144N	150.763W		4.50MB	126			N	32 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
248	10 MAR 1974	10:00:14.1	63.160N	150.503W		4.50MB	117			N	REPORTED FELT INFORMATION 36 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
249	8 MAY 1974	04:27:13.1	63.669N	150.727W		4.60MB	11			N	REPORTED FELT INFORMATION 62 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.70 SCALE =ML AUTHORITY= PMR
250	21 MAY 1974	23:31:41.2	63.312N	151.245W	II	4.20MB	12			N	REPORTED FELT INFORMATION 29 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.60 SCALE =ML AUTHORITY= PMR
251	24 JUN 1974	21:20:22.1	63.167N	149.881W		5.50MB	75			N	18 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
252	11 JUL 1974	02:17:57.8	62.388N	151.253W		4.20MB	92			N	25 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
253	13 JUL 1974	14:48:50.0	62.227N	151.217W	IV	4.40MB	85			N	REPORTED FELT INFORMATION 30 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
254	1 DEC 1974	15:56:32.3	62.210N	150.532W		4.00MB	64			N	20 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
255	10 DEC 1974	16:05:18.2	61.808N	146.893W		4.40MB	27			N	11 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 3.30 SCALE =ML AUTHORITY= PMR
256	29 DEC 1974	18:25:00.7	61.597N	150.511W	V	5.60MB	67			N	REPORTED FELT INFORMATION HYPOCENTER DEPTH SOLUTION RESTRAINED WITH P-P ARRIVALS 81 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
257	30 DEC 1974	03:33:16.6	61.982N	149.686W	V	5.10MB	62			N	REPORTED FELT INFORMATION HYPOCENTER DEPTH SOLUTION RESTRAINED WITH P-P ARRIVALS 88 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
258	1 JAN 1975	03:55:12.0	61.909N	149.738W	V	5.90MB	66			N	REPORTED DAMAGE 118 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS

TABLE C-1 (CONTINUED)

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
259	13 JAN 1975	00:31:55.6	61.434N	150.494W		IV	4.80MB		66			N	REPORTED FELT INFORMATION 45 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
260	20 JAN 1975	05:51:23.1	63.770N	149.233W			4.40MB		123			N	19 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
261	12 FEB 1975	15:45:35.1	63.518N	148.725W		IV	4.00MB		33			N	REPORTED FELT INFORMATION HYPOCENTER SOLUTION HELD AT 33 KM (NORMAL DEPTH) 32 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.50 SCALE =ML AUTHORITY= PMR
262	12 MAR 1975	14:05:31.5	61.915N	150.307W			3.90MB		10			N	REPORTED FELT INFORMATION 22 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.00 SCALE =ML AUTHORITY= PMR
263	13 APR 1975	19:32:48.8	63.401N	149.791W			4.00MB		114			N	21 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
264	18 MAY 1975	15:42:59.1	63.170N	150.263W		V	5.40MB		106			N	REPORTED FELT INFORMATION HYPOCENTER DEPTH SOLUTION RESTRAINED WITH P-P ARRIVALS 223 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
265	20 MAY 1975	16:29:50.0	63.028N	150.003W			4.20MB		125			N	14 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
266	11 JUN 1975	05:14:08.2	62.165N	149.635W			4.30MB		59			N	REPORTED FELT INFORMATION 41 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
267	24 JUN 1975	12:15:31.3	63.098N	150.946W			4.00MB		133			N	18 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
268	1 AUG 1975	07:04:33.0	61.919N	150.763W			4.60MB		79			N	22 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
269	17 SEP 1975	13:18:14.2	63.422N	149.827W			4.60MB		133			N	20 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
270	21 OCT 1975	01:16:28.7	61.313N	147.371W			4.60MB		33			N	HYPOCENTER SOLUTION HELD AT 33 KM (NORMAL DEPTH) 17 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
271	24 DEC 1975	14:25:21.6	62.571N	148.193W			4.10MB		72			N	28 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
272	13 MAR 1976	14:33:42.5	63.503N	148.673W		V	3.90MB		22			N	REPORTED FELT INFORMATION 17 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
													ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.20 SCALE =ML AUTHORITY= PMR
273	26 MAR 1976	14:40:14.2	63.602N	147.653W		IV	4.10MB		33			N	REPORTED FELT INFORMATION HYPOCENTER SOLUTION HELD AT 33 KM (NORMAL DEPTH) 26 P AND/OR P′ ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.20 SCALE =ML AUTHORITY= PMR
274	8 MAY 1976	11:25:36.3	61.620N	151.517W		IV	4.40MB		16			N	REPORTED FELT INFORMATION 43 P AND/OR P′ ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.40 SCALE =ML AUTHORITY= PMR
275	11 MAY 1976	16:46:15.8	61.491N	146.966W		III	4.20MB		67			N	REPORTED FELT INFORMATION 18 P AND/OR P′ ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
276	24 JUN 1976	13:36:59.2	61.965N	150.895W			4.80MB		73			N	19 P AND/OR P′ ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
277	11 JUL 1976	02:00:11.1	63.301N	150.803W			4.50MB		133			N	26 P AND/OR P′ ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
278	12 JUL 1976	01:59:15.3	62.858N	150.682W			4.60MB		128			N	11 P AND/OR P′ ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
279	15 JUL 1976	08:09:47.4	62.700N	149.831W		IV	4.20MB		24			N	REPORTED FELT INFORMATION 32 P AND/OR P′ ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.60 SCALE =ML AUTHORITY= PMR
280	30 JUL 1976	13:54:32.2	61.332N	147.445W			3.90MB		40			N	REPORTED FELT INFORMATION 22 P AND/OR P′ ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.00 SCALE =ML AUTHORITY= PMR
281	27 AUG 1976	17:07:23.6	62.243N	149.471W			4.00MB		65			N	14 P AND/OR P′ ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 3.70 SCALE =ML AUTHORITY= PMR
282	30 AUG 1976	10:01:12.9	61.301N	151.431W			4.10MB		82			N	16 P AND/OR P′ ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
283	4 SEP 1976	23:23:46.0	62.931N	150.653W			5.40MB		123			N	14 P AND/OR P′ ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
284	26 SEP 1976	08:25:41.8	61.732N	151.897W			4.00MB		110			N	12 P AND/OR P′ ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
285	26 SEP 1976	09:28:54.0	61.472N	151.921W			4.00MB		95		*	N	11 P AND/OR P′ ARRIVALS USED IN HYPOCENTER SOLUTION NOAA FEELS THIS IS A LESS RELIABLE SOLUTION

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
													ORIGINAL DATA SOURCE = GS
286	18 OCT 1976	00:36:31.6	63.290N	150.737W		IV	4.90MB		126			N	REPORTED FELT INFORMATION 63 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
287	24 OCT 1976	17:19:53.7	62.647N	149.139W			4.90MB		75			N	REPORTED FELT INFORMATION 96 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
288	27 OCT 1976	03:43:41.4	61.708N	151.543W			4.20MB		98			N	15 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
289	3 NOV 1976	16:40:44.6	63.085N	150.957W			4.40MB		133			N	16 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
290	4 NOV 1976	07:04:38.9	63.643N	150.839W			4.30MB		12			N	14 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.30 SCALE =ML AUTHORITY= PMR
291	4 DEC 1976	04:20:22.8	63.214N	150.796W			4.30MB		129			N	14 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
292	13 DEC 1976	17:27:53.6	61.873N	150.703W			4.30MB		74			N	15 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
293	24 DEC 1976	01:50:17.2	63.417N	151.409W			4.10N'		33			N	HYPOCENTER SOLUTION HELD AT 33 KM (NORMAL DEPTH) 13 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.10 SCALE =ML AUTHORITY= PMR
294	15 JAN 1977	21:00:43.2	62.801N	150.374W			4.30MB		100			N	16 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
295	1 FEB 1977	08:51:45.7	62.152N	151.285W			4.00MB		83			N	17 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
296	5 MAR 1977	06:13:01.1	63.220N	150.509W			4.20MB		122			N	20 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
297	20 APR 1977	15:02:51.6	62.848N	151.046W			4.50MB		114			N	20 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
298	25 APR 1977	02:28:54.4	61.424N	147.198W			4.20N'		36			N	13 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.20 SCALE =ML AUTHORITY= PMR
299	1 MAY 1977	01:56:00.7	63.205N	150.869W			4.00MB		134			N	12 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
300	2 JUN 1977	16:29:46.3	61.314N	150.329W		V	3.60MB		67			N	REPORTED FELT INFORMATION 19 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION

TABLE C-1 (CONTINUED)

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
													ORIGINAL DATA SOURCE = GS
301	6 JUN 1977	10:08:11.5	62.163N	149.548W		III	4.10MB		60			N	REPORTED FELT INFORMATION 17 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
302	17 JUN 1977	08:26:28.9	61.492N	150.319W		IV	4.30MB		74			N	REPORTED FELT INFORMATION 30 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
303	8 JUL 1977	19:59:39.9	61.168N	150.855W		IV	4.70MB		72			N	REPORTED FELT INFORMATION 73 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
304	22 JUL 1977	05:57:00.5	61.027N	150.401W			3.80MB		51			N	REPORTED FELT INFORMATION 22 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.00 SCALE =ML AUTHORITY= PMR
305	23 AUG 1977	13:42:40.1	63.719N	149.379W			4.10MB		126			N	28 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
306	30 AUG 1977	06:50:39.9	63.161N	151.109W		IV	5.00MB		130			N	REPORTED FELT INFORMATION HYPOCENTER DEPTH SOLUTION RESTRAINED WITH P-P ARRIVALS 131 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
307	9 SEP 1977	15:58:56.4	62.187N	149.527W			4.60MB		59			N	REPORTED FELT INFORMATION 33 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
308	19 OCT 1977	02:16:02.6	62.883N	150.559W			5.00MB		102			N	107 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
309	6 NOV 1977	09:23:28.2	61.994N	150.734W			4.10MB		78			N	15 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
310	20 NOV 1977	18:53:57.8	62.429N	150.661W		V	4.90MB		79			N	REPORTED FELT INFORMATION 61 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.90 SCALE =ML AUTHORITY= PMR
311	5 JAN 1978	19:56:09.8	61.329N	151.650W		III	4.40MB		110			N	POSSIBLE TSUNAMI GENERATED BY EARTHQUAKE POSSIBLE SEICHE ASSOCIATED WITH EARTHQUAKE REPORTED FELT INFORMATION 18 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
312	28 JAN 1978	02:25:01.6	63.063N	150.963W			4.40MB		126			N	POSSIBLE TSUNAMI GENERATED BY EARTHQUAKE POSSIBLE SEICHE ASSOCIATED WITH EARTHQUAKE 25 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
313	31 MAR 1978	00:38:13.4	61.766N	151.409W		IV	5.10MB		90			N	POSSIBLE TSUNAMI GENERATED BY EARTHQUAKE POSSIBLE SEICHE ASSOCIATED WITH EARTHQUAKE REPORTED FELT INFORMATION HYPOCENTER DEPTH SOLUTION RESTRAINED WITH P-P ARRIVALS 154 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
314	10 APR 1978	10:47:02.9	63.075N	150.640W			4.20MB		131			N	POSSIBLE TSUNAMI GENERATED BY EARTHQUAKE POSSIBLE SEICHE ASSOCIATED WITH EARTHQUAKE 33 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
315	5 MAY 1978	05:32:47.4	63.302N	150.971W		IV	5.20MB		134			N	POSSIBLE TSUNAMI GENERATED BY EARTHQUAKE POSSIBLE SEICHE ASSOCIATED WITH EARTHQUAKE REPORTED FELT INFORMATION 138 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
316	12 MAY 1978	12:16:03.9	62.250N	149.398W		IV	5.10MB		67			N	POSSIBLE TSUNAMI GENERATED BY EARTHQUAKE POSSIBLE SEICHE ASSOCIATED WITH EARTHQUAKE REPORTED FELT INFORMATION 100 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
317	23 JUL 1978	15:19:35.5	63.307N	147.256W			5.00MB		33			N	POSSIBLE TSUNAMI GENERATED BY EARTHQUAKE POSSIBLE SEICHE ASSOCIATED WITH EARTHQUAKE REPORTED FELT INFORMATION HYPOCENTER SOLUTION HELD AT 33 KM (NORMAL DEPTH) 50 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.80 SCALE =ML AUTHORITY= PMR
318	8 AUG 1978	09:30:03.3	61.388N	146.908W		IV	4.30MB		53			N	POSSIBLE TSUNAMI GENERATED BY EARTHQUAKE POSSIBLE SEICHE ASSOCIATED WITH EARTHQUAKE REPORTED FELT INFORMATION 54 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
319	13 AUG 1978	00:49:41.0	62.280N	149.709W			4.10MB		65			N	POSSIBLE TSUNAMI GENERATED BY EARTHQUAKE POSSIBLE SEICHE ASSOCIATED WITH EARTHQUAKE REPORTED FELT INFORMATION 36 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
320	22 AUG 1978	03:20:07.2	61.649N	151.961W			4.00MB		123		*	N	POSSIBLE TSUNAMI GENERATED BY EARTHQUAKE POSSIBLE SEICHE ASSOCIATED WITH EARTHQUAKE 18 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION NOAA FEELS THIS IS A LESS RELIABLE SOLUTION ORIGINAL DATA SOURCE = GS

