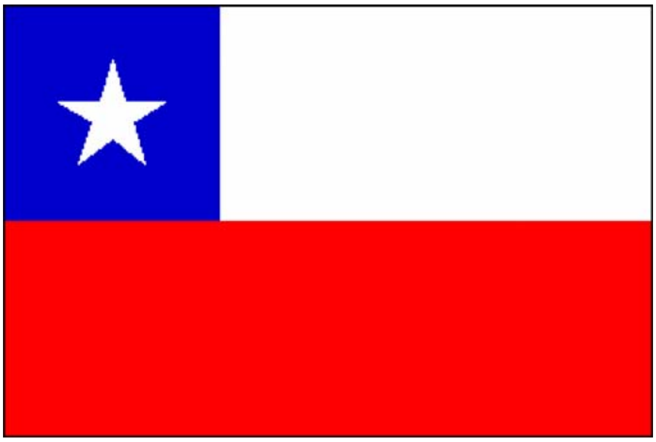
Chapter 4

World Coal Quality Inventory: Chile



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Chapter 4 of

World Coal Quality Inventory: South America

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U.S. Geological Survey Open-File Report 2006-1241

U.S. Department of the Interior
U.S. Geological Survey

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Metric Conversion Factors

Imperial Units	SI conversion
acre	4,046.87 square meters
acre-foot	1,233.49 cubic meters
British thermal unit (Btu)	1,005.056 joules
British thermal unit / pound (Btu / lb)	2,326 joules / kilogram
Fahrenheit (ºF)	Centigrade (ºC) = [(ºF-32)x5]/9
foot (ft)	0.3048 meters
inch (in)	0.0254 meters
mile (mi)	1.609 kilometers
pound (lb)	0.4536 kilograms
short ton (ton)	0.9072 metric tons
short tons / acre-foot	0.7355 kilograms / cubic meter
square mile (mi^2)	2.59 square kilometers

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Introduction

The U.S. Geological Survey (USGS), in cooperation with many of the world's coal producing countries has undertaken a project called the World Coal Quality Inventory (WoCQI). The WoCQI contains coal and ancillary information on samples obtained from major and minor coal-producing regions throughout the world. Sample collection and analytical procedures are described in the Executive Summary (Chapter 1, this volume). As part of the WoCQI, 23 coal samples from Chile were collected and analyzed.

Chile

Lignitic to bituminous coal deposits are widely distributed in the Arauco, Valdivia-Los Lagos, and Magallanes Basins of central and southern Chile (fig. 1). These Paleogene-Neogene sedimentary Basins are located in a coastal plain and continental platform on the western side of the Andean Cordillera. Their subsidence apparently is an isostatic response to the development and uplift of the nearby Andean orogen, which began in the Late Cretaceous (González and others, 1998; Helle and others, 2000; Hildago and others, 2002). In total, the three Basins host approximately 1.2 billion metric tons of coal reserves. The vast majority of Chilean coal is lignitic to subbituminous in rank and is located in the Magallanes Basin in the far south of the country, away from the major population centers (International Energy Agency (IEA) Coal Research, 1996; Helle and others, 2000; Fossil Energy International, 2003).

Geology of Coal Areas

The Arauco, Valdivia-Los Lagos, and Magallanes coal basins host the major coal deposits of Chile. From north to south, coal deposits are described in these basins.

Arauco Basin: The Arauco Basin in central Chile (fig. 2) hosts a number of important bituminous coal deposits in Eocene strata. The lower Eocene Curanilahue Formation (fig. 3) consists of sandstones, shales, and coals and is subdivided into three members; in ascending stratigraphic order, the Lota, the Intercalación, and the Colico members (Collao and others, 1987). In total, the stratigraphic package is, at most, about 340 m thick. The Lota and Colico Members were deposited in coastal lagoon and swamp environments during marine regression (Pineda, 1983). No coal beds are reported from the Intercalación Member which consists of marine fossiliferous glauconitic sandstones and represents a sea-level transgression between the upper and lower members of the Curanilahue. The lowermost member, the Lota, consists of rhythmic alternations of coarse and fine sandstones, shales and coal beds (Collao and others, 1987). There are nine bituminous coal beds in the Lota Member, which are relatively high in sulfur and ash and range in thickness from 0.05-1.2 m (Collao and others, 1987). A detailed palynological and geochemical study of five of the coal beds in the Lota Member indicated that the coals were deposited during a climatic period of relatively high humidity and temperature (Collao and others, 1987).

The middle-upper Eocene Trihueco Formation (fig. 3) is approximately 70 percent sandstone, 25 percent mudrock, and minor amounts of tuff, limestone, and coal and ranges from about 120-320 m in total thickness. The formation was deposited in an ensialic back-arc basin environment which formed as a result of plate subduction and intracontinental spreading and subsidence during the evolution of the Andean orogen (Levi and Aguirre, 1981; Aguirre, 1985).

Valdivia-Los Lagos Basin: Lignitic to subbituminous coals of the Valdivia-Los Lagos Basin (fig. 4) are hosted in the Oligocene-Miocene Santo Domingo Formation (fig. 3) and currently are mined from the Mulpún and Milahuillín mines. Coals of the Basin formed in isolated and irregular sub-basins of limited aerial extent (Helle and others, 2000). Helle and others (2000) describe the Santo Domingo Formation as containing a lower section of alternating paralic coal beds 0.4-2.0 m thick that are separated by marine claystones and sandstones, and an upper section containing a limnic coal bed as much as 10 m thick. This coal bed occurs at the Oligocene-Miocene boundary and is overlain by marine sediments.

Magallanes Basin: Lignitic to subbituminous coals of the Magallanes Basin in southern Chile (fig. 5) constitute the majority of Chilean coal resources. The Basin is relatively large compared to the Arauco and Valdivia-Los Lagos Basins and extends 700 km along a NNW-SSE axis with a maximum width of 370 km (Biddle and others, 1986). Coals are hosted primarily in the upper part of the Oligocene-Miocene Loreto Formation, a thick sequence of sandstones, siltstones, carbonaceous claystones, and coals (Helle and others, 2000) that was deposited in a delta and lagoon environment (Castro, 1997). The coal-bearing strata are folded into gentle synclines and anticlines, bringing coal beds to the surface and to as much as 2500 m deep (Hildalgo and others. 2002). There are thirteen coal beds in the Pecket deposit (Pecket mine), which range in thickness from 0.3-3 m (Hildago and others, 2002); only the upper six beds are accessible to mining by open-pit methods at the Pecket mine (Helle and others, 2000). Hildago and others (2002) conducted a detailed petrographic, geochemical, and mineralogical investigation of the Pecket deposit in order to characterize the combustion properties of the coal for its use as a thermal energy source in electricity generation. Their study found that the Pecket coals are characterized by high vitrinite content and scarce inertinite, which suggests that the peat accumulated in a forested swamp environment infrequently exposed to subaerial conditions (Hildago and others, 2002). Low pyrite content suggests limited marine influence in the sedimentary environment and the presence of quartz-rich sediments between coal beds indicates possible fluvial incursions into the peat swamp

(Hildago and others, 2002).

Coal Resource Assessments

Coal is Chile's most abundant fossil fuel resource and accounts for over eighty-five percent of Chile's thermal energy reserves (International Energy Agency Coal Research, 1996). Estimated resources of the Magallanes Basin are about five billion metric tons (Ministerio de Relaciones Exteriores, 1988). Resources of the Valdivia-Los Lagos Basin are estimated to be 100 million metric tons and resources of the Arauco Basin are estimated to be on the order of five million metric tonnes (Helle and others, 2000). Total reserves are about 1.2 billion metric tons, most of which is in the Magallanes Basin (Fossil Energy International, 2003). Given the magnitude of Chilean coal resources and considering the historical and current rates of coal production, existing reserves are predicted to last well over one hundred years into the future (International Energy Agency Coal Research, 1996).

Coal Production

Commercial coal mining and the utilization of coal as an energy resource in Chile dates to 1824, when coal was first produced from the Lota mine in the Arauco Basin (fig. 2) (Helle and others, 2000). Coals of the Lebu deposit have been exploited continuously since the 1800s and represent one of the primary historical energy resources of Chile (Helle and others, 2000). An account of historical mining operations in Chile is given in Toenges and others (1948), which includes detailed descriptions of the Colico mine and the Lota and Schwager mines, where coal was produced from underground mines located beneath the Pacific Ocean. Domestic coal production in 2003 was approximately 0.5 million metric tons and was primarily from the Lota mines and in the extreme south on the Tierra del Fuego (EIA, 2005). Underground mines in the Arauco Basin hosted two-thirds of Chilean coal production in the late 1980s (Ministerio de Relaciones Exteriores, 1988), and recent exploitation has focused on the deposits at Lebu and Trongol.

Mining in the Magallanes Basin began in the middle of the nineteenth century, when coal was produced from the Loreto mine in the Punta Arenas area (Hildago and others, 2002). After the development of the Pecket deposit in the Magallanes Basin in 1987, optimistic forecasts predicted that national coal production would double over the coming decade (Ministerio de Relaciones Exteriores, 1988). Drought in the late 1980s and early 1990s decreased the availability of domestic hydroelectricity and resulted in increased thermal coal demand (International Energy Agency Coal Research, 1996). However this trend did not continue into the latter half of the 1990s and coal production and utilization as an energy resource has been on the decline in Chile since 1990 (IEA Coal Research, 1996; Hannover Industrial Fair, 1999). Coal production decreased steadily from 2.19 million metric tons in 1990 to 0.36 million metric tons in 2000 (Table 1; Fossil Energy International, 2003). The Lota mine of the Arauco Basin closed in 1997 as high extraction and beneficiation costs made operations unprofitable (Inter Press Service, 1997). Countrywide production is expected to continue to fall in the coming years as the use of natural gas fuels more of Chile's energy demand (Energy Information Administration, 2002a).

The state-run agency Empresa Nacional del Carbón (ENACAR) produced all of Chile's coal prior to 1985. This agency was privatized prior to exploitation of the Pecket deposit and now ENACAR accounts for about a quarter of domestic coal production, operating in the Arauco Basin (International Energy Agency Coal Research, 1996). Other producers in the Arauco Basin include Carvile and Carbonífera Schwager. Coal production in the Magallanes Basin is handled by Compañía Carbones de Chile (COCAR), a private company formed by Chilean and foreign investors.

Coal Uses

Coal primarily is consumed in Chile for electrical power generation. Coal-fired power stations supplied nineteen percent of Chile's power output in 1993 (International Energy Agency, 1995a, b). Eleven coal-fired power stations were operating or in commission by the end of 1995, for a total installed coal-fired capacity of about 1500 megawatts (International Energy Agency Coal Research, 1996). Domestic coal consumption in 2000 was approximately 4.63 million metric tons (Fossil Energy International, 2003) of which 72% was used to generate electricity and 14% was used in steel industry. The remainder of Chile's coal consumption in 2000 was for industry, including cement production, production of food products, and for production of iron and steel products (Fossil Energy International, 2003).

Coal Trade

From 1980 to 1998, imported coal consumed in Chile increased from fifty to eighty-four percent of total coal consumption on a weight basis, primarily as a result of the higher cost of domestically-produced coal (Asia-Pacific Energy Research Center, 1998). Thermal coal is imported from Australia, Indonesia, Colombia, Venezuela, and other countries (Coal Week International, 1994; International Coal Report, 1996a, b), and coking coal is imported for use in the steel industry (International Energy Agency Coal Research, 1996). Future growth in coal imports will be constrained by existing port infrastructure (International Energy Agency Coal Research, 1996). Much of the coal currently mined in the Magallanes Basin is shipped by boat from Puntas Arenas (fig. 5) for consumption in central Chile, which decreases port capacity for coal imported from outside Chile. Coals produced in Chile are consumed internally. Coal has not been exported since 1990 (Energy Information Administration, 2003).

Coal Quality

The USGS, in partnership with the Instituto de Geología Económica Aplicada of the Universidad de Concepción, analyzed 23 samples (Table 2) from active mines in the Arauco, Valdivia-Los Lagos, and

Magallanes Basins, as part of the WoCQI project. Channel coal samples were collected from beds in active mines by G. Alfaro of the Instituto de Geología Económica Aplicada of the Universidad de Concepción and sent to the USGS for analysis.

USGS personnel visited the Lebu and Pecket mines in April 2002 for additional sample collection. Samples were analyzed by the USGS following the analytical methods described in Bullock and others (2002). In addition, samples were analyzed in commercial laboratories following standard American Society for Testing and Materials (ASTM) methods and procedures (ASTM, 1998). Coal quality parameters include proximate and ultimate analyses, sulfur form analyses, free swelling indices, ash fusion temperatures, and major-, minor-, and trace-element concentration analyses (Tables 3-6).

Twenty-three coal samples total were collected; from the Trihueco and Colico Formations in the Arauco Basin (seven samples; six from the Lebu mine, one from the Trongol mine), the Santo Domingo and Malihue Formations in the Valdivia-Los Lagos Basin (six samples; four from the Mulpún mine, and one each from the Malihue and Milahuillín mines), and the Loreto Formation in the Magallanes Basin (ten samples, all from the Pecket mine).

Arauco Basin: Proximate analytical results for coal samples from the Arauco Basin indicate that, on an as-received basis, ash yield ranges from 1.92-33.88 weight percent at the Lebu mine, and 6.56 weight percent in the sample from Trongol (Table 4). Sulfur content ranges from 0.92-3.91 weight percent; the high ash Chiflon sample contains 1.89 weight percent sulfur (Table 4).

On a moist, mineral-free basis (m, mmf), the seven samples from the Arauco Basin range from 14010-14580 Btu/lb (Table 4). Free swelling indices for the seven samples (Table 3) range from 1.5-5.5, indicating that some samples may have good coking properties, particularly the samples from the Alto and

Chico beds at Lebu. On a dry, whole-coal basis, average concentrations of the trace elements arsenic (As) and mercury (Hg) are 1.12 and 0.069 parts-per-million (ppm), respectively. The Chiflon sample contains the highest Hg concentration of the Arauco Basin samples (0.082 ppm) (Table 6).

Valdivia-Los Lagos Basin: Six samples from the Valdivia-Los Lagos Basin range in ash yield from 2.38-85.62 weight percent on an as-received basis (Table 4). The high-ash carbonaceous shale from Malihue is not considered in the following discussion; however, data for this sample is included in Tables 2-6. Excluding the Malihue sample, which is unlikely to represent a large proportion of utilized Valdivia-Las Lagos Basin coal, the remaining five samples average 17.38 weight percent ash. Sulfur content ranges from 0.28-3.85 weight percent (Table 4).

On a moist, mineral-free basis (m, mmf), the seven samples from the Valdivia-Los Lagos Basin range from 460-10940 Btu/lb (Table 4). Free swelling indices indicate that Valdivia-Los Lagos Basin coals are non-agglomerating. The sample from the 3005 seam of the Mulpún deposit contains elevated As and Hg concentrations (72.1 and 2.2 ppm, respectively) relative to the other Valdivia-Los Lagos coals; this sample also contains the highest total sulfur and pyritic sulfur concentrations, suggesting that the high As and Hg concentrations are related to pyrite abundance (Table 6). Helle and others (2000) demonstrated that coals from the Pupunahue deposit of the Valdivia-Los Lagos Basin were moderately elevated in As concentrations relative to other Chilean coals.

Magallanes Basin: Lignitic to subbituminous coals of the Magallanes Basin in southern Chile are hosted in the Oligocene-Miocene Loreto Formation and are mined from the Pecket deposit near Punta Arenas. On an as-received basis, ten samples have ash yields ranging from 11.13-22.90 weight percent. As-received sulfur content is low, averaging 0.51 weight percent, and this value is inflated by the 2.41 weight percent sulfur content of sample 3 (Table 4). Gross calorific value range from 8,520-10,120 Btu/lb (m,mmf basis).

Concentrations of some trace elements from Pecket coals show a positive correlation with ash yield; Ba (r = 0.80), Cs (r = 0.73), Ga (r = 0.67), Ge (r = 0.73), Mn (r = 0.89), Rb (r = 0.76) all show a strong inorganic affinity. In contrast to results obtained by Helle and others (2000), the relation between ash yield and concentrations of B (r = 0.26), and S (r = 0.29) do not suggest an organic affinity for these elements. Concentrations of Mo and U are not related to ash yield and these elements may be associated with organic material. Rb and Cs concentrations show a typical robust correlation with ash yield, and with each other (r = 0.995), implying their association in the akali-metal-rich clay groups kaolinite and smectite, the primary inorganic phases present in Pecket coals (Helle and others, 2000).