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
321	21 SEP 1978	14:45:19.6	61.108N	151.808W		IV	4.50MB	81		*	N	POSSIBLE TSUNAMI GENERATED BY EARTHQUAKE POSSIBLE SEICHE ASSOCIATED WITH EARTHQUAKE REPORTED FELT INFORMATION 29 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION NOAA FEELS THIS IS A LESS RELIABLE SOLUTION ORIGINAL DATA SOURCE = GS
322	28 SEP 1978	23:53:13.7	63.986N	147.712W			4.40MB	33			N	POSSIBLE TSUNAMI GENERATED BY EARTHQUAKE POSSIBLE SEICHE ASSOCIATED WITH EARTHQUAKE REPORTED FELT INFORMATION HYPOCENTER SOLUTION HELD AT 33 KM (NORMAL DEPTH) 26 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.50 SCALE =ML AUTHORITY= PMR
323	6 OCT 1978	05:54:05.2	61.932N	150.665W		III	4.60N'	6			N	POSSIBLE TSUNAMI GENERATED BY EARTHQUAKE POSSIBLE SEICHE ASSOCIATED WITH EARTHQUAKE REPORTED FELT INFORMATION 17 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.60 SCALE =ML AUTHORITY= PMR
324	19 NOV 1978	12:06:13.7	63.328N	151.119W			4.00MB	33		*	N	POSSIBLE TSUNAMI GENERATED BY EARTHQUAKE POSSIBLE SEICHE ASSOCIATED WITH EARTHQUAKE HYPOCENTER SOLUTION HELD AT 33 KM (NORMAL DEPTH) 29 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION NOAA FEELS THIS IS A LESS RELIABLE SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.30 SCALE =ML AUTHORITY= PMR
325	24 NOV 1978	00:28:12.8	62.027N	150.519W			4.50MB	74			N	POSSIBLE TSUNAMI GENERATED BY EARTHQUAKE POSSIBLE SEICHE ASSOCIATED WITH EARTHQUAKE REPORTED FELT INFORMATION 37 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
326	3 DEC 1978	19:39:31.2	62.306N	149.750W		IV	4.70MB	74			N	POSSIBLE TSUNAMI GENERATED BY EARTHQUAKE POSSIBLE SEICHE ASSOCIATED WITH EARTHQUAKE REPORTED FELT INFORMATION 78 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS
327	17 DEC 1978	13:15:26.0	63.953N	147.424W		IV	4.80MB	22			N	POSSIBLE TSUNAMI GENERATED BY EARTHQUAKE POSSIBLE SEICHE ASSOCIATED WITH EARTHQUAKE REPORTED FELT INFORMATION 88 P AND/OR P' ARRIVALS USED IN HYPOCENTER SOLUTION ORIGINAL DATA SOURCE = GS LOCAL MAGNITUDE = 4.60 SCALE =ML AUTHORITY= PMR

APPENDIX D - SUSTINA STUDY AREA MICROEARTHQUAKE CATALOG

The catalog of microearthquakes that were recorded during the summer field study of 1980 is presented in Table D-1. The data collection methodology is discussed in Appendix B; analyses and interpretations are discussed in Section 9. The explanation for the catalog headings are as follows:

CAT. NO. - Sequence number of the listed events.

DATE - Date the earthquake occurred by day, month, and year according to the origin time in Universal Coordinated Time (UCT).

TIME - Origin time of the earthquake in hours, minutes, and seconds in Universal Coordinated Time (UCT). Time is rounded to the nearest 0.1 seconds.

LAT, LONG - North latitude and west longitude of the epicenter in degrees. Implied accuracy is to the nearest 0.001 degrees (0.1 km), but uncertainty in the location is more properly interpreted from the RMS and ERH values.

MAG - Magnitude of the earthquake calculated using the duration of coda waves. Values are calibrated to be equivalent to local Richer magnitudes (M_L).

H - Depth of earthquake (focal depth) in kilometers. Values are rounded to the nearest one kilometer.

S - Source of location and magnitude values; all were calculated by Woodward-Clyde Consultants.

LOCATION AND COMMENTS - Six parameters are used to measure the quality of the earthquake location.

NO - The total number of P and S arrivals used in the location.

GAP - Largest azimuthal separation of the stations, in degrees, from the epicenter.

D1 - Distance in kilometers from epicenter to closest station used to locate the event.

RMS - Root-mean-square travel-time residual, in seconds, for all the stations used in the location. The residual is defined as $(t_o - t_c)$, where t_o is the observed travel time and t_c is the calculated travel time from the earthquake focus to each station.

ERH - Greatest horizontal standard error of the epicenter, in kilometers.

ERZ - Standard error of the focal depth, in kilometers.

TABLE D-1

1980 MICROEARTHQUAKE CATALOG

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q S	LOCATION AND COMMENTS
1	2 JUL 1980	09:19:02.4	62.496N	148.826W			2.56		52		WC	NO= 10,GAP= 275,D1= 13,RMS= .06,ERH= 1.1,ERZ= 1.1
2	2 JUL 1980	10:42:56.5	62.874N	148.676W			2.81		15		WC	NO= 10,GAP= 210,D1= 8,RMS= .30,ERH= 3.3,ERZ= 3.4
3	2 JUL 1980	10:49:03.3	62.846N	148.848W			1.93		16		WC	NO= 10,GAP= 232,D1= 15,RMS= .35,ERH= 5.4,ERZ= 5.8
4	2 JUL 1980	22:20:11.7	62.894N	148.625W			1.70		15		WC	NO= 8,GAP= 262,D1= 9,RMS= .14,ERH= 2.6,ERZ= 2.2
5	3 JUL 1980	12:06:44.4	63.087N	147.871W			1.54		14		WC	NO= 7,GAP= 287,D1= 18,RMS= .06,ERH= 1.5,ERZ= 2.1
6	4 JUL 1980	17:33:48.8	62.557N	150.050W			1.87		18		WC	NO= 9,GAP= 326,D1= 27,RMS= .12,ERH= 2.9,ERZ= 1.1
7	5 JUL 1980	03:56:14.3	62.300N	148.383W			2.11		19		WC	NO= 8,GAP= 299,D1= 32,RMS= .21,ERH= 3.8,ERZ= 1.9
8	5 JUL 1980	06:54:09.9	62.967N	148.749W			2.81		68		WC	NO= 10,GAP= 193,D1= 29,RMS= .09,ERH= 1.6,ERZ= 1.9
9	5 JUL 1980	23:27:54.1	62.626N	148.861W			1.34		16		WC	NO= 12,GAP= 161,D1= 1,RMS= .32,ERH= 2.8,ERZ= 3.6
10	6 JUL 1980	01:54:19.3	62.613N	148.917W			0.93		17		WC	NO= 12,GAP= 185,D1= 4,RMS= .32,ERH= 2.7,ERZ= 3.5
11	6 JUL 1980	15:29:11.0	62.491N	148.270W			2.55		48		WC	NO= 16,GAP= 227,D1= 11,RMS= .38,ERH= 4.4,ERZ= 5.2
12	7 JUL 1980	16:35:37.8	62.593N	148.886W			1.46		15		WC	NO= 14,GAP= 164,D1= 3,RMS= .38,ERH= 2.9,ERZ= 6.4
13	7 JUL 1980	18:33:35.6	62.654N	149.549W			2.16		66		WC	NO= 14,GAP= 164,D1= 5,RMS= .17,ERH= 2.3,ERZ= 2.3
14	8 JUL 1980	01:22:07.8	63.066N	149.169W			1.40		15		WC	NO= 14,GAP= 212,D1= 19,RMS= .26,ERH= 2.3,ERZ= 3.7
15	9 JUL 1980	07:03:53.4	62.701N	148.502W			2.05		68		WC	NO= 13,GAP= 122,D1= 26,RMS= .14,ERH= 1.5,ERZ= 2.3
16	9 JUL 1980	08:27:47.4	62.939N	149.514W			3.24		81		WC	NO= 9,GAP= 124,D1= 3,RMS= .17,ERH= 3.0,ERZ= 3.8
17	9 JUL 1980	21:27:02.2	62.375N	148.660W			2.77		45		WC	NO= 12,GAP= 240,D1= 35,RMS= .21,ERH= 3.3,ERZ= 4.9
18	10 JUL 1980	03:39:49.9	62.981N	149.326W			2.34		87		WC	NO= 13,GAP= 115,D1= 12,RMS= .29,ERH= 3.6,ERZ= 5.1
19	10 JUL 1980	04:46:00.9	62.392N	148.643W			2.21		47		WC	NO= 15,GAP= 236,D1= 33,RMS= .43,ERH= 5.2,ERZ= 6.9
20	10 JUL 1980	10:54:28.0	63.175N	149.034W			3.11		73		WC	NO= 13,GAP= 137,D1= 36,RMS= .20,ERH= 2.1,ERZ= 3.3
21	11 JUL 1980	10:09:35.6	62.419N	147.992W			3.03		49		WC	NO= 15,GAP= 278,D1= 16,RMS= .39,ERH= 5.5,ERZ= 7.8
22	12 JUL 1980	09:13:08.2	62.617N	149.150W			1.75		61		WC	NO= 15,GAP= 147,D1= 15,RMS= .23,ERH= 2.5,ERZ= 3.1
23	12 JUL 1980	14:22:56.5	62.480N	149.415W			1.96		62		WC	NO= 11,GAP= 274,D1= 8,RMS= .11,ERH= 2.0,ERZ= 2.1
24	13 JUL 1980	05:57:43.0	62.596N	148.965W			3.68		55		WC	NO= 12,GAP= 162,D1= 6,RMS= .13,ERH= 1.6,ERZ= 2.1
25	13 JUL 1980	10:17:45.0	63.173N	148.757W			2.53		9		WC	NO= 14,GAP= 236,D1= 26,RMS= .25,ERH= 2.4,ERZ= 8.8
26	13 JUL 1980	11:15:44.2	62.426N	148.998W			2.61		54		WC	NO= 16,GAP= 227,D1= 22,RMS= .14,ERH= 1.8,ERZ= 2.0

TABLE D-I (CONTINUED)