Coal Utilization Impacts

Prior to 1980 and the election of a democratic government, environmental impacts of mining and natural resource processing in Chile were not assessed (Trade and Environment Database, 1997; Lagos and Velasco, 1999). In the period 1980 to the present, the elected administrations have taken significant steps towards reducing the effects of mining-related environmental degradation, particularly with copper production, historically Chile's most important natural resource. The introduction of Decree 185 in 1991 which restricts SO_2, As, and particulate emissions established the same air quality standards for Chile as the Clean Air Act set for the United States and introduced the regulation of emissions related to coal consumption (Lagos and Velasco, 1999). The increasingly restrictive regulation of carbon emissions in Chile may lead to decommission of older coal-fired power generation capacity rather than the introduction of expensive pollution control upgrades (IEA Coal Research, 1996). In addition, the development of relatively cleaner natural gas-fired power generation will ultimately curtail emissions (Energy Information Administration, 2002b).

Coalbed Methane

The coalbed methane resources of Chile are poorly defined. Several coalbed methane investigations have been conducted by Chile's national oil and gas company, Empresa Nacional del Petróleo (ENAP), and foreign consultants and companies, but results of these studies are confidential (Schwochow, 1997). All coal basins in Chile have potential for coalbed methane accumulations. An initial survey of the geology and cumulative coal bed thicknesses indicates that Chile's coal basins are similar to other basins in the world that are currently producing coalbed methane. The bituminous coals of the Arauco Basin (fig. 1), which are located near large population centers and sustained gas markets, may have the greatest potential for thermal coal gas accumulation in Chile. However, numerous faults in the Arauco Basin and the offshore extension of a large part of the basin may hamper exploration and production efforts in this region. In the Valdivia-Los Lagos Basin, residual gas measurements made on near-surface subbituminous coal samples from Mulpún (Alfaro G., 2000, Universidad de Concepcion, unpublished report) indicate a minimum gas content of 3 m_3 /ton. Little is known about the gas content of the lignite to subbituminous coals of the Magallanes Basin. Because of the remote location of the Magallanes Basin, any coal gas resources identified may be an important fuel source for the town of Punta Arenas and surrounding communities.

Conclusions

Chile hosts approximately 1.2 billion metric tons of coal reserves; however, most of the reserves are located in the Magallanes Basin in the far south of the country, far from the major population centers and coal consumers. Coal production has experienced a steady decline over the last decade as natural gas has fueled more of the national energy demand and high production costs have limited mining operations. Possibilities for the exploitation of coal bed methane as an energy resource are largely unknown in these coal basins, but the coal geology and cumulative thicknesses of Chile's coal basins suggest that production is achievable.

Acknowledgements

The authors are indebted to Mike Trippi and John Bullock of the USGS for sample preparation and analysis. Comments from technical reviewers Kris Dennen and Bob Milici improved the clarity and presentation of the manuscript.

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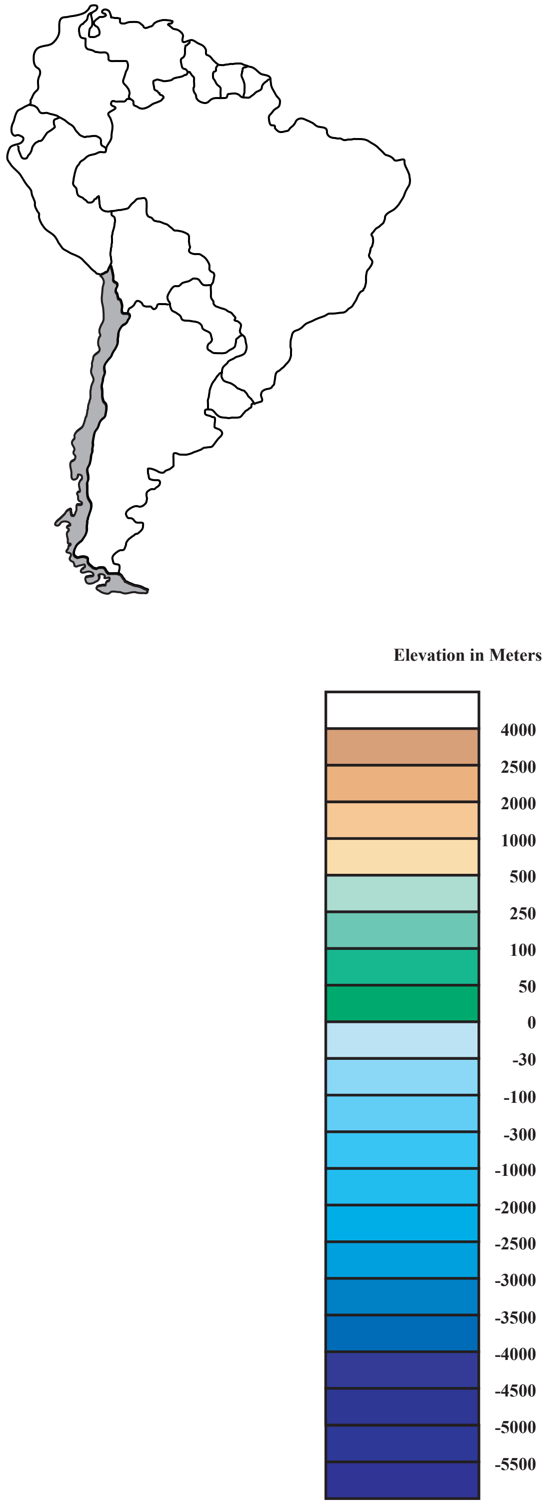