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
27	13 JUL 1980	19:00:45.3	62.820N	148.343W			2.02		60			WC	NO= 13,GAP= 76,D1= 32,RMS= .09,ERH= 1.1,ERZ= 1.6
28	13 JUL 1980	20:48:41.8	62.924N	149.788W			2.72		82			WC	NO= 14,GAP= 271,D1= 12,RMS= .14,ERH= 2.2,ERZ= 2.3
29	15 JUL 1980	13:57:19.3	62.617N	148.867W			1.59		17			WC	NO= 12,GAP= 208,D1= 1,RMS= .27,ERH= 2.8,ERZ= 3.0
30	15 JUL 1980	16:03:24.1	62.453N	148.629W			1.75		15			WC	NO= 8,GAP= 261,D1= 21,RMS= .20,ERH= 3.5,ERZ= 4.5
31	15 JUL 1980	20:12:09.2	62.583N	148.138W			3.40		53			WC	NO= 11,GAP= 137,D1= 4,RMS= .10,ERH= 1.9,ERZ= 2.4
32	15 JUL 1980	20:45:39.5	62.471N	148.290W			3.46		37			WC	NO= 12,GAP= 233,D1= 13,RMS= .45,ERH= 6.0,ERZ= 11.0
33	16 JUL 1980	01:10:04.8	62.530N	148.626W			0.72		14			WC	NO= 6,GAP= 225,D1= 15,RMS= .08,ERH= 2.9,ERZ= 2.5
34	16 JUL 1980	15:12:26.9	62.743N	148.914W			2.08		58			WC	NO= 15,GAP= 65,D1= 15,RMS= .22,ERH= 2.6,ERZ= 3.5
35	17 JUL 1980	08:53:09.0	62.596N	148.901W			1.90		13			WC	NO= 16,GAP= 163,D1= 3,RMS= .47,ERH= 3.1,ERZ= 7.6
36	17 JUL 1980	10:06:26.5	62.554N	148.346W			1.03		23			WC	NO= 10,GAP= 195,D1= 12,RMS= .19,ERH= 3.1,ERZ= 1.7
37	17 JUL 1980	12:54:14.7	62.629N	148.794W			1.59		2			WC	NO= 8,GAP= 247,D1= 36,RMS= .16,ERH= 2.4,ERZ= 63.4
38	17 JUL 1980	12:57:29.9	62.601N	148.874W			0.89		1			WC	NO= 10,GAP= 221,D1= 39,RMS= .29,ERH= 3.4,ERZ= 99.0 DEPTH RESTRICTED DUE TO POOR RESOLUTION.
39	17 JUL 1980	15:53:21.1	62.600N	148.876W			0.85		5			WC	NO= 9,GAP= 222,D1= 39,RMS= .19,ERH= 2.7,ERZ= 19.9
40	17 JUL 1980	21:34:03.6	62.627N	148.861W			1.37		15			WC	NO= 8,GAP= 252,D1= 36,RMS= .25,ERH= 6.8,ERZ= 18.5
41	18 JUL 1980	04:38:45.6	62.596N	148.888W			1.04		5			WC	NO= 9,GAP= 225,D1= 39,RMS= .30,ERH= 5.1,ERZ= 55.3
42	18 JUL 1980	23:40:14.2	62.871N	149.379W			2.46		71			WC	NO= 9,GAP= 113,D1= 13,RMS= .08,ERH= 2.0,ERZ= 1.8
43	19 JUL 1980	08:07:10.4	62.427N	148.458W			1.28		48			WC	NO= 8,GAP= 264,D1= 23,RMS= .07,ERH= 1.7,ERZ= 1.8
44	19 JUL 1980	10:33:13.1	62.616N	148.833W			1.00		15			WC	NO= 8,GAP= 158,D1= 1,RMS= .11,ERH= 1.9,ERZ= 3.2
45	19 JUL 1980	14:21:23.5	63.002N	148.450W			2.22		65			WC	NO= 10,GAP= 155,D1= 13,RMS= .53,ERH= 9.6,ERZ= 9.3
46	19 JUL 1980	20:19:48.2	62.671N	149.611W			1.20		19			WC	NO= 12,GAP= 207,D1= 2,RMS= .19,ERH= 2.7,ERZ= 1.5
47	19 JUL 1980	20:40:02.8	62.475N	148.055W			0.32		18			WC	NO= 7,GAP= 283,D1= 9,RMS= .24,ERH= 6.6,ERZ= 6.6
48	19 JUL 1980	20:52:55.5	62.793N	149.474W			1.25		1			WC	NO= 12,GAP= 206,D1= 13,RMS= .23,ERH= 3.0,ERZ= 99.0
49	20 JUL 1980	06:12:03.8	62.890N	149.060W			1.79		6			WC	NO= 10,GAP= 178,D1= 10,RMS= .16,ERH= 1.8,ERZ= 6.1
50	20 JUL 1980	08:01:25.9	62.417N	148.694W			1.25		13			WC	NO= 10,GAP= 227,D1= 23,RMS= .31,ERH= 3.6,ERZ= 8.3
51	20 JUL 1980	10:12:38.0	62.629N	148.776W			0.56		12			WC	NO= 8,GAP= 143,D1= 4,RMS= .19,ERH= 3.9,ERZ= 4.8

TABLE D-1 (CONTINUED)

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
52	20 JUL 1980	12:33:43.0	62.307N	149.673W			1.79		20				WC NO= 13,GAP= 293,D1= 29,RMS= .30,ERH= 3.6,ERZ= 1.9
53	20 JUL 1980	14:50:02.5	62.417N	148.689W			1.18		17				WC NO= 10,GAP= 227,D1= 24,RMS= .32,ERH= 3.8,ERZ= 6.4
54	20 JUL 1980	20:01:56.6	62.625N	148.759W			0.01		11				WC NO= 7,GAP= 153,D1= 5,RMS= .15,ERH= 2.9,ERZ= 4.1
55	21 JUL 1980	03:31:13.3	62.623N	148.781W			1.06		11				WC NO= 8,GAP= 152,D1= 4,RMS= .22,ERH= 3.8,ERZ= 6.8
56	21 JUL 1980	04:10:06.3	62.633N	148.752W			0.75		9				WC NO= 7,GAP= 143,D1= 5,RMS= .17,ERH= 4.0,ERZ= 8.4
57	21 JUL 1980	09:10:29.2	62.906N	148.838W			0.67		11				WC NO= 9,GAP= 142,D1= 6,RMS= .12,ERH= 1.7,ERZ= 2.7
58	21 JUL 1980	13:12:43.7	62.917N	148.761W			2.12		63				WC NO= 11,GAP= 124,D1= 8,RMS= .13,ERH= 1.9,ERZ= 2.3
59	22 JUL 1980	12:32:46.3	62.629N	148.785W			0.70		12				WC NO= 7,GAP= 140,D1= 4,RMS= .09,ERH= 1.4,ERZ= 2.9
60	22 JUL 1980	20:26:31.9	62.657N	148.709W			0.88		4				WC NO= 10,GAP= 127,D1= 9,RMS= .32,ERH= 2.1,ERZ= 12.8
61	22 JUL 1980	23:26:35.7	62.976N	148.137W			1.37		7				WC NO= 7,GAP= 175,D1= 11,RMS= .21,ERH= 3.9,ERZ= 8.9
62	23 JUL 1980	09:51:21.2	62.546N	148.602W			3.06		55				WC NO= 5,GAP= 213,D1= 15,RMS= .04,ERH= 19.6,ERZ= 39.4
63	23 JUL 1980	10:07:31.8	62.472N	148.383W			2.46		50				WC NO= 14,GAP= 222,D1= 17,RMS= .73,ERH= 9.0,ERZ= 9.7
64	23 JUL 1980	22:24:52.2	62.402N	149.573W			1.32		16				WC NO= 11,GAP= 279,D1= 17,RMS= .33,ERH= 4.4,ERZ= 2.6
65	24 JUL 1980	01:10:20.8	62.849N	149.709W			2.31		79				WC NO= 8,GAP= 268,D1= 18,RMS= .07,ERH= 2.4,ERZ= 2.8 DEPTH RESTRICTED DUE TO POOR RESOLUTION.
66	24 JUL 1980	06:57:07.8	62.604N	148.894W			1.20		10				WC NO= 9,GAP= 187,D1= 3,RMS= .31,ERH= 3.5,ERZ= 6.6
67	24 JUL 1980	09:51:53.9	62.604N	148.869W			1.03		10				WC NO= 10,GAP= 160,D1= 2,RMS= .34,ERH= 3.2,ERZ= 6.4
68	24 JUL 1980	12:27:11.6	62.476N	149.279W			1.26		1				WC NO= 10,GAP= 229,D1= 12,RMS= .24,ERH= 4.3,ERZ= 99.0 DEPTH RESTRICTED DUE TO POOR RESOLUTION.
69	24 JUL 1980	13:32:35.9	62.506N	149.583W			2.15		65				WC NO= 11,GAP= 270,D1= 8,RMS= .29,ERH= 5.2,ERZ= 5.7
70	24 JUL 1980	13:51:11.0	62.625N	148.795W			0.88		10				WC NO= 7,GAP= 248,D1= 36,RMS= .07,ERH= 1.3,ERZ= 4.3
71	24 JUL 1980	23:50:50.1	62.738N	149.106W			0.60		1				WC NO= 9,GAP= 152,D1= 19,RMS= .29,ERH= 2.5,ERZ= 99.0
72	25 JUL 1980	06:19:10.6	63.043N	149.348W			3.16		79				WC NO= 8,GAP= 249,D1= 25,RMS= .07,ERH= 2.6,ERZ= 3.4
73	25 JUL 1980	11:38:59.1	62.624N	148.797W			0.85		13				WC NO= 7,GAP= 146,D1= 3,RMS= .10,ERH= 1.4,ERZ= 3.2
74	25 JUL 1980	18:18:32.9	62.455N	148.436W			1.18		25				WC NO= 8,GAP= 253,D1= 20,RMS= .11,ERH= 2.3,ERZ= 2.8
75	26 JUL 1980	00:26:39.2	62.614N	149.654W			2.00		15				WC NO= 14,GAP= 247,D1= 9,RMS= .30,ERH= 3.0,ERZ= 3.2
76	28 JUL 1980	03:31:25.8	62.502N	148.434W			1.59		27				WC NO= 8,GAP= 230,D1= 18,RMS= .15,ERH= 2.6,ERZ= 3.3

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
77	28 JUL 1980	08:09:58.3	62.594N	148.880W			1.42		10				WC NO= 10,GAP= 190,D1= 3,RMS= .35,ERH= 3.6,ERZ= 6.9
78	28 JUL 1980	11:34:47.9	63.054N	149.145W			1.21		17				WC NO= 7,GAP= 238,D1= 17,RMS= .29,ERH= 6.8,ERZ= 11.7
79	29 JUL 1980	08:39:05.4	62.631N	148.778W			0.90		11				WC NO= 8,GAP= 140,D1= 4,RMS= .13,ERH= 2.2,ERZ= 4.3
80	29 JUL 1980	12:44:08.0	62.921N	148.431W			0.89		4				WC NO= 7,GAP= 119,D1= 19,RMS= .10,ERH= 1.2,ERZ= 11.4
81	29 JUL 1980	14:14:29.7	62.624N	148.796W			0.78		13				WC NO= 7,GAP= 147,D1= 3,RMS= .08,ERH= 1.3,ERZ= 2.5
82	31 JUL 1980	06:26:15.1	63.084N	149.602W			2.62		88				WC NO= 12,GAP= 271,D1= 14,RMS= .09,ERH= 2.1,ERZ= 2.1
83	31 JUL 1980	06:47:31.9	62.980N	149.044W			2.00		71				WC NO= 13,GAP= 173,D1= 8,RMS= .12,ERH= 1.8,ERZ= 1.8
84	31 JUL 1980	22:07:36.7	62.600N	148.874W			0.97		6				WC NO= 9,GAP= 221,D1= 2,RMS= .32,ERH= 4.1,ERZ= 5.9
85	1 AUG 1980	03:09:43.0	62.898N	148.236W			3.43		64				WC NO= 12,GAP= 115,D1= 16,RMS= .07,ERH= 1.2,ERZ= 1.5
86	1 AUG 1980	05:45:11.9	62.581N	149.004W			2.71		58				WC NO= 13,GAP= 167,D1= 9,RMS= .09,ERH= 1.2,ERZ= 1.8
87	1 AUG 1980	14:57:27.9	62.590N	148.890W			0.59		17				WC NO= 7,GAP= 191,D1= 3,RMS= .50,ERH= 6.5,ERZ= 14.0
88	2 AUG 1980	01:40:08.0	62.437N	148.115W			1.23		14				WC NO= 7,GAP= 287,D1= 13,RMS= .07,ERH= 1.9,ERZ= 1.5
89	2 AUG 1980	06:53:10.4	62.469N	147.943W			2.21		45				WC NO= 14,GAP= 287,D1= 13,RMS= .28,ERH= 3.7,ERZ= 3.4
90	3 AUG 1980	10:18:37.5	62.606N	148.847W			1.34		55				WC NO= 13,GAP= 160,D1= 1,RMS= .14,ERH= 1.7,ERZ= 2.1
91	3 AUG 1980	18:59:01.0	62.605N	148.917W			1.87		16				WC NO= 16,GAP= 159,D1= 4,RMS= .37,ERH= 2.4,ERZ= 5.9
92	3 AUG 1980	19:27:28.7	62.595N	148.924W			0.96		14				WC NO= 12,GAP= 163,D1= 4,RMS= .39,ERH= 2.6,ERZ= 7.0
93	3 AUG 1980	22:21:37.0	62.614N	148.846W			0.92		15				WC NO= 8,GAP= 177,D1= 0,RMS= .32,ERH= 4.8,ERZ= 7.3
94	4 AUG 1980	06:24:57.2	62.368N	148.033W			1.34		16				WC NO= 12,GAP= 298,D1= 21,RMS= .11,ERH= 1.4,ERZ= 1.0
95	4 AUG 1980	13:47:56.2	62.611N	148.890W			0.78		15				WC NO= 9,GAP= 157,D1= 2,RMS= .43,ERH= 4.3,ERZ= 8.7
96	4 AUG 1980	23:42:53.5	62.600N	148.911W			1.17		15				WC NO= 12,GAP= 189,D1= 4,RMS= .41,ERH= 4.1,ERZ= 7.6
97	5 AUG 1980	01:59:02.7	62.405N	148.004W			2.06		50				WC NO= 11,GAP= 288,D1= 18,RMS= .30,ERH= 4.9,ERZ= 5.6
98	5 AUG 1980	03:08:56.3	62.611N	148.902W			0.89		17				WC NO= 8,GAP= 185,D1= 3,RMS= .29,ERH= 4.7,ERZ= 7.2
99	5 AUG 1980	05:04:36.5	62.604N	148.886W			0.70		17				WC NO= 10,GAP= 187,D1= 2,RMS= .27,ERH= 3.3,ERZ= 5.7
100	5 AUG 1980	06:01:20.2	62.910N	149.340W			1.98		16				WC NO= 12,GAP= 223,D1= 22,RMS= .33,ERH= 3.6,ERZ= 8.1
101	5 AUG 1980	09:10:12.7	62.609N	148.919W			0.67		16				WC NO= 9,GAP= 204,D1= 4,RMS= .24,ERH= 2.7,ERZ= 5.1
102	5 AUG 1980	12:59:27.1	63.119N	148.520W			3.21		66				WC NO= 10,GAP= 222,D1= 16,RMS= .12,ERH= 3.4,ERZ= 4.1

TABLE D-1 (CONTINUED)

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL INTEN (MM)	MAG SM	H (KM)	DIS (KM)	Q S	LOCATION AND COMMENTS
103	5 AUG 1980	16:15:14.1	62.598N	148.895W		1.12	14		WC	NO= 14,GAP= 162,D1= 3,RMS= .47,ERH= 2.7,ERZ= 7.8
104	6 AUG 1980	10:00:53.1	63.016N	148.766W		1.32	11		WC	NO= 13,GAP= 179,D1= 10,RMS= .41,ERH= 2.8,ERZ= 9.2
105	6 AUG 1980	11:36:50.9	62.609N	148.879W		1.07	15		WC	NO= 14,GAP= 185,D1= 2,RMS= .44,ERH= 2.8,ERZ= 7.7
106	6 AUG 1980	15:31:11.8	62.852N	148.535W		0.59	2		WC	NO= 10,GAP= 94,D1= 22,RMS= .13,ERH= .7,ERZ= 23.8 DEPTH RESTRICTED DUE TO POOR RESOLUTION.
107	6 AUG 1980	23:50:14.1	62.859N	149.306W		1.90	72		WC	NO= 11,GAP= 113,D1= 17,RMS= .12,ERH= 2.5,ERZ= 2.0
108	7 AUG 1980	07:55:00.8	62.604N	148.804W		0.70	14		WC	NO= 7,GAP= 197,D1= 3,RMS= .17,ERH= 2.8,ERZ= 5.1
109	7 AUG 1980	09:50:30.8	62.635N	148.865W		1.06	14		WC	NO= 8,GAP= 155,D1= 2,RMS= .30,ERH= 4.3,ERZ= 7.4
110	7 AUG 1980	14:38:55.5	62.607N	148.899W		0.92	17		WC	NO= 11,GAP= 186,D1= 3,RMS= .27,ERH= 2.6,ERZ= 5.1
111	8 AUG 1980	04:59:36.6	62.613N	148.878W		0.77	16		WC	NO= 13,GAP= 184,D1= 2,RMS= .36,ERH= 2.5,ERZ= 6.4
112	8 AUG 1980	07:39:48.6	62.608N	148.865W		1.15	15		WC	NO= 12,GAP= 219,D1= 1,RMS= .39,ERH= 3.4,ERZ= 6.9
113	8 AUG 1980	09:41:19.7	62.603N	149.547W		1.01	4		WC	NO= 10,GAP= 247,D1= 11,RMS= .39,ERH= 6.4,ERZ= 16.2
114	8 AUG 1980	12:13:00.2	62.480N	148.519W		1.31	27		WC	NO= 14,GAP= 224,D1= 23,RMS= .32,ERH= 3.5,ERZ= 4.7
115	8 AUG 1980	15:51:21.6	62.624N	148.874W		1.00	17		WC	NO= 11,GAP= 188,D1= 2,RMS= .30,ERH= 2.7,ERZ= 5.7
116	9 AUG 1980	01:27:11.6	62.877N	148.987W		1.46	16		WC	NO= 13,GAP= 100,D1= 9,RMS= .33,ERH= 1.8,ERZ= 5.1
117	9 AUG 1980	06:16:39.2	63.129N	148.525W		1.17	6		WC	NO= 7,GAP= 253,D1= 17,RMS= .17,ERH= 2.8,ERZ= 10.2
118	10 AUG 1980	14:28:38.9	62.751N	148.243W		1.90	60		WC	NO= 13,GAP= 185,D1= 18,RMS= .13,ERH= 2.0,ERZ= 2.2
119	10 AUG 1980	16:23:45.5	63.035N	149.255W		1.51	13		WC	NO= 8,GAP= 241,D1= 42,RMS= .28,ERH= 4.2,ERZ= 17.3
120	11 AUG 1980	11:41:02.8	62.809N	148.364W		0.01	2		WC	NO= 8,GAP= 144,D1= 21,RMS= .08,ERH= .5,ERZ= 15.1 DEPTH RESTRICTED DUE TO POOR RESOLUTION.
121	11 AUG 1980	12:36:31.9	62.309N	148.428W		1.54	44		WC	NO= 10,GAP= 290,D1= 32,RMS= .17,ERH= 2.8,ERZ= 3.8
122	12 AUG 1980	02:15:07.0	62.370N	148.110W		1.81	45		WC	NO= 8,GAP= 296,D1= 21,RMS= .06,ERH= 1.2,ERZ= 1.1
123	12 AUG 1980	06:25:45.5	62.816N	149.338W		1.48	16		WC	NO= 13,GAP= 169,D1= 2,RMS= .26,ERH= 1.9,ERZ= 3.0
124	12 AUG 1980	17:46:46.6	62.427N	148.259W		2.28	46		WC	NO= 12,GAP= 265,D1= 16,RMS= .21,ERH= 2.7,ERZ= 3.3
125	12 AUG 1980	21:24:35.7	62.826N	148.326W		1.73	64		WC	NO= 8,GAP= 135,D1= 19,RMS= .12,ERH= 2.5,ERZ= 2.5
126	12 AUG 1980	22:54:57.3	62.351N	150.182W		1.85	19		WC	NO= 12,GAP= 318,D1= 43,RMS= .23,ERH= 3.2,ERZ= 1.7
127	13 AUG 1980	00:08:47.3	62.791N	148.215W		3.28	61		WC	NO= 13,GAP= 97,D1= 14,RMS= .23,ERH= 2.8,ERZ= 3.6

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
128	13 AUG 1980	03:32:59.1	62.662N	148.830W			2.03		57				WC NO= 14,GAP= 84,D1= 5,RMS= .15,ERH= 1.6,ERZ= 2.1
129	13 AUG 1980	09:01:53.7	62.469N	149.928W			1.90		19				WC NO= 14,GAP= 295,D1= 26,RMS= .29,ERH= 3.3,ERZ= 1.9
130	13 AUG 1980	14:43:58.1	62.618N	148.867W			0.70		14				WC NO= 10,GAP= 170,D1= 1,RMS= .40,ERH= 3.8,ERZ= 7.6
131	13 AUG 1980	20:20:15.3	62.966N	149.253W			2.03		71				WC NO= 11,GAP= 172,D1= 16,RMS= .16,ERH= 2.6,ERZ= 2.7
132	13 AUG 1980	21:01:48.5	62.873N	148.258W			0.44		64				WC NO= 8,GAP= 101,D1= 16,RMS= .04,ERH= .9,ERZ= 1.6
133	14 AUG 1980	20:40:17.7	63.290N	149.497W			1.43		1				WC NO= 7,GAP= 287,D1= 37,RMS= .18,ERH= 3.7,ERZ= 99.0 DEPTH RESTRICTED DUE TO POOR RESOLUTION.
134	14 AUG 1980	21:33:02.0	62.821N	149.129W			0.67		17				WC NO= 11,GAP= 127,D1= 10,RMS= .35,ERH= 2.9,ERZ= 5.8
135	15 AUG 1980	00:55:29.4	62.410N	148.978W			1.34		51				WC NO= 9,GAP= 244,D1= 24,RMS= .14,ERH= 2.6,ERZ= 2.9
136	15 AUG 1980	13:13:38.4	62.447N	148.186W			3.50		56				WC NO= 11,GAP= 262,D1= 13,RMS= .12,ERH= 2.2,ERZ= 3.2
137	15 AUG 1980	18:36:09.1	62.436N	148.314W			1.01		51				WC NO= 9,GAP= 267,D1= 17,RMS= .08,ERH= 1.5,ERZ= 1.6
138	16 AUG 1980	11:23:28.1	62.871N	148.361W			1.71		60				WC NO= 8,GAP= 157,D1= 21,RMS= .14,ERH= 2.9,ERZ= 3.2
139	16 AUG 1980	17:56:02.2	63.276N	148.497W			1.78		18				WC NO= 10,GAP= 301,D1= 28,RMS= .26,ERH= 3.7,ERZ= 2.2
140	16 AUG 1980	18:36:25.7	62.891N	149.202W			2.27		63				WC NO= 15,GAP= 135,D1= 16,RMS= .26,ERH= 2.8,ERZ= 3.7
141	16 AUG 1980	21:06:48.8	62.599N	148.890W			0.65		18				WC NO= 8,GAP= 189,D1= 3,RMS= .34,ERH= 3.6,ERZ= 4.9
142	17 AUG 1980	13:32:54.9	62.365N	148.311W			2.36		48				WC NO= 14,GAP= 263,D1= 24,RMS= .18,ERH= 2.7,ERZ= 2.7
143	17 AUG 1980	14:54:41.9	62.369N	149.635W			1.65		16				WC NO= 10,GAP= 287,D1= 22,RMS= .32,ERH= 5.0,ERZ= 3.0
144	18 AUG 1980	01:41:23.5	63.019N	148.481W			2.15		1				WC NO= 9,GAP= 167,D1= 14,RMS= .12,ERH= 1.7,ERZ= 97.6
145	18 AUG 1980	15:39:07.6	63.098N	148.915W			1.56		14				WC NO= 8,GAP= 237,D1= 17,RMS= .24,ERH= 4.1,ERZ= 9.2
146	18 AUG 1980	17:01:27.1	62.497N	148.987W			0.96		21				WC NO= 8,GAP= 248,D1= 15,RMS= .28,ERH= 9.2,ERZ= 5.1
147	18 AUG 1980	23:28:03.1	63.120N	148.845W			0.92		12				WC NO= 9,GAP= 218,D1= 19,RMS= .27,ERH= 3.7,ERZ= 9.6
148	19 AUG 1980	00:25:37.2	62.640N	148.831W			0.85		16				WC NO= 8,GAP= 115,D1= 3,RMS= .40,ERH= 9.6,ERZ= 7.8
149	19 AUG 1980	01:19:29.1	62.505N	149.300W			1.31		11				WC NO= 14,GAP= 215,D1= 10,RMS= .39,ERH= 3.7,ERZ= 6.1
150	19 AUG 1980	10:51:59.6	62.528N	149.148W			1.68		15				WC NO= 16,GAP= 191,D1= 16,RMS= .45,ERH= 3.1,ERZ= 5.2
151	20 AUG 1980	05:34:49.0	62.451N	148.663W			1.31		15				WC NO= 8,GAP= 264,D1= 21,RMS= .16,ERH= 2.4,ERZ= 3.7
152	20 AUG 1980	07:14:45.9	62.406N	148.248W			3.40		47				WC NO= 14,GAP= 261,D1= 18,RMS= .60,ERH= 10.0,ERZ= 9.7

TABLE D-1 (CONTINUED)

TABLE D-1 (CONTINUED)