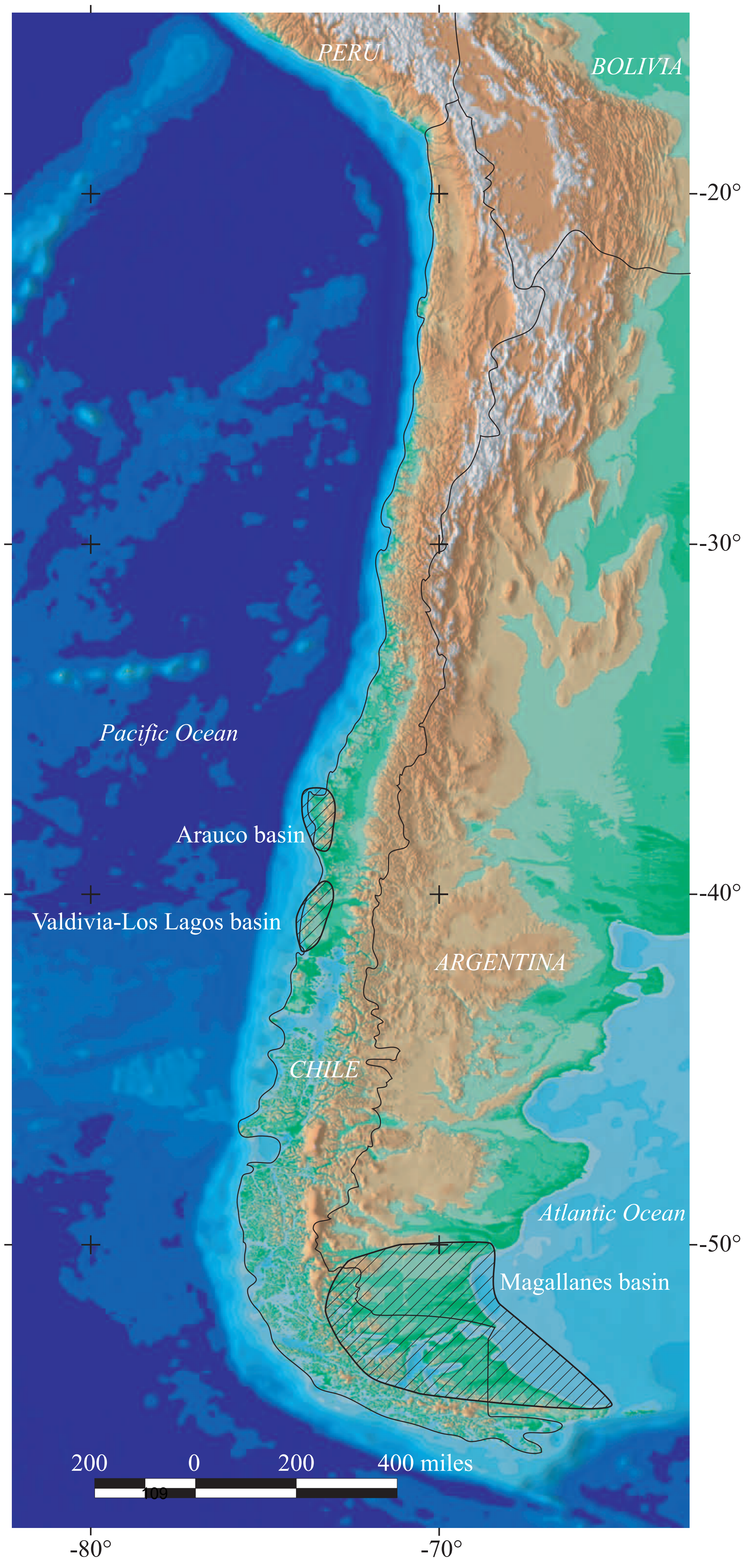

Figure 1. Shaded relief image of southern South America (geographic projection), showing the international boundary of Chile, and the locations of the Arauco, Valdivia-Los Lagos, and Magallanes coal basins. Shaded relief image from U.S. Geological Survey (1996) global 30-arc second elevation data set.

Chile shaded gray in index map of South American continent.

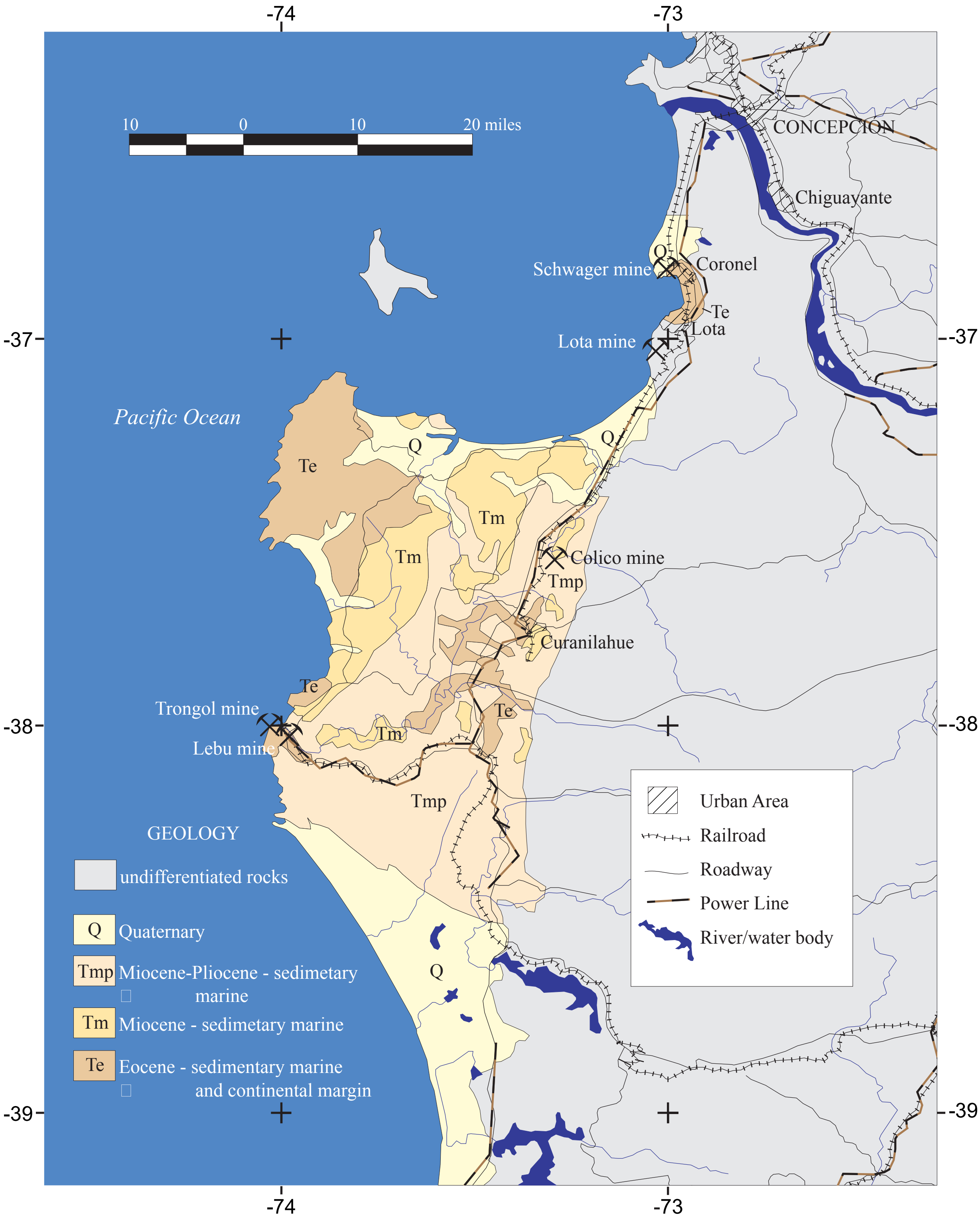

Figure 2. Map of Arauco basin showing locations of coal mines. Geology from Escobar and others (1982).

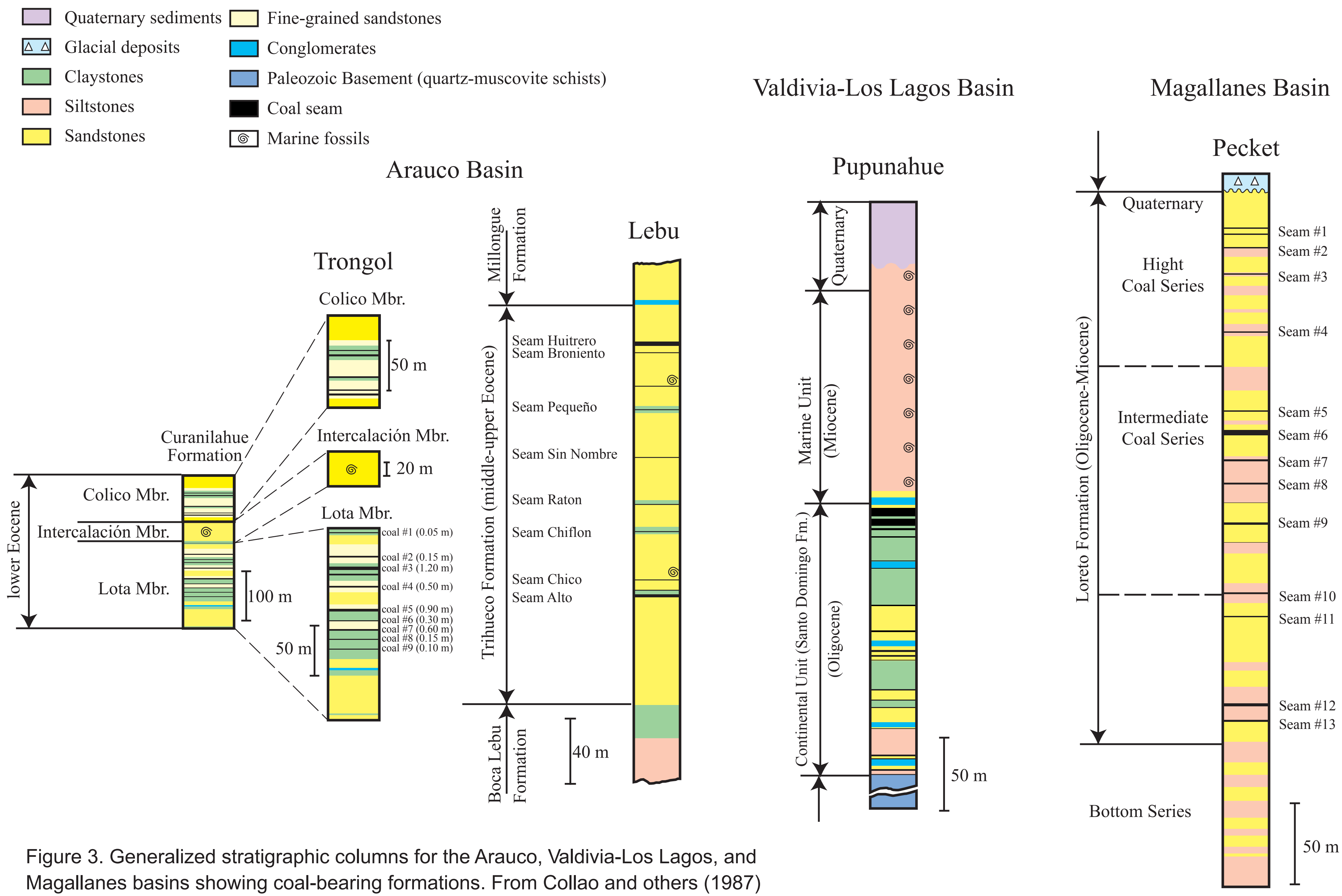

Figure 3. Generalized stratigraphic columns for the Arauco, Valdivia-Los Lagos, and Magallanes basins showing coal-bearing formations. From Collao and others (1987) and Helle and others (2000). Abbreviations: Fm.=Formation, Mbr.=Member, m=meters, #=number.