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL INTEN (MM)	MAG SM	H (KM)	DIS (KM)	Q S	LOCATION AND COMMENTS
153	20 AUG 1980	13:41:47.8	62.962N	149.860W		1.70	16			WC NO= 14,GAP= 285,D1= 15,RMS= .32,ERH= 3.5,ERZ= 1.8
154	20 AUG 1980	23:43:35.2	62.416N	148.236W		2.28	43			WC NO= 8,GAP= 282,D1= 17,RMS= .10,ERH= 2.1,ERZ= 2.2
155	21 AUG 1980	13:01:42.5	62.596N	148.900W		1.46	15			WC NO= 15,GAP= 163,D1= 3,RMS= .47,ERH= 3.3,ERZ= 7.5
156	21 AUG 1980	14:45:20.5	62.498N	149.012W		0.37	20			WC NO= 11,GAP= 223,D1= 15,RMS= .34,ERH= 5.7,ERZ= 2.9
157	21 AUG 1980	16:12:01.9	62.923N	148.677W		1.70	59			WC NO= 10,GAP= 141,D1= 28,RMS= .14,ERH= 2.3,ERZ= 3.1
158	21 AUG 1980	17:04:54.5	62.942N	148.584W		0.72	1			WC NO= 8,GAP= 141,D1= 17,RMS= .77,ERH= 5.0,ERZ= 99.0 DEPTH RESTRICTED DUE TO POOR RESOLUTION.
159	22 AUG 1980	13:24:12.7	62.938N	150.187W		1.62	17			WC NO= 12,GAP= 303,D1= 40,RMS= .13,ERH= 1.5,ERZ= 1.1
160	23 AUG 1980	22:00:05.0	62.954N	149.300W		1.06	70			WC NO= 10,GAP= 229,D1= 33,RMS= .47,ERH= 12.3,ERZ= 10.5
161	24 AUG 1980	01:50:34.6	62.493N	148.926W		1.15	19			WC NO= 8,GAP= 295,D1= 14,RMS= .22,ERH= 3.9,ERZ= 3.5
162	24 AUG 1980	04:29:43.4	62.619N	148.888W		1.65	17			WC NO= 12,GAP= 180,D1= 2,RMS= .30,ERH= 2.7,ERZ= 3.1
163	24 AUG 1980	04:30:51.5	62.626N	148.863W		1.06	16			WC NO= 12,GAP= 129,D1= 2,RMS= .38,ERH= 3.0,ERZ= 5.3
164	24 AUG 1980	12:44:37.1	62.961N	149.141W		2.24	76			WC NO= 8,GAP= 167,D1= 21,RMS= .20,ERH= 6.3,ERZ= 4.5
165	24 AUG 1980	14:00:45.7	62.433N	148.657W		1.79	45			WC NO= 10,GAP= 236,D1= 23,RMS= .15,ERH= 2.6,ERZ= 2.3
166	24 AUG 1980	16:23:06.1	62.901N	148.572W		0.81	2			WC NO= 8,GAP= 201,D1= 25,RMS= .12,ERH= 1.1,ERZ= 30.1 DEPTH RESTRICTED DUE TO POOR RESOLUTION.
167	24 AUG 1980	22:36:26.5	62.738N	148.839W		1.31	59			WC NO= 8,GAP= 185,D1= 43,RMS= .07,ERH= 1.4,ERZ= 1.9
168	25 AUG 1980	04:45:35.3	62.895N	149.462W		2.53	71			WC NO= 14,GAP= 127,D1= 9,RMS= .15,ERH= 2.4,ERZ= 2.1
169	25 AUG 1980	10:06:50.5	62.600N	148.897W		1.06	15			WC NO= 11,GAP= 188,D1= 3,RMS= .47,ERH= 5.1,ERZ= 8.7
170	25 AUG 1980	12:16:40.6	62.611N	148.893W		1.04	16			WC NO= 12,GAP= 185,D1= 2,RMS= .39,ERH= 3.0,ERZ= 7.0
171	25 AUG 1980	16:17:09.4	63.130N	149.304W		1.31	17			WC NO= 12,GAP= 244,D1= 23,RMS= .24,ERH= 2.9,ERZ= 2.6
172	25 AUG 1980	20:10:06.6	63.070N	149.158W		1.40	8			WC NO= 9,GAP= 213,D1= 24,RMS= .12,ERH= 2.1,ERZ= 6.5
173	27 AUG 1980	00:15:16.0	62.428N	148.383W		1.87	45			WC NO= 13,GAP= 235,D1= 20,RMS= .09,ERH= 1.2,ERZ= 1.4
174	27 AUG 1980	01:10:50.1	62.906N	148.870W		1.46	65			WC NO= 8,GAP= 143,D1= 35,RMS= .06,ERH= 1.1,ERZ= 1.6
175	27 AUG 1980	09:10:13.1	62.839N	148.388W		1.68	60			WC NO= 12,GAP= 96,D1= 23,RMS= .15,ERH= 1.6,ERZ= 2.6
176	27 AUG 1980	10:28:31.7	62.656N	149.191W		1.48	67			WC NO= 8,GAP= 179,D1= 22,RMS= .20,ERH= 5.4,ERZ= 4.9
177	27 AUG 1980	15:40:32.8	62.490N	149.036W		1.18	18			WC NO= 14,GAP= 203,D1= 13,RMS= .34,ERH= 3.1,ERZ= 3.6

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL INTEN (MM)	MAG SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
178	27 AUG 1980	18:16:31.2	62.495N	149.019W		0.96	21				WC NO= 8,GAP= 199,D1= 12,RMS= .26,ERH= 6.0,ERZ= 2.5 DEPTH RESTRICTED DUE TO POOR RESOLUTION.
179	27 AUG 1980	20:34:24.1	62.483N	148.983W		1.29	21				WC NO= 10,GAP= 227,D1= 12,RMS= .16,ERH= 2.0,ERZ= 1.9
180	28 AUG 1980	11:30:04.2	62.592N	149.099W		1.53	55				WC NO= 13,GAP= 163,D1= 11,RMS= .18,ERH= 2.3,ERZ= 2.7
181	28 AUG 1980	19:03:42.6	62.506N	149.011W		0.59	21				WC NO= 8,GAP= 192,D1= 11,RMS= .34,ERH= 7.2,ERZ= 5.1
182	29 AUG 1980	09:12:28.2	62.496N	148.942W		1.09	19				WC NO= 10,GAP= 264,D1= 10,RMS= .23,ERH= 2.6,ERZ= 2.8
183	29 AUG 1980	11:56:49.7	62.500N	148.999W		1.20	19				WC NO= 10,GAP= 220,D1= 11,RMS= .45,ERH= 5.6,ERZ= 5.5
184	29 AUG 1980	19:12:18.1	62.497N	148.971W		1.26	18				WC NO= 10,GAP= 218,D1= 11,RMS= .30,ERH= 3.6,ERZ= 3.5
185	29 AUG 1980	19:55:43.6	62.478N	148.960W		1.18	19				WC NO= 8,GAP= 277,D1= 11,RMS= .06,ERH= .9,ERZ= .9
186	30 AUG 1980	00:54:36.5	62.590N	149.073W		1.67	56				WC NO= 14,GAP= 161,D1= 10,RMS= .21,ERH= 2.5,ERZ= 3.1
187	30 AUG 1980	06:33:17.3	62.616N	148.888W		1.70	16				WC NO= 15,GAP= 108,D1= 4,RMS= .48,ERH= 2.8,ERZ= 5.0
188	30 AUG 1980	08:17:33.9	62.505N	148.960W		0.85	19				WC NO= 11,GAP= 212,D1= 10,RMS= .24,ERH= 2.9,ERZ= 2.7
189	30 AUG 1980	09:05:18.1	62.509N	148.960W		0.92	18				WC NO= 12,GAP= 210,D1= 9,RMS= .28,ERH= 3.1,ERZ= 2.9
190	30 AUG 1980	11:13:15.4	62.519N	149.296W		1.09	10				WC NO= 11,GAP= 216,D1= 22,RMS= .41,ERH= 4.6,ERZ= 9.8
191	30 AUG 1980	15:39:48.6	62.341N	148.279W		1.43	46				WC NO= 10,GAP= 278,D1= 25,RMS= .09,ERH= 1.6,ERZ= 1.5
192	30 AUG 1980	16:15:08.0	62.616N	148.859W		0.65	15				WC NO= 9,GAP= 120,D1= 4,RMS= .32,ERH= 4.0,ERZ= 5.4
193	31 AUG 1980	10:49:53.5	62.484N	149.010W		1.12	19				WC NO= 16,GAP= 204,D1= 13,RMS= .32,ERH= 2.3,ERZ= 3.0
194	31 AUG 1980	10:52:53.0	62.487N	148.942W		0.61	19				WC NO= 10,GAP= 253,D1= 10,RMS= .19,ERH= 2.7,ERZ= 2.2
195	31 AUG 1980	15:01:30.7	62.731N	149.769W		1.40	19				WC NO= 8,GAP= 265,D1= 9,RMS= .11,ERH= 1.8,ERZ= 1.1
196	31 AUG 1980	22:21:12.5	62.497N	148.937W		0.75	17				WC NO= 10,GAP= 247,D1= 10,RMS= .19,ERH= 2.3,ERZ= 2.9
197	1 SEP 1980	01:49:29.8	62.895N	149.020W		0.85	12				WC NO= 13,GAP= 141,D1= 6,RMS= .31,ERH= 2.4,ERZ= 3.1
198	1 SEP 1980	19:33:08.5	62.351N	148.191W		1.62	46				WC NO= 12,GAP= 279,D1= 23,RMS= .05,ERH= .9,ERZ= .8
199	2 SEP 1980	05:18:11.4	62.471N	149.042W		1.23	15				WC NO= 17,GAP= 214,D1= 15,RMS= .43,ERH= 3.8,ERZ= 5.6
200	2 SEP 1980	09:39:23.7	62.477N	149.011W		1.56	16				WC NO= 18,GAP= 209,D1= 13,RMS= .41,ERH= 3.2,ERZ= 4.0
201	2 SEP 1980	09:48:50.7	62.719N	148.327W		2.53	51				WC NO= 11,GAP= 92,D1= 21,RMS= .08,ERH= 1.4,ERZ= 2.6
202	2 SEP 1980	13:28:09.0	62.490N	149.005W		0.77	19				WC NO= 14,GAP= 200,D1= 12,RMS= .33,ERH= 2.8,ERZ= 3.4

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
203	2 SEP 1980	23:12:08.2	62.868N	148.626W			1.96		16			WC	NO= 14,GAP= 121,D1= 6,RMS= .27,ERH= 1.7,ERZ= 2.9
204	3 SEP 1980	01:03:52.9	62.931N	148.132W			1.56		62			WC	NO= 7,GAP= 158,D1= 14,RMS= .15,ERH= 5.9,ERZ= 4.0
205	3 SEP 1980	05:53:34.6	62.619N	148.791W			0.61		13			WC	NO= 9,GAP= 120,D1= 6,RMS= .15,ERH= 1.6,ERZ= 3.1
206	3 SEP 1980	12:13:10.2	62.630N	149.450W			1.98		61			WC	NO= 13,GAP= 192,D1= 11,RMS= .15,ERH= 2.2,ERZ= 2.3
207	3 SEP 1980	14:33:08.0	62.490N	148.933W			1.24		19			WC	NO= 10,GAP= 250,D1= 10,RMS= .17,ERH= 2.9,ERZ= 2.0
208	3 SEP 1980	14:33:10.7	62.513N	148.942W			1.24		17			WC	NO= 10,GAP= 239,D1= 8,RMS= .34,ERH= 5.7,ERZ= 4.0
209	3 SEP 1980	15:06:44.8	62.958N	148.940W			1.00		16			WC	NO= 7,GAP= 262,D1= 9,RMS= .16,ERH= 4.7,ERZ= 3.1
210	4 SEP 1980	06:43:10.5	62.521N	149.015W			0.59		15			WC	NO= 11,GAP= 184,D1= 10,RMS= .46,ERH= 4.4,ERZ= 5.5
211	5 SEP 1980	07:51:50.7	62.919N	149.040W			0.96		10			WC	NO= 12,GAP= 194,D1= 8,RMS= .77,ERH= 6.8,ERZ= 13.7
212	5 SEP 1980	12:00:13.4	63.070N	148.577W			1.40		68			WC	NO= 9,GAP= 222,D1= 18,RMS= .07,ERH= 1.7,ERZ= 1.5
213	6 SEP 1980	03:41:26.1	62.663N	148.943W			1.40		61			WC	NO= 16,GAP= 115,D1= 10,RMS= .19,ERH= 1.9,ERZ= 2.6
214	6 SEP 1980	16:15:37.8	62.491N	149.005W			1.40		18			WC	NO= 17,GAP= 200,D1= 12,RMS= .42,ERH= 2.9,ERZ= 4.0
215	7 SEP 1980	11:28:34.3	62.882N	148.135W			1.43		59			WC	NO= 10,GAP= 133,D1= 11,RMS= .12,ERH= 2.0,ERZ= 2.2
216	7 SEP 1980	14:37:14.6	62.492N	148.928W			0.61		18			WC	NO= 10,GAP= 248,D1= 10,RMS= .14,ERH= 2.0,ERZ= 1.7
217	8 SEP 1980	06:40:34.9	62.929N	148.773W			1.76		68			WC	NO= 7,GAP= 147,D1= 9,RMS= .10,ERH= 2.2,ERZ= 2.3
218	8 SEP 1980	21:52:57.4	62.713N	148.394W			1.48		50			WC	NO= 12,GAP= 128,D1= 23,RMS= .09,ERH= 1.0,ERZ= 1.5
219	8 SEP 1980	23:29:29.1	62.846N	148.462W			1.43		62			WC	NO= 10,GAP= 128,D1= 23,RMS= .14,ERH= 2.6,ERZ= 2.7
220	9 SEP 1980	22:48:33.6	62.954N	148.687W			1.81		71			WC	NO= 9,GAP= 152,D1= 14,RMS= .13,ERH= 3.6,ERZ= 3.2
221	10 SEP 1980	14:09:08.5	62.486N	148.980W			1.04		19			WC	NO= 13,GAP= 200,D1= 12,RMS= .30,ERH= 3.0,ERZ= [illegible].2
222	10 SEP 1980	16:48:23.7	62.725N	148.252W			0.93		35			WC	NO= 8,GAP= 138,D1= 20,RMS= .11,ERH= 1.7,ERZ= 2.8
223	10 SEP 1980	22:43:22.5	62.732N	148.252W			1.12		33			WC	NO= 10,GAP= 131,D1= 19,RMS= .11,ERH= 1.2,ERZ= 2.3
224	10 SEP 1980	23:17:19.1	62.685N	149.370W			1.01		1			WC	NO= 12,GAP= 159,D1= 13,RMS= .26,ERH= 1.5,ERZ= 99.0
225	11 SEP 1980	01:52:22.8	62.631N	149.476W			1.00		13			WC	NO= 12,GAP= 197,D1= 10,RMS= .26,ERH= 2.4,ERZ= 3.7
226	11 SEP 1980	03:07:51.8	62.864N	148.1[illegible]W			3.37		58			WC	NO= 13,GAP= 110,D1= 13,RMS= .21,ERH= 2.8,ERZ= 3.5
227	11 SEP 1980	11:40:38.4	62.513N	148.969W			1.56		52			WC	NO= 16,GAP= 182,D1= 9,RMS= .19,ERH= 2.0,ERZ= 2.3
228	11 SEP 1980	12:09:53.0	62.862N	148.153W			2.68		60			WC	NO= 15,GAP= 116,D1= 11,RMS= .11,ERH= 1.1,ERZ= 1.4