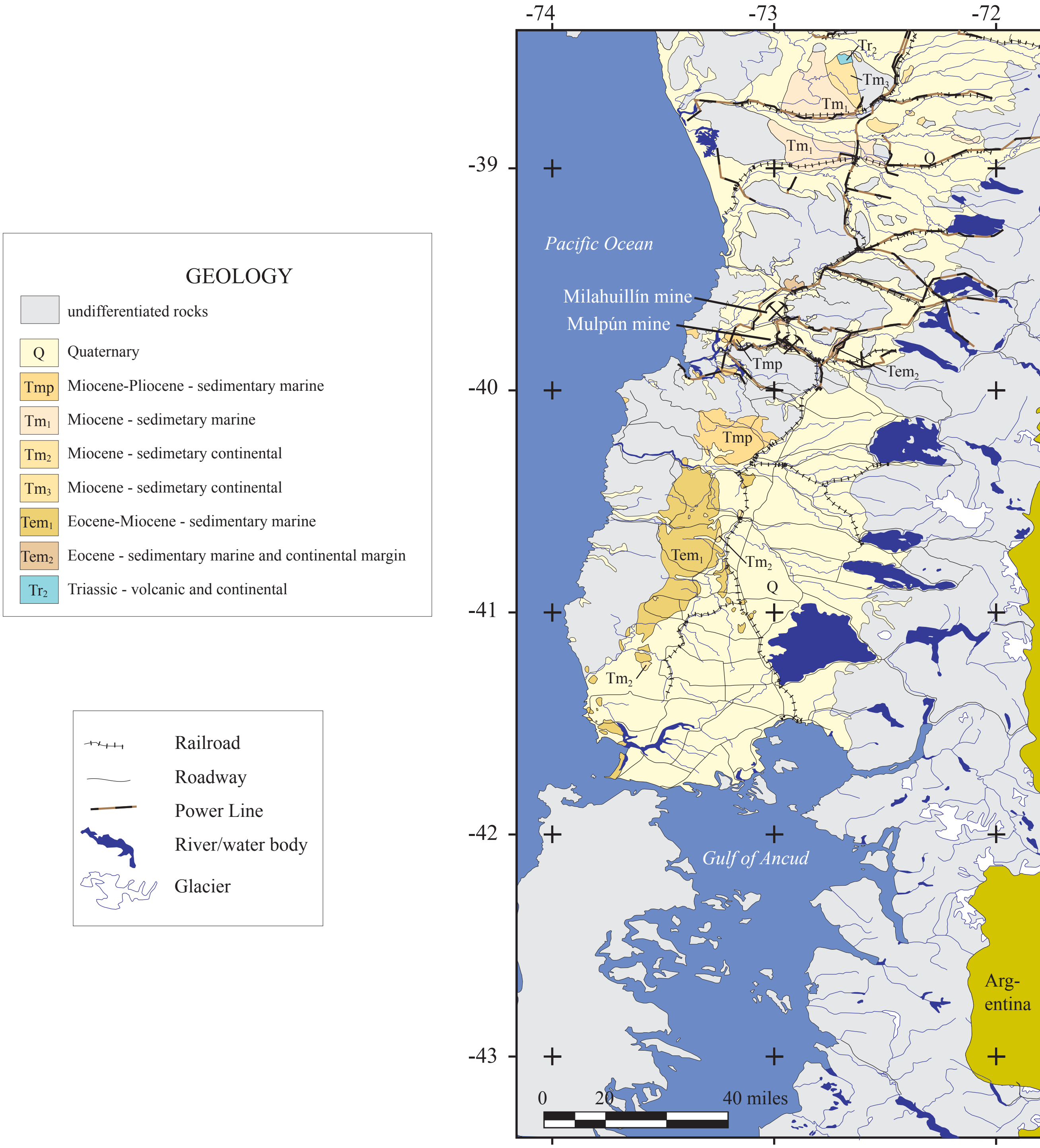

Figure 4. Map of Valdivia-Los Lagos basin showing locations of coal mines. Geology from Escobar and others (1982).

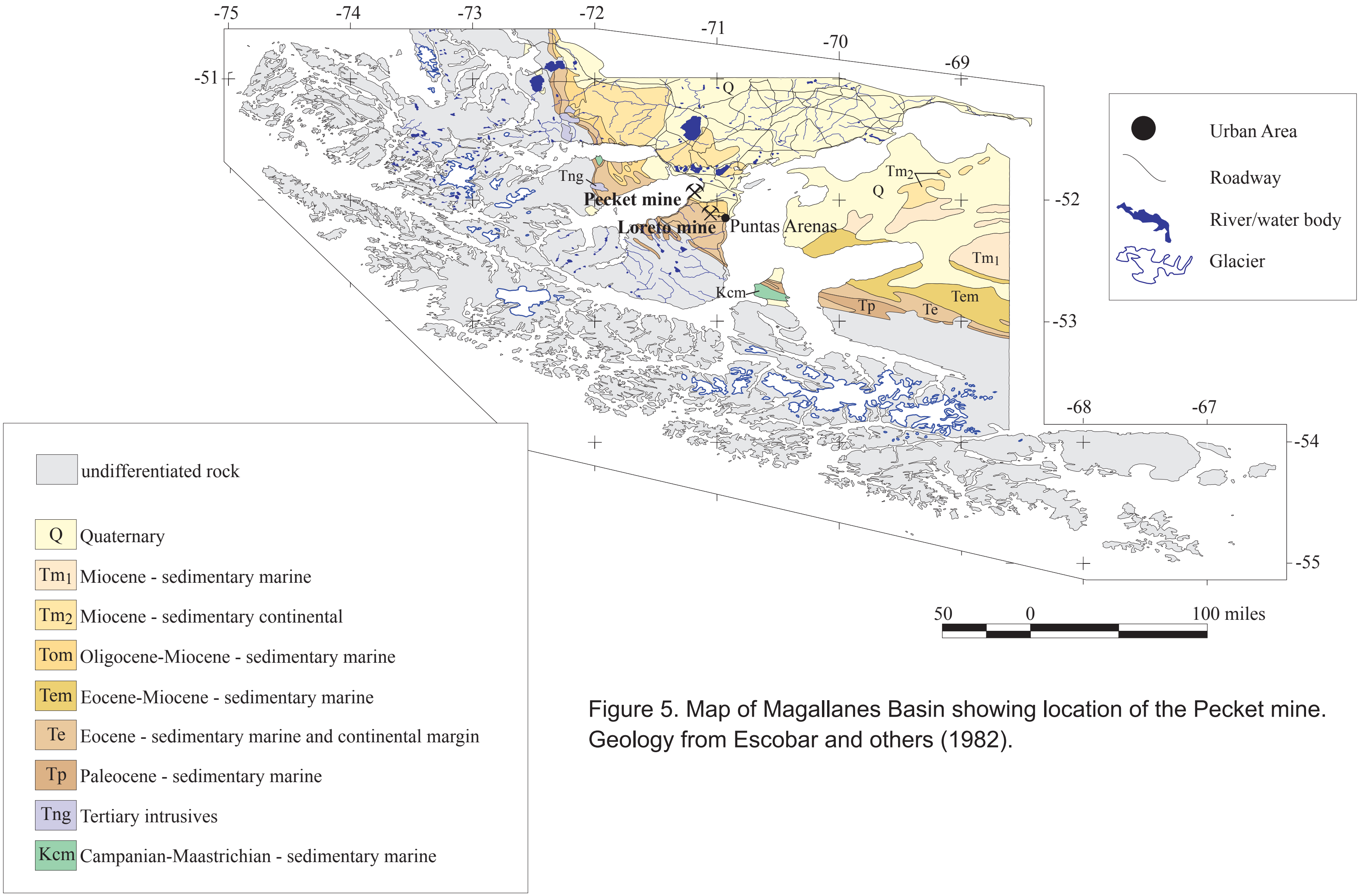

Figure 5. Map of Magallanes Basin showing location of the Pecket mine. Geology from Escobar and others (1982).