TABLE D-1 (CONTINUED)

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
229	11 SEP 1980	14:13:30.6	62.844N	149.408W			1.03		15				WC NO= 11,GAP= 117,D1= 5,RMS= .21,ERH= 1.7,ERZ= 2.5
230	11 SEP 1980	21:15:34.6	62.583N	148.757W			1.51		56				WC NO= 14,GAP= 90,D1= 6,RMS= .09,ERH= 1.0,ERZ= 1.3
231	12 SEP 1980	03:37:45.9	62.842N	148.982W			1.60		63				WC NO= 12,GAP= 117,D1= 6,RMS= .17,ERH= 2.6,ERZ= 3.0
232	12 SEP 1980	04:27:59.4	62.779N	149.432W			1.70		15				WC NO= 19,GAP= 118,D1= 8,RMS= .36,ERH= 2.0,ERZ= 3.5
233	12 SEP 1980	05:48:35.6	62.587N	149.397W			1.09		1				WC NO= 12,GAP= 224,D1= 16,RMS= .27,ERH= 2.6,ERZ= 99.0
234	12 SEP 1980	20:27:21.2	62.592N	148.903W			0.50		16				WC NO= 10,GAP= 134,D1= 2,RMS= .30,ERH= 2.4,ERZ= 3.6
235	14 SEP 1980	00:19:28.6	62.517N	149.619W			2.34		60				WC NO= 6,GAP= 282,D1= 20,RMS= .13,ERH= 5.8,ERZ= 4.6
236	14 SEP 1980	17:57:15.7	62.804N	149.283W			0.39		1				WC NO= 6,GAP= 105,D1= 21,RMS= .05,ERH= .7,ERZ= 35.7
237	15 SEP 1980	23:02:45.0	62.776N	148.356W			2.43		66				WC NO= 15,GAP= 80,D1= 22,RMS= .14,ERH= 1.5,ERZ= 1.9
238	16 SEP 1980	01:19:53.4	62.608N	148.889W			0.70		14				WC NO= 13,GAP= 127,D1= 18,RMS= .25,ERH= 1.6,ERZ= 4.7
239	17 SEP 1980	02:57:31.8	62.662N	149.551W			1.79		15				WC NO= 13,GAP= 198,D1= 5,RMS= .20,ERH= 1.8,ERZ= 3.2
240	17 SEP 1980	03:30:05.9	62.971N	149.152W			1.03		14				WC NO= 9,GAP= 172,D1= 16,RMS= .28,ERH= 3.4,ERZ= 5.2
241	17 SEP 1980	15:19:14.5	62.759N	149.349W			0.65		13				WC NO= 7,GAP= 178,D1= 15,RMS= .19,ERH= 4.8,ERZ= 5.8
242	17 SEP 1980	19:56:57.8	63.056N	149.225W			1.78		7				WC NO= 16,GAP= 212,D1= 20,RMS= .25,ERH= 1.8,ERZ= 6.8
243	18 SEP 1980	08:33:12.6	62.490N	148.440W			1.29		23				WC NO= 13,GAP= 190,D1= 17,RMS= .17,ERH= 1.4,ERZ= .9
244	18 SEP 1980	14:52:44.7	62.833N	148.615W			2.11		60				WC NO= 7,GAP= 149,D1= 16,RMS= .24,ERH= 5.3,ERZ= 6.1
245	19 SEP 1980	11:09:03.3	62.805N	149.576W			1.15		12				WC NO= 8,GAP= 248,D1= 13,RMS= .19,ERH= 2.6,ERZ= 3.6
246	20 SEP 1980	10:50:16.7	62.964N	149.396W			0.85		10				WC NO= 7,GAP= 205,D1= 8,RMS= .18,ERH= 2.1,ERZ= 3.7
247	21 SEP 1980	06:59:06.1	62.829N	148.408W			1.26		67				WC NO= 9,GAP= 167,D1= 24,RMS= .06,ERH= 1.8,ERZ= 1.3
248	21 SEP 1980	09:41:52.8	62.709N	148.864W			2.66		53				WC NO= 16,GAP= 84,D1= 14,RMS= .17,ERH= 1.4,ERZ= 2.2
249	21 SEP 1980	13:47:52.8	62.375N	148.774W			1.32		48				WC NO= 13,GAP= 270,D1= 9,RMS= .15,ERH= 2.0,ERZ= 2.3
250	21 SEP 1980	23:13:07.8	62.607N	149.541W			0.82		10				WC NO= 8,GAP= 286,D1= 10,RMS= .10,ERH= 1.6,ERZ= 2.2
251	22 SEP 1980	10:18:14.2	62.977N	149.020W			1.31		17				WC NO= 11,GAP= 171,D1= 12,RMS= .30,ERH= 2.1,ERZ= 4.1
252	22 SEP 1980	11:49:18.0	62.619N	149.530W			1.45		8				WC NO= 13,GAP= 219,D1= 9,RMS= .17,ERH= 1.7,ERZ= 3.0
253	22 SEP 1980	21:59:52.8	62.413N	148.760W			1.15		20				WC NO= 14,GAP= 264,D1= 5,RMS= .22,ERH= 2.1,ERZ= 1.4
254	23 SEP 1980	03:42:01.5	62.674N	149.417W			1.60		62				WC NO= 11,GAP= 171,D1= 10,RMS= .24,ERH= 3.8,ERZ= 3.7

TABLE D-1 (CONTINUED)

CAT. NO.	DATE DAY-MO-YEAR	TIME(GMT) HR-MIN-SEC	LAT	LONG	SL	INTEN (MM)	MAG	SM	H (KM)	DIS (KM)	Q	S	LOCATION AND COMMENTS
255	23 SEP 1980	23:51:58.3	62.972N	148.359W			1.96		10				WC NO= 15,GAP= 126,D1= 12,RMS= .30,ERH= 1.7,ERZ= 4.6
256	24 SEP 1980	00:34:32.2	62.671N	148.944W			1.96		60				WC NO= 10,GAP= 116,D1= 23,RMS= .10,ERH= 1.6,ERZ= 2.1
257	24 SEP 1980	05:15:55.3	62.975N	148.347W			1.56		10				WC NO= 8,GAP= 143,D1= 11,RMS= .13,ERH= 1.1,ERZ= 3.2
258	24 SEP 1980	05:18:16.2	62.307N	148.148W			1.68		18				WC NO= 13,GAP= 288,D1= 36,RMS= .25,ERH= 2.9,ERZ= 1.6
259	24 SEP 1980	07:50:04.7	62.525N	149.176W			1.48		54				WC NO= 8,GAP= 242,D1= 16,RMS= .17,ERH= 4.1,ERZ= 4.0
260	24 SEP 1980	12:02:00.3	62.564N	149.164W			2.16		57				WC NO= 12,GAP= 183,D1= 15,RMS= .07,ERH= 1.1,ERZ= 1.1
261	24 SEP 1980	12:18:04.8	62.972N	148.928W			1.42		58				WC NO= 6,GAP= 167,D1= 32,RMS= .12,ERH= 6.0,ERZ= 6.6
262	25 SEP 1980	03:44:52.7	62.489N	148.994W			1.98		20				WC NO= 15,GAP= 200,D1= 12,RMS= .29,ERH= 2.7,ERZ= 2.1
263	25 SEP 1980	21:05:29.3	62.983N	149.093W			2.00		10				WC NO= 16,GAP= 176,D1= 15,RMS= .30,ERH= 1.8,ERZ= 7.4
264	26 SEP 1980	00:41:00.9	63.278N	148.927W			1.62		3				WC NO= 9,GAP= 263,D1= 43,RMS= .11,ERH= 3.0,ERZ= 35.0 DEPTH RESTRICTED DUE TO POOR RESOLUTION.
265	26 SEP 1980	02:11:13.2	62.441N	148.680W			1.28		14				WC NO= 14,GAP= 228,D1= 4,RMS= .22,ERH= 2.0,ERZ= 2.3
266	27 SEP 1980	20:05:18.0	63.050N	148.950W			1.87		13				WC NO= 9,GAP= 272,D1= 19,RMS= .39,ERH= 6.2,ERZ= 14.6
267	27 SEP 1980	21:57:24.7	62.733N	148.941W			1.60		61				WC NO= 8,GAP= 196,D1= 16,RMS= .04,ERH= 1.1,ERZ= 1.0
268	28 SEP 1980	07:40:21.5	62.460N	148.707W			1.06		19				WC NO= 8,GAP= 283,D1= 16,RMS= .14,ERH= 2.2,ERZ= 3.1

APPENDIX E - ESTIMATION OF PRELIMINARY MAXIMUM CREDIBLE EARTHQUAKES

E.1 - Introduction

The approach to estimating the preliminary maximum credible earthquakes (PMCEs) in a region, and thereby to establishing a basis for estimating the ground motion at a specific site, is based on the premise that significant earthquake activity is associated with faults with recent displacement. The evaluation of the PMCE that may be associated with a given fault is closely related to the tectonic, geologic, and seismologic evaluations of fault activity in the region of the site. Therefore, it is necessary to identify and describe the characteristics and behavior of the faults which have had recent displacement in the region that may be significant to the site even though they may not pass through the site. After the faults significant to a site have been identified, the PMCE for these sources can be estimated.

The term preliminary maximum credible earthquake as it is used in this report is Woodward-Clyde Consultants' preliminary estimate, based on limited available data, of the maximum credible earthquake that can occur along a fault with recent displacement. Additional geologic and seismologic studies need to be conducted to refine judgments regarding the size of the maximum credible earthquake that can occur along these faults. Until these additional studies are conducted, the maximum credible earthquakes described in this report are considered preliminary in nature and are so designated.

Estimates of the PMCE that can occur along a given fault consider one or more aspects of the relative behavior between faults. Those aspects of behavior--fault parameters--can be compared among faults being evaluated to establish a relative fault ranking with respect to themselves and with respect to other faults from around the world. Within the ranking, various faults having similar fault parameters are expected to behave like one another (within rational limits) and, thus, have similar earthquake potential. Hence, the predictive capabilities of the geologist/seismologist in estimating PMCEs depend largely upon the available data on the fault(s) being evaluated.

The principal fault parameters used in evaluating fault behavior include: 1) tectonic setting; 2) geologic-structural setting; 3) style of faulting; 4) physical geometry and mechanical properties of the fault; 5) geologic history of the fault; 6) geologic strain or slip rate; 7) the size, periodicity, and energy of seismic events; 8) historical seismicity; 9) fault rupture length; and 10) slip per fault-rupture event.

While it would be most desirable to use all of these fault parameters together in an evaluation of maximum magnitude, in actual practice, only a few of the parameters are available for most individual faults. Of these fault parameters, rupture length and slip per event are most frequently used by themselves to estimate directly the potential earthquake magnitudes. Empirical relationships have been used relating historical rupture lengths and slip per event to magnitude. By selection of an appropriate rupture length or by use of geologic evidence of slip per event, a corresponding maximum magnitude can be derived from the empirical relations.

Such techniques, when used by themselves, can provide results with large errors because they fail to consider the complexities of fault behavior. For example, strike-slip faults in Japan often rupture 100 percent of their length whereas faults in California rupture approximately 30 percent of their lengths during the largest earthquakes. Although rupture length is the single most widely used parameter to estimate magnitudes of earthquakes (primarily because fault rupture length appears to be an easy parameter to estimate), there are no consistent or reliable guidelines for selection of the appropriate length of rupture that considers fault behavior.

The rather arbitrary selection of a rupture length, such as 50 percent or 100 percent of fault length, without consideration of other fault parameters affecting fault behavior, should be considered preliminary and the magnitude estimates should be used for comparison purposes only. The most rational approach in estimating maximum credible magnitude considers both qualitative and quantitative (i. e., empirical) parameters for ranking faults and characterizing maximum credible earthquakes. Estimates resulting from the various techniques should be consistent among themselves as well as reasonable according to qualitative factors of the evaluation.

For this preliminary study, because of the lack of more detailed information, the PMCE for the crustal faults and lineaments was estimated using fault rupture length. It is recognized that this can result in an unrealistically large earthquake being hypothesized for a given fault. However, the relatively uniform availability of data for this parameter allows an equal basis for comparison of earthquake potential. In addition to the known faults, estimates of PMCEs for the candidate significant features and significant features have been estimated to provide an understanding of the potential impact of these features should they be shown to have recent displacement. Thus, the estimates presented here are not intended as a final assessment of the maximum credible earthquake for these sources but are preliminary in nature. A review of the method is presented below.

E.2 - Fault Parameter Method--Magnitude versus Rupture Length

Empirical correlations based primarily on geologic effects resulting from the release of strain (or energy) from an earthquake-generating volume were initialy proposed by Tsuboi (1956). Tocher (1958) used this concept to formulate relationships of surface-rupture length and displacement to magnitude for specific faults in the California-Nevada region. The method was further refined by several workers including Bonilla and Buchanan (1970) who prepared a compilation of the relationships of length, magnitude, and displacement. Their formulations and graphs have often been used in estimating maximum credible earthquakes for active fault zones. Slemmons (1977) has updated and revised many of the relationships. Other workers, such as Wyss (1979), have proposed using the area of fault rupture in the subsurface to estimate maximum magnitude.

Slemmons' (1977) empirical relationships have been used during this study to estimate maximum credible earthquakes from feature lengths. The judgments used to apply Slemmons' relationships to the features are discussed below. It is important, however, to discuss some of the constraints associated with this method. These constraints include the fact that we know very little about predicting future rupture lengths on faults. We do know that most surface faulting in the western United States ruptures only a small fraction of the total length of the entire fault zone. This fractional rupture-length behavior of faults led to the proposal by Wentworth and others (1969) that future faulting should be assumed to occur along one-half the total fault length. Although this is perhaps reasonable for the western United States, application of this criterion may not be appropriate elsewhere in the world. Another significant problem in using this method is estimating the total length of the fault zone because many faults have complex branching (en echelon or other patterns), and portions of a fault may be concealed. It is clear that judgments of fault length can have significant impact on the half-length criterion for rupture suggested by Wentworth and others (1969).

The judgments used to estimate the PMCEs during this study include:

a) The observed length of the fault or lineament is assumed to represent the length of fault that could rupture during a single event. In concept, this is different from the half-fault length method of Wentworth (1969), but, when dealing with features of poorly defined length, it is probably a conservative approach. In effect, it is assumed that the observed length of fault is at least half of its total length; thus, many of the length estimates used for the magnitude estimates during this study are probably conservatively long when compared to the half-length method.

b) The exception to (a) is the Denali fault. The extreme length of this fault, more than 1,250 miles (2,000 km) makes it extremely unlikely that the entire length would rupture during a single event. For the purposes of this preliminary investigation, it is assumed that up to one third of the observed length could rupture during a single event. This fraction of the total fault length is consistent with other worldwide observations of ruptures on long strike-slip faults. It is still a conservative approach, as only the Alaskan earthquake of 1964 and the Chilean earthquake of 1960 are known to have had rupture lengths greater than 415 miles (665 km) and neither of these ruptures occurred along strike-slip faults (Slemmons, 1977). The maximum surface rupture length during the 1906 earthquake along the San Andreas fault was 270 miles, (432 km) (Streitz and Sherburne, 1980).

c) Slemmons' (1977) equations for estimating PMCEs were used. These equations are:

Thrust fault	$M_{max} = 4.145 + 0.717 \text{ Log } L$
Normal fault	$M_{max} = 1.845 + 1.150 \text{ Log } L$
Strike-Slip fault	$M_{max} = 0.597 + 1.351 \text{ Log } L$
Reverse-Oblique fault	$M_{max} = 4.398 + 0.568 \text{ Log } L$
Worldwide faults	$M_{max} = 1.606 + 1.182 \text{ Log } L$

Where M_{max} is the maximum credible earthquake and L is the length in meters.

Where the specific fault type is known, the appropriate equation was used. For lineaments and faults for which the fault type was not known, the equation for worldwide faults was used.

These equations are mean values calculated by Slemmons (1977). To provide an independent assessment of the conservatism of these equations, Wyss's (1979) relationship for magnitude versus fault rupture area was used, that is Wyss's method replaced the method of taking plus or minus one standard deviation for Slemmons' (1977) relationships. This also permitted an assessment of recent discussions in the scientific community (e. g., Mark, 1977; Mark and Bonilla, 1977, Wyss, 1979, 1980; Bonilla, 1980, among others) about how various methods of calculation of maximum credible earthquakes affect the conservatism involved in estimating maximum credible earthquakes.

d) Wyss (1979; 1980) advocates the use of source area versus magnitude as an empirical relation to estimate magnitudes of future earthquakes. Theoretically, this method could provide a more accurate means for estimating maximum magnitude because it takes into account both the rupture length at depth and the width of the rupture area. However, the means of obtaining these values and the utility of this method in contrast to the rupture-length method is a topic of continuing discussion (see for instance, Bonilla (1980)). For this study, as discussed above, Wyss's relationship is used as an independent check on the results obtained using Slemmons' (1977) mean value relationships. The Wyss relationship is:

$M_{max} = \text{Log } A + 4.15$

Where $A = LW$

L = half length of the fault

W = the down dip length of the fault

$W \leq 2/3\ L$ and generally should be 3 to 12 miles (5 to 20 km)

For comparing results of the two methods, the following assumptions were made in the Wyss relationship:

12 miles (20 km) is used for W where the length is greater than 19 miles (30 km) and $W \leq 2/3\ L$ is used for W where the length is less than 19 miles (30 km). The results compare quite consistently for events of magnitude (M_S) greater than approximately 7.0. For magnitudes (M_S) less than 7.0, the Wyss relationship gives a smaller magnitude compared to the results using Slemmons' (1977) relationship.

E.3 - Results

PMCEs were estimated for the boundary faults using Slemmons' (1977) relationships described above in Section E.2. In addition, a preliminary maximum credible earthquake of magnitude (M_S) 8.5 has been assigned to the Benioff zone using the 1964 magnitude (M_S) 8.4 event as a basis. A summary of these results is presented in Section 11.

APPENDIX F - QUALITY ASSURANCE

Woodward-Clyde Consultants maintains a company-wide program of quality assurance pertaining to all aspects of its professional, technical, and support services. The objective of the program is to maintain the quality of company activities including the implementation and completion of a large project such as the seismic studies being conducted for the Susitna Hydroelectric Project.

For the purposes of this program, quality assurance is defined as: A management program of planned and systematic actions, having the objective of providing adequate confidence that services are performed in accordance with standards of professional practice and the requirements of the Client (Acres American Inc.).

The essential components of the quality assurance program are: to establish lines of responsibility, authority, and accountability; to provide a qualified staff; to define the method of operation and to provide documentation of activities; to establish internal review (peer review) procedures; and to provide procedures for auditing.

F.1 - Responsibility, Authority, and Accountability

Dr. Ulrich Luscher is the Principal-in-Charge of the seismic studies conducted for the Susitna Hydroelectric Project. He is responsible for all aspects of the project. George Brogan is the Project Manager who is responsible to the Principal-in-Charge for completion of the scope of services defined in the contract between Acres American Inc. and Woodward-Clyde Consultants.

Professional and technical staff have performed the services required by the Project under the direction of the Project Manager. Outside consultants have also worked under the direction of the Project Manager as part of the professional staff.

F.2 - Methods of Operation

The methods of operation have been established to meet the scope of services in a timely, cost-effective, repeatable manner. They are intended to provide a product that meets the level of quality commensurate with standards of professional practice, the Project, and Acres American Inc. The components of the method are summarized below.

Work Plan

The initial effort on the Project was to prepare a work plan. The plan was based on the Task 4 contractual agreement and describes subtask objectives, task descriptions, time schedules, and budgets.

The work plan identifies the plan for staffing of the project, including the Principal-in-Charge, the Project Manager, and key professional staff members. In addition, the work plan identifies the review staff, project consultants, subcontractors, other firms with whom services must be coordinated, and areas of potential difficulties and/or delays. The completed work plan was approved by the Project Manager and served as the basic guide for providing services on the Project.

Woodward-Clyde Consultants assigned an identification number (14658A) to the Project. A master file is located in the Orange, California, office of Woodward-Clyde Consultants. Upon completion of the project, the file will be kept, abstracted, or disposed of according to the policies established by Acres American Inc. and/or by the Regional Managing Principal of Woodward-Clyde Consultants. All significant information, including the location and content of secondary project files (such as specialized discipline files) are contained in the master file.

Data Acquisition

Data were acquired as outlined in the work plan. Data acquisition was accomplished using methods described in Section 2.5 and in Appendices A and B. Data were acquired with the objective of obtaining results that are objective, true, repeatable, and of known accuracy.

Data Analysis

All data analyses and interpretations are based on logical, systematic procedures. Where it has been appropriate to the project, background considerations and technical concepts utilized in each analysis have been recorded as the analysis was performed, in order that the analytical process could be reconstructed by a knowledgeable reviewer. Only certified or cross-checked computer programs have been used in connection with project calculations and analyses. Certification of project computer programs, such as the Woodward-Clyde Consultants' Earthquake Data Bank, has been conducted in the past and accepted for previous major projects for federal agencies and/or utility clients.

Development of opinions, recommendations, and conclusions has been the major purpose of the project activities. All opinions, criteria, designs, specifications, drawings, recommendations, and conclusions which have been developed are the professional responsibility of the Project Manager. The Project Manager has reviewed the professionals under his responsibility to verify that they have the required capabilities to analyze data and to develop opinions, recommendations, and conclusions commensurate with the needs of the Susitna Hydroelectric Project Task 4 scope of services.

Statement of Opinions, Recommendations, and Conclusions

At appropriate stages, indicated results, conclusions, and recommendations have been discussed with Acres American Inc. Formal discussions have were held on 10 June 1980 prior to initiation of the field studies, on 21 through 23 August 1980 at the conclusion of the field program, and on 22 through 24 October 1980 midway through the data analysis portion of the investigation.

This report constitutes the formal presentation of opinions, recommendations, and conclusions for the 1980 work plan. A similar report will be prepared at the conclusion of the 1981 work plan after project feasibility has been evaluated.

Opinions, recommendations, and conclusions occasionally have been provided orally. Where appropriate, these opinions, recommendations, and conclusions have been documented in the project file.

Peer Review

Review is an integral part of all professional services rendered by Woodward-Clyde Consultants. It consists of requiring that one or more peers review opinions, recommendations, and conclusions to determine their adequacy on the basis of the data which have been acquired and the analysis which has been done. The Project Manager is responsible for the selection of peer reviewers, for assuring that the peer review is made and documented, for verifying that the peer reviewer has the necessary knowledge and skill to perform the review adequately (and is not directly involved in the activity reviewed), and for seeing that the results of the peer review are incorporated in the study. For this project, peer review was supplemented by a formal review board composed of experts in the field of seismic geology. These experts include members of Woodward-Clyde Consultants and an outside consultant described below in Section F.4.

F.3 - Documentation of Activities

Activities including data acquisition and analysis, which are key parts of the study and which lead to the opinions, interpretations, and conclusions upon which this report is based, have been documented in accordance with procedures described in Sections 2.5 and 12 and in Appendices A and B of this report. Documentation is summarized as appropriate in this report. Additional documentation of activities which are important to providing repeatability of results, accurate results, and results that can be adequately reviewed by an independent review are filed in the project master file in the Orange, California, office of Woodward-Clyde Consultants. Supervision of adequate documentation procedures has been the responsibility of the Project Manager. This responsibility has been delegated to key professional members of the project team when appropriate.

F.4 - Internal Review Procedures

As summarized in Section F.2, internal review procedures for this project have included review by the project peer reviewers and by an internal review board (designated the Internal Review Panel). Project peer reviewers were members of the Internal Review Panel and were not involved with the technical production of the portion of the study for which they were providing peer review.

The Internal Review Panel consisted of the peer reviewers, senior members of the Susitna Hydroelectric Project team experienced in seismic studies and Alaska geologic and seismologic conditions, and an outside consultant--Bob Forbes, Professor Emeritus of Geology, University of Alaska at Fairbanks. Table F-1 lists the peer reviewers, the Internal Review Panel members, and their respective review responsibilities. The peer reviewers possess the technical qualifications, practical experience, and professional judgment, in the opinion of the Project Manager and the Principal-in-Charge, to conduct the review of the project. The discussion below presents the details of the review process and the documentation of the results.