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Table 1. Coal production and consumption in Chile in millions of metric tons, 1990-2000. From Fossil Energy International (2003).

Year	Production	Consumption
1990	2.19	3.76
1991	2.20	2.99
1992	1.62	2.67
1993	1.35	2.69
1994	1.18	3.21
1995	1.14	1.03
1996	1.01	4.84
1997	1.04	6.33
1998	0.94	5.91
1999	0.48	6.15
2000	0.36	4.63

Table 2. Sample location and description information for Chilean coal samples. Latitude and longitude coordinates in decimal degrees obtained by GPS at time of sample location. Abbreviations: n.d.=no data.

	Sample ID	Latitude	Longitude	Name of Mine/Concession	Name of Bed	Formation	Age
Arauco	Chile-3	-37.61000	-73.63300	Trongol	n.d.	Colico	Eocene
	Manto Alto Lebu	-37.61600	-73.64500	Lebu	Manto Alto	Trihueco	Eocene
	Manto Chico Lebu	-37.61600	-73.64500	Lebu	Manto Chico	Trihueco	Eocene
	Manto Chiflon Lebu	-37.61600	-73.64500	Lebu	Manto Chiflon	Trihueco	Eocene
	Manto Huitrero Lebu	-37.61600	-73.64500	Lebu	Manto Huitrero	Trihueco	Eocene
	Lebu #1	-37.63328	-73.63668	Lebu	n.d.	Trihueco	Eocene
	Lebu #2	-37.63328	-73.63668	Lebu	n.d.	Trihueco	Eocene
Valdivia-Los Lagos	Chile-1	-39.75000	-72.96000	Mulpún	n.d.	Santo Domingo	Oligocene
	Mulpún 3004	-39.75000	-72.96000	Mulpún	Mulpún 3004	Santo Domingo	Oligocene
	Mulpún 3005	-39.75000	-72.96000	Mulpún	Mulpún 3005	Santo Domingo	Oligocene
	Milahuillín	-39.66000	-72.99000	Milahuillín	n.d.	Santo Domingo	Oligocene
	Malihue	-39.77500	-76.96000	Malihue	n.d.	Malihue?	Oligocene?
	Mulpún 3006	-39.75000	-72.96000	Mulpún	Mulpún 3006	Santo Domingo	Oligocene
Magallanes	Chile-2	-52.95000	-71.18200	Pecket	n.d.	Loreto	Oligocene to Miocene
	1	-52.95000	-71.18200	Pecket	n.d.	Loreto	Oligocene to Miocene
	2A	-52.95000	-71.18200	Pecket	n.d.	Loreto	Oligocene to Miocene
	2B	-52.95000	-71.18200	Pecket	n.d.	Loreto	Oligocene to Miocene
	3	-52.95000	-71.18200	Pecket	n.d.	Loreto	Oligocene to Miocene
	4	-52.95000	-71.18200	Pecket	n.d.	Loreto	Oligocene to Miocene
	5	-52.95000	-71.18200	Pecket	n.d.	Loreto	Oligocene to Miocene
	6	-52.95000	-71.18200	Pecket	n.d.	Loreto	Oligocene to Miocene
	Pecket #1	-52.95543	-71.15400	Pecket	n.d.	Loreto	Oligocene to Miocene
	Pecket #2	-52.95543	-71.15447	Pecket	n.d.	Loreto	Oligocene to Miocene

Table 3. Free swelling indices and ash fusion temperatures for Chilean coal samples. Abbreviations: FSI=free swelling index (ASTM D720), AFT-ID=ash fusion temperature-initial deformation, AFT-ST=softening temperature, AFT-HT=hemi temperature, AFT-FT=fluid temperature (all in reducing atmosphere, ASTM D1857).

	Sample ID	FSI	AFT-ID (°F)	AFT-ST (°F)	AFT-HT (°F)	AFT-FT (°F)
Arauco	Chile-3	3.5	1,950	1,970	1,980	2,000
	Manto Alto Lebu	5.0	1,890	1,930	1,940	1,990
	Manto Chico Lebu	5.5	1,860	1,890	1,910	1,950
	Manto Chiflon Lebu	1.5	>2,800	>2,800	>2,800	>2,800
	Manto Huitrero Lebu	4.0	>2,800	>2,800	>2,800	>2,800
	Lebu #1	3.5	1,910	1,930	1,940	1,980
	Lebu #2	4.0	2,280	2,380	2,440	2,500
Valdivia-Los Lagos	Chile-1	0.5	2,390	2,400	2,410	2,430
	Mulpún 3004	0.0	>2,800	>2,800	>2,800	>2,800
	Mulpún 3005	0.0	2,040	2,080	2,100	2,150
	Milahuillín	0.0	1,820	1,900	1,930	2,060
	Malihue	0.0	2,100	2,170	2,210	2,250
	Mulpún 3006	0.0	2,620	2,740	2,760	2,780
Magallanes	Chile-2	0.5	2,430	2,460	2,480	2,510
	1	0.0	2,080	2,170	2,290	2,460
	2A	0.0	2,140	2,200	2,330	2,400
	2B	0.0	2,130	2,170	2,250	2,390
	3	0.0	2,060	2,110	2,200	2,310
	4	0.0	2,170	2,220	2,260	2,450
	5	0.0	2,240	2,290	2,320	2,380
	6	0.0	2,340	2,410	2,420	2,430
	Pecket #1	0.0	2,120	2,100	2,200	2,410
	Pecket #2	0.0	2,270	2,330	2,360	2,600

Table 4. Proximate and ultimate analyses, gross calorific value, and forms of sulfur on an as-received basis for 23 Chilean coal samples.

[Abbreviations: Moist = moisture; % = weight percent; VM = volatile matter; FC = fixed carbon; Ash = ash yield; °C = degrees Centigrade; H= hydrogen; C = carbon; N = nitrogen; S = sulfur; O = oxygen; CV = gross calorific value; Btu/lb = British thermal units per pound; m,mmf = moist,mineral matter free; MJ/kg = Megajoules per kilogram; Sulf = sulfate sulfur; Pyr Sulf = pyritic sulfur; Org Sulf= organic sulfur.]