The review process included a critical evaluation of the basis and validity of all significant conclusions, opinions, evaluations, recommendations, designs, and other material required as an end result of the project services. The review (including peer review) did not include a complete check of detailed calculations, but emphasized establishing the validity of the technical approach and other procedures used to form an opinion of the suitability of the end result. Specific items considered in the review were:

- Verification of scope and objectives
- Validity of the technical approach
- Validity of data used in analysis of evaluations
- Thoroughness and completeness of the services
- Validity and suitability of end results
- Clarity of presentation, including sketches, drawings, and reports
- Clarity of statement of limitation
- Fullfilment of agreement between Woodward-Clyde Consultants and the Client (Acres American Inc.)

As a final step in their review, the reviewers (including peer reviewers) discussed their findings with the originators and resolved or defined any items of disagreement. When differences remained between originator and reviewers, they were resolved under the direction of the Project Manager or the Principal-in-Charge prior to completion of the review process.

The review process involved the following:

(a) A review was conducted by one peer review member and two members of the Internal Review Panel of the status of the investigation immediately prior to the geologic field reconnaissance study. This review included evaluation of the planned field reconnaissance study. The review was conducted on 27 June 1980. Results of the review were incorporated into the field study. Informal notes document the results of the review.

(b) A peer review was conducted midway through the geologic field reconnaissance study. This review was conducted by a peer reviewer from 29 through 31 July 1980. A memorandum summarizing the results of the review are on file in the master project file.

(c) A review of the geologic field reconnaissance study was conducted by peer reviewers and by the Internal Review Panel members in the field at the conclusion of the field study. The review was conducted from 22 through 24 August 1980. A memorandum summarizing the results of the review are on file in the master project file.

(d) A review of the short-term seismologic monitoring program was conducted by a member of the Internal Review Panel during operation of the network. The review was conducted from 2 through 24 August 1980. Review comments were incorporated into the network operations.

(e) A review of the draft report was made by peer reviewers and by the members of the Internal Review Panel. This review was conducted between 1 and 5 December 1980. Written comments on the reports were incorporated into the final report issued to Acres American Inc. Peer review statements (Figure F-1) were completed by the appropriate peer reviewer and filed in the master project file.

F.5 - Audits

The Quality Assurance Officer in the Orange, California, office of Woodward-Clyde Consultants monitors proper conduct of peer review procedures for projects such as Task 4 of the Susitna Hydroelectric project. In addition, the Quality Assurance Officer of the Western Region of Woodward-Clyde Consultants periodically holds quality assurance audits to verify the proper conduct of the peer review procedures. Procedures for audits are covered in the Woodward-Clyde Consultants Quality Assurance Manual.

TABLE F-1

PROJECT PEER REVIEW AND INTERNAL REVIEW PANEL MEMBERS

Review Member	Affiliation	Subtask Review Responsibility	
		Peer	Internal Review Panel
Dr. Duane Packer	Woodward-Clyde Consultants	4.01, 4.03, 4.05, 4.06	4.01 through 4.06
Dr. Tom Turcotte	Woodward-Clyde Consultants	4.02, 4.06	None
Dr. W. U. Savage	Woodward-Clyde Consultants	4.04	4.02, 4.04, 4.06
George Brogan	Woodward-Clyde Consultants	None	4.01 through 4.06
Dr. Robert Forbes	University of Alaska, Fairbanks	None	4.05, 4.06
Dr. I. M. Idriss	Woodward-Clyde Consultants	4.07, 4.08	None

Notes: Subtask descriptions are:

4.01 - Review of available data
4.02 - Short-term seismologic monitoring
4.03 - Preliminary evaluation of reservoir-induced seismicity
4.04 - Remote sensing analysis
4.05 - Seismic geology reconnaissance
4.06 - Evaluation and reporting
4.07 - Preliminary ground motion studies
4.08 - Preliminary analysis of dam stability

PEER REVIEW DOCUMENTATION

Project____ No.____________

Specified Scope of Review____

____

____

REVIEWER'S STATEMENTS

A. I have reviewed the above-referenced project in accordance with the specified scope. My conclusions are as follows:

	Satis-factory	See Comment Number	Not Applicable
1. Conformation to required scope and definition of service			
2. Basic field and laboratory data			
3. References, documents, and correspondence in files			
4. Assumptions, technical approaches, and solutions			
5. Checking of calculations, drawings, graphs, and tables			
6. Specifications, opinions, judgments, conclusions, and recommendations			
7. Organization, clarity, and completeness of report			
8. Others____________			

Comments:____

____

____

Attached are additional comments Nos.____________________ .

Reviewer____________________ Date____________

B. I have discussed my comments with the originator,____________________,

and all have been resolved as described in attachments________________,

except Nos.____

Reviewer____________________ Date____________

Comments not resolved by reviewer discussions with originator have been resolved as described in attachments____________________

Responsible Principal____________________ Date____________

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PEER REVIEW DOCUMENTATION

APPENDIX G - GLOSSARY

Allochthonous	Formed or occurring elsewhere than in place; of foreign origin or introduced.
Aleutian Megathrust	The major collision boundary between the Pacific and North American Plates where the Pacific Plate is descending into the earth's mantle.
Amygdaloidal	Gas cavities in igneous rocks that have been filled with secondary minerals such as quartz, calcite, chalcedony, or zeolite.
Anastomosing Stream	A stream that divides into or follows a complex network of several small, branching and reuniting shallow channels separated from each other by islands or bars, resembling in plan the strands of a complex braid.
Anelasticity	The effect of attenuation of a seismic wave; it is symbolized by Q.
Aseismic	An area of generally low seismicity that can have tectonic deformation which is not accompanied by earthquakes.
Batholith	A large, generally discordant mass of igneous rock which was intruded originally at depth and now has more than 40 square miles (104 km^2) in surface exposure. It is composed predominantly of medium to coarse grained rocks, often of granodiorite composition.

Benioff zone	Seismicity associated with plates of the earth's crust which are sinking into the upper mantle. In Alaska, the Benioff zone is associated with underthrusting of the Pacific plate beneath the North American plate.
Candidate Feature	A term used in this study to identify faults and lineaments that may affect Project design considerations based on the application of length-distance screening criteria prior to field reconnaissance studies.
Candidate Significant Feature	A term used in this study to identify faults and lineaments that may affect Project design considerations based on length-distance screening criteria and a preliminary assessment of seismic source potential and potential surface rupture through either site using the results of the field reconnaissance studies.
Cataclastic	The granular fragmental texture induced in rocks by mechanical crushing.
Consanguineous	The relationship that exists between igneous rocks that are presumably derived from the same parent magma.
Crag and Tail	An elongate hill or ridge resulting from glaciation. The crag is a steep face or knob of ice-smoothed, resistant bedrock at the end of the ridge from which glacial ice came. The tail is a tapering, streamlined, gentle

	slope of intact weaker rock and/or till that was protected in part from the glacial ice by the crag.
Dextral Fault	A strike-slip fault along which, in plan view, the side opposite the observer appears to have moved to the right.
Drift	All rock material transported by a glacier and deposited directly by or from the ice or by meltwater from the glacier.
Drumlin	An elongate or oval hill of glacial drift.
Ductile	A rock that is able to sustain, under a given set of conditions, 5 to 10 percent deformation before fracturing or faulting.
Dynamometamorphism	The alteration of rock characteristics primarily by mechanical energy (pressure and movement).
End Moraine	A ridge of glacial sediments deposited at the margins of an actively flowing glacier.
Fault	A surface or zone of closely spaced fractures along which materials on one side have been displaced with respect to those on the other side.
Fault with Recent Displacement	As defined for this study, a fault which has had displacement within approximately the last 100,000 years.

Flysch	A thick and extensive deposit largely of sandstone that is formed in a marine environment (geosyncline) adjacent to a rising mountain belt.
Geosyncline	A mobile downwarping of the crust of the earth, either elongate or basin-like, that is subsiding as sedimentary and volcanic rocks accumulate to thicknesses of thousands of meters. Geosynclines are usually measured in scores of kilometers.
Glacial Scour	The eroding action of a glacier, including the removal of surficial material and the abrasion, scratching, and polishing of the bedrock surface by rock fragments dragged along by the glacier.
Gouge	Soft clayey material often present between a vein and a wall or along a fault.
Hypocenter	That point within the earth that is the center of an earthquake and the origin of its elastic waves.
Intercalated	A material that exists as a layer or layers between layers or beds of other rock; interstratified.
Kame	A short ridge, hill, or mound of poorly stratified sediments deposited by glacial meltwater.

Kettle — A steep-sided, usually basin- or bowl-shaped hole or depression without surface drainage in glacial deposits.

Klippe — An outlying isolated remnant of an overthrust rock mass.

Lee — The side of a hill, knob, or prominent rock facing away from the direction from which an advancing glacier or ice sheet moved; facing the downstream side of a glacier.

Lineament — A linear trend with implied structural control (including but not limited to fractures, faults, etc.) typically identified on remotely sensed data.

Lit-par-lit — Having the characteristic of a layered rock, the layers of which have been penetrated by numerous thin, roughly parallel sheets of igneous material.

Magnitude — Magnitude is used to measure the size of instrumentally recorded earthquakes. Several magnitude scales are in common usage (Richter, 1958). The differences in these magnitudes are caused by the way in which they are each calculated, specifically, the periods (frequency) of the waves which are used in each measurement. M_L is the original Richter magnitude which was developed for Southern California earthquakes recorded on Wood-Anderson seismometers (free period 0.8 second) at distances of 372 miles (600 km) or less. M_S and M_b use signals recorded at teleseismic distances 1,240 miles (2,000 km or greater). M_S measures the amplitude of surface waves with periods of 20 seconds and the M_b is a measure of the 1 second body waves. The variations in the magnitude calculations are due in part to the fact that different size earthquakes generate relatively different amounts of energy in these frequency bands.

Metabasalt — Volcanic rock (basalt) altered by temperature and pressure to a metamorphic rock.

Microearthquake — An earthquake having a magnitude (M_L) of three or less on the Richter scale; it is generally not felt.

Migmatite — A rock (gneiss) produced by the injection of igneous material between the laminae of a schistose formation.

Miogeosyncline — A geosyncline in which volcanism is not associated with sedimentation.

Modified Mercalli Scale — An earthquake intensity scale, having twelve divisions ranging from I (not felt by people) to XII (damage nearly total).

Noncomformity — A substantial hiatus in the geologic record that typically implies uplift and erosion. The gap occurs between older igneous or metamorphic rocks and younger sedimentary rocks.

Normal Fault	A fault along which the upper (hanging) wall has moved down relative to the lower wall (footwall).
Pluton	An igneous intrusion formed at great depth.
Pyroclastic	Formed by fragmentation as a result of a volcanic explosion or aerial expulsion from a volcanic vent.
Rejuvenation	Renewed downcutting by a stream caused by regional uplift or a drop in sea level.
Reservoir-Induced Seismicity	The phenomenon of earth movement and resultant seismicity that has a temporal and spatial relationship to a reservoir and is triggered by nontectonic stress.
Reverse Fault	A fault in which the upper (hanging) wall appears to have moved up relative to the lower wall (footwall).
Significant Feature	A term used in this study to identify the faults and lineaments that are considered to have a potential effect on Project design considerations pending additional studies. Selection of these features was made on the basis of length-distance screening criteria and final assessment of their seismic source potential and potential for surface rupture through either site using the results of the field reconnaissance studies.

Slickensides	A polished and smoothly striated surface that results from friction during movement along a fault plane.
Solifluction	The slow (0.2 to 2 inches/yr (0.5 to 5 cm/yr)) creeping of wet soil and other saturated fragmental material down a slope, especially the flow initiated by frost action and augmented by meltwater from alternate freezing and thawing of snow and ground ice.
Stade	A substage of a glacial stage; time represented by glacial deposits.
Stoss	The side or slope of a hill, knob, or prominent rock facing the direction from which an advancing glacier or ice sheet moved; facing the upstream side of a glacier.
Stoss and Lee Topography	An arrangement, in a strongly glaciated area, of small hills or prominent rocks having gentle slopes on the stoss side, and somewhat steeper, plucked slopes on the lee side.
Stratovolcano	A volcano composed of explosively erupted cinders and ash interbedded with occasional lava flows.

Talkeetna Terrain	Region (including the Project) of relatively uniform response within the current stress regime. The Terrain has the following boundaries: the Denali-Totschunda fault on the north and east, the Castle Mountain fault on the south, a broad zone of deformation and volcanoes on the west and the Benioff zone at depth. The Terrain is inferred to be a relatively stable tectonic unit with major strain release occurring along its boundaries.
Thrust fault	A low angle reverse fault.
Whaleback	A small, elongate, protruding knob or hillock of bedrock, most commonly granitic, sculptured by a large glacier so that its long axis is oriented in the direction of ice movement. It is characterized by an upstream side that is gently inclined and smoothly rounded but striated and by a downstream side that is steep and rough.

APPENDIX H - REFERENCES

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