	Proximate Analyses				Ultimate Analyses								Forms of Sulfur		
Field Number	Moist (%)	VM (%)	FC (%)	Ash (%) (750°C)	H (%)	C (%)	N (%)	S (%)	O (%)	CV (Btu/lb)	CV m, mmf (Btu/lb)	CV (MJ/kg)	Sulf (%)	Pyr Sulf (%)	Org Sulf (%)
Chile-3	3.68	45.50	44.26	6.56	5.54	71.70	1.09	3.57	7.86	13,270.	14,240	31	0.09	1.40	2.08
Manto Alto Lebu	2.46	46.06	45.74	5.74	5.48	73.57	1.76	3.84	7.15	13,510.	14,450	31	0.08	1.37	2.39
Manto Chico Lebu	2.88	45.65	49.04	2.43	5.54	77.08	1.95	1.30	8.82	13,900.	14,270	32	0.02	0.38	0.90
Manto Chiflon Lebu	2.64	32.95	30.53	33.88	4.01	49.87	1.14	1.89	6.57	9,250.	14,530	22	0.42	0.55	0.92
Manto Huitrero Lebu	2.77	42.27	46.10	8.86	5.36	71.79	1.27	2.11	7.84	13,190.	14,580	31	0.12	0.85	1.14
Lebu #1	3.94	43.82	50.32	1.92	5.38	76.55	1.94	0.92	9.35	13,730.	14,010	32	0.02	0.11	0.79
Lebu #2	2.08	45.60	44.42	7.90	5.32	72.36	1.54	3.91	6.89	13,230.	14,510	31	0.08	1.31	2.52
Chile-1	20.12	33.74	40.34	5.80	4.02	55.57	1.06	0.28	13.15	9,710.	10,330	23	0.01	0.02	0.25
Mulpún 3004	13.26	23.58	19.04	44.12	2.63	29.17	0.66	0.43	9.73	5,080.	9,580	12	0.02	0.04	0.37
Mulpún 3005	12.78	32.43	33.55	21.24	3.79	46.86	0.96	3.85	10.52	8,490.	10,940	20	0.15	2.49	1.21
Milahuillín	20.35	33.45	43.82	2.38	3.70	58.89	0.65	0.50	13.53	10,010.	10,250	23	0.01	0.05	0.44
Malihue	8.82	5.50	0.06	85.62	0.49	0.79	0.01	0.10	4.17	40.	460	0.1	0.01	0.09	0.00
Mulpún 3006	16.74	32.55	37.36	13.35	3.91	52.21	1.14	0.48	12.17	9,090.	10,540	21	0.01	0.01	0.46
Chile-2	24.02	37.35	26.45	12.18	3.53	46.31	0.63	0.24	13.09	8,050.	9,080	19	0.01	0.01	0.22
1	21.41	33.13	29.99	15.47	3.43	45.24	0.53	0.22	13.70	8,470.	10,120	18	0.02	0.02	0.18
2A	22.16	30.85	27.51	19.48	3.15	41.48	0.58	0.33	12.82	7,750.	9,760	17	0.02	0.02	0.29
2B	23.68	30.46	27.24	18.62	3.16	41.50	0.58	0.32	12.14	7,180.	8,880	17	0.03	0.02	0.27
3	20.26	31.58	25.26	22.90	3.27	40.56	0.54	2.62	9.85	7,190.	9,220	17	0.18	1.63	0.81
4	19.64	34.35	24.89	21.12	3.55	42.72	0.60	0.44	11.93	7,280.	9,280	18	0.03	0.03	0.38
5	22.02	34.35	32.50	11.13	3.73	48.40	0.62	0.25	13.85	7,560.	8,520	20	0.02	0.02	0.21

Table 4. Proximate and ultimate analyses, gross calorific value, and forms of sulfur on an as-received basis for 23 Chilean coal samples—continued.

	Proximate Analyses				Ultimate Analyses								Forms of Sulfur		
Field Number	Moist (%)	VM (%)	FC (%)	Ash (%) (750°C)	H (%)	C (%)	N (%)	S (%)	O (%)	CV (Btu/lb)	CV m, mmf (Btu/lb)	CV (MJ/kg)	Sulf (%)	Pyr Sulf (%)	Org Sulf (%)
6	21.09	35.56	30.33	13.02	3.72	47.38	0.62	0.20	13.97	8,240.	9,520	19	0.03	0.02	0.15
Pecket #1	25.54	28.41	24.95	21.10	3.05	38.76	0.45	0.25	10.85	6,630.	8,520	15	0.02	0.03	0.20
Pecket #2	24.71	29.87	25.12	20.30	3.02	39.42	0.46	0.27	11.82	6,870.	8,730	16	0.02	0.03	0.22

Table 5. Analytical data (on an as-determined, ash basis) for ash yield and major- and minor- oxides for 23 Chilean coal samples.

[Abbreviations: Ash = ash yield; %=weight percent; Total = sum of oxides on an ash basis; °C= degrees Centigrade; <=less than. Values were derived following methods described in Bullock and others (2002).]

Field Number	Ash (525°C) (%)	SiO_2 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O (%)	Fe_2O_3 (%)	TiO_2 (%)	P_2O_5 (%)	SO_3 (%)	Total
Chile-3	7.30	22.3	10.7	16.6	1.30	1.20	0.190	34.5	0.490	<0.020	14.0	101.3
Manto Alto Lebu	6.26	23.4	12.2	5.20	1.80	1.60	0.520	30.8	0.720	0.050	8.00	84.3
Manto Chico Lebu	2.67	19.3	11.7	6.80	2.70	2.40	0.180	32.3	0.960	0.070	11.6	88.0
Manto Chiflon Lebu	34.9	83.8	3.00	1.20	0.210	0.170	0.170	4.80	0.190	<0.020	1.70	95.3
Manto Huitrero Lebu	9.27	67.2	2.10	3.70	0.610	0.960	0.060	15.2	0.210	0.040	4.80	94.9
Lebu #1	2.18	30.0	8.90	8.60	2.80	2.50	0.110	21.5	0.530	0.060	13.1	88.1
Lebu #2	8.44	48.8	9.40	4.00	1.30	0.690	0.250	22.3	0.540	0.060	5.80	93.1
Chile-1	7.00	39.6	29.4	9.70	1.00	3.10	1.00	4.20	1.70	2.70	5.10	97.5
Mulpún 3004	50.0	54.4	27.7	1.00	1.10	0.690	2.80	3.20	1.40	0.080	1.50	93.9
Mulpún 3005	24.3	46.8	20.8	2.50	0.71	1.20	1.10	16.8	0.840	0.080	3.80	94.6
Milahuillín	2.30	14.6	13.1	10.4	1.50	0.250	0.520	24.3	0.560	0.060	10.7	76.0
Malihue	93.0	42.3	19.3	4.10	2.00	2.60	0.840	8.00	0.730	0.140	0.180	80.2
Mulpún 3006	15.3	48.0	26.8	4.00	1.00	1.60	1.80	2.50	1.40	0.260	4.90	92.3
Chile-2	15.7	40.6	27.4	11.6	1.70	2.70	0.250	3.00	1.20	<0.020	13.5	102.0
1	19.5	44.1	20.1	11.5	2.70	2.00	0.280	5.60	0.740	0.020	2.50	89.5
2A	23.3	35.0	15.7	8.60	2.00	1.90	0.270	4.40	0.630	<0.020	2.10	70.6
2B	23.1	49.7	19.7	9.70	2.40	1.90	0.390	5.50	0.710	<0.020	5.00	95.0
3	28.1	40.7	15.9	8.20	2.40	1.80	0.270	12.2	0.570	0.050	11.0	93.1
4	25.5	48.2	20.3	9.00	2.00	1.60	0.690	4.20	0.760	0.020	5.50	92.3
5	14.1	37.2	24.8	13.3	1.80	2.60	0.150	2.80	1.70	0.050	6.60	91.0

Table 5. Analytical data (on an as-determined, dry basis) for ash yield and major- and minor- oxides for 23 Chilean coal samples—continued.

Field Number	Ash (525°C) (%)	SiO_2 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O (%)	Fe_2O_3 (%)	TiO_2 (%)	P_2O_5 (%)	SO_3 (%)	Total
6	15.9	42.5	24.8	12.2	1.90	2.20	0.340	3.20	1.20	0.040	4.70	93.1
Pecket #1	25.3	49.2	19.8	9.3	2.20	1.80	0.460	5.70	0.790	0.040	2.50	91.8
Pecket #2	23.6	48.6	21.6	8.8	2.00	1.60	0.390	5.90	0.790	0.040	2.90	92.6

Table 6. Major-, minor-, and trace- element data for 23 Chilean coal samples calculated to a dry, whole-coal basis.

[All values in µg/g (ppm), except ash yield, Si, Al, Ca, Mg, Na, K, Fe, Ti, P and S which are in weight percent. Ash=ash yield, %=weight percent, °C=degrees Centigrade. Values were derived following methods described in Bullock and others (2002).]

Field Number	Ash (%) (525°C)	Si (%)	Al (%)	Ca (%)	Mg (%)	Na (%)	K (%)	Fe (%)	Ti (%)	P (%)
Chile-3	7.40	0.769	0.418	0.876	0.0579	0.0657	0.0116	1.78	0.0217	0.000644
Manto Alto Lebu	6.40	0.699	0.412	0.237	0.0693	0.0758	0.0276	1.38	0.0276	0.00139
Manto Chico Lebu	2.70	0.247	0.170	0.133	0.0446	0.0487	0.00409	0.618	0.0158	0.000836
Manto Chiflon Lebu	35.6	14.0	0.566	0.305	0.0451	0.0449	0.0503	1.20	0.0406	0.00311
Manto Huitrero Lebu	9.50	2.98	0.106	0.251	0.0349	0.0676	0.00473	1.01	0.0120	0.00166
Lebu #1	2.20	0.311	0.105	0.136	0.0375	0.0412	0.00203	0.334	0.00705	0.000581
Lebu #2	8.50	1.95	0.425	0.244	0.0669	0.0437	0.0177	1.33	0.0276	0.00223
Chile-1	7.40	1.38	1.16	0.515	0.0448	0.171	0.0617	0.218	0.0757	0.0876
Mulpún 3004	52.3	13.3	7.66	0.374	0.347	0.268	1.22	1.17	0.439	0.0182
Mulpún 3005	25.7	5.63	2.83	0.460	0.110	0.229	0.235	3.03	0.130	0.00899
Milahuillín	2.50	0.173	0.176	0.189	0.023	0.00471	0.0110	0.432	0.00853	0.000665
Malihue	97.9	19.4	10.0	2.87	1.18	1.89	0.683	5.48	0.428	0.0598
Mulpún 3006	16.6	3.72	2.35	0.474	0.0999	0.197	0.248	0.290	0.139	0.0188
Chile-2	16.9	3.20	2.45	1.40	0.173	0.338	0.035	0.354	0.121	0.00147
1	21.6	4.46	2.30	1.78	0.352	0.321	0.0503	0.847	0.0959	0.00189
2A	25.9	4.25	2.16	1.59	0.313	0.366	0.0582	0.799	0.0980	0.00226
2B	25.6	5.94	2.66	1.77	0.370	0.360	0.0827	0.983	0.109	0.00223
3	30.7	5.83	2.58	1.80	0.444	0.409	0.0687	2.62	0.105	0.00669
4	27.8	6.27	2.99	1.79	0.335	0.330	0.159	0.817	0.127	0.00243
5	15.6	2.71	2.05	1.48	0.169	0.301	0.0194	0.305	0.159	0.00340

Table 6. Major-, minor-, and trace- element data for 23 Chilean coal samples calculated to a dry, whole-coal basis—continued.

Field Number	Ash (%) (525°C)	Si (%)	Al (%)	Ca (%)	Mg (%)	Na (%)	K (%)	Fe (%)	Ti (%)	P (%)
6	17.3	3.45	2.28	1.51	0.199	0.283	0.0490	0.388	0.125	0.00303
Pecket #1	28.5	6.55	2.98	1.89	0.378	0.380	0.109	1.13	0.135	0.00497
Pecket #2	27.0	6.14	3.09	1.70	0.326	0.321	0.0875	1.12	0.128	0.00472

Table 6. Major-, minor-, and trace- element data for 23 Chilean coal samples calculated to a dry, whole-coal basis—continued. µg/g=microgram per gram, <=less than

Field Number	As (µg/g)	B (µg/g)	Ba (µg/g)	Be (µg/g)	Bi (µg/g)	Cd (µg/g)	Cl (µg/g)	Co (µg/g)	Cr (µg/g)	Cs (µg/g)
Chile-3	1.45	336.	8.19	0.133	0.0185	0.0133	162	1.12	4.76	0.288
Manto Alto Lebu	1.68	149.	26.4	0.141	0.00958	0.0134	500	1.52	3.07	0.186
Manto Chico Lebu	0.594	111.	12.5	0.186	0.00383	0.00657	451	0.652	0.734	0.0422
Manto Chiflon Lebu	1.65	64.5	22.9	1.25	<0.0360	<0.0360	531	3.88	7.87	0.367
Manto Huitrero Lebu	0.148	207.	23.1	<0.095	<0.0095	<0.0095	420	0.750	0.684	0.0703
Lebu #1	0.166	117.	15.6	0.0732	0.00666	0.00266	366	0.559	0.297	0.0171
Lebu #2	2.15	159.	24.9	0.196	0.0145	0.0205	233	1.47	3.76	0.145
Chile-1	2.56	192.	117.	0.401	0.0468	0.0126	<160	3.28	10.8	0.862
Mulpún 3004	1.88	46.8	420.	1.99	0.152	0.146	470	10.9	69.5	13.4
Mulpún 3005	72.1	155.	181.	1.52	0.144	0.180	540	7.29	27.3	3.63
Milahuillín	3.15	1280.	82.1	0.668	0.00381	0.0427	188	2.28	3.40	0.831
Malihue	3.95	355.	333.	1.27	<0.098	0.137	305	22.2	20.7	1.96
Mulpún 3006	1.20	217.	161.	0.795	0.103	0.0862	347	6.00	28.8	4.37
Chile-2	2.23	203.	93.9	0.506	0.115	0.0236	172	5.05	3.60	0.0642
1	1.42	259.	154.	0.605	0.223	<0.0220	410	4.48	4.17	0.171
2A	0.903	171.	136.	0.882	0.145	0.0285	501	7.81	8.35	0.778
2B	0.427	205.	153.	1.79	0.0894	0.0281	387	8.02	17.1	0.692
3	4.78	278.	250.	1.59	0.0490	<0.0310	436	7.05	6.99	0.346
4	0.815	222.	124.	1.50	0.0890	0.0306	393	5.98	11.4	1.06
5	0.637	215.	91.8	0.670	0.0390	0.0156	343	9.41	4.91	0.0530

Table 6. Major-, minor-, and trace- element data for 23 Chilean coal samples calculated to a dry, whole-coal basis—continued.

Field Number	As (µg/g)	B (µg/g)	Ba (µg/g)	Be (µg/g)	Bi (µg/g)	Cd (µg/g)	Cl (µg/g)	Co (µg/g)	Cr (µg/g)	Cs (µg/g)
6	0.309	229.	90.0	1.60	0.0399	<0.0180	436	13.3	12.8	0.142
Pecket #1	1.05	240.	161.	1.08	0.0655	0.0398	326	6.60	12.8	0.541
Pecket #2	0.730	229.	163.	0.892	0.0595	0.0270	<180	4.95	7.33	0.622

Table 6. Major-, minor-, and trace- element data for 23 Chilean coal samples calculated to a dry, whole-coal basis—continued.

Field Number	Cu (µg/g)	Ga (µg/g)	Ge (µg/g)	Hg (µg/g)	Li (µg/g)	Mn (µg/g)	Mo (µg/g)	Nb (µg/g)	Ni (µg/g)	Pb (µg/g)
Chile-3	4.34	0.760	0.657	0.13	4.91	95.2	0.177	0.177	1.57	1.30
Manto Alto Lebu	1.28	1.09	0.533	0.11	5.41	63.9	0.266	0.323	1.26	0.607
Manto Chico Lebu	1.46	0.476	0.329	0.031	2.52	13.0	0.274	0.132	0.531	0.315
Manto Chiflon Lebu	0.855	2.79	11.1	0.082	9.87	45.9	0.627	0.556	11.3	1.03
Manto Huitrero Lebu	3.01	0.266	0.237	0.041	4.98	69.4	0.197	0.0722	1.14	0.468
Lebu #1	1.24	0.273	0.397	<0.030	2.13	10.3	0.124	0.0954	0.439	0.229
Lebu #2	2.87	1.19	0.615	0.061	8.31	52.6	0.435	0.307	3.56	0.853
Chile-1	19.5	3.07	0.639	0.032	4.76	13.2	0.476	0.780	6.35	3.46
Mulpún 3004	27.9	16.8	2.81	0.28	44.7	178.	1.14	7.42	27.5	17.0
Mulpún 3005	49.9	6.67	1.56	2.2	16.0	34.8	1.72	2.22	22.7	10.6
Milahuillín	4.62	2.95	0.993	0.033	1.33	17.0	2.28	0.295	8.74	1.10
Malihue	66.5	21.1	3.87	0.032	22.6	608.	2.15	4.62	13.6	14.2
Mulpún 3006	31.5	6.46	1.01	0.097	11.5	26.0	0.817	2.59	12.6	9.08
Chile-2	13.0	5.47	0.574	0.022	11.9	88.0	0.574	1.96	0.675	4.12
1	10.7	4.93	0.740	0.033	11.2	187.	1.16	1.72	3.44	3.18
2A	45.4	6.82	0.789	0.045	15.0	221.	0.926	1.94	3.68	6.43
2B	35.5	5.80	0.728	0.033	14.5	222.	0.593	1.38	4.68	4.88
3	9.63	5.58	4.17	0.32	13.1	282.	0.711	1.90	8.03	3.49
4	29.8	7.68	3.89	0.022	19.1	174.	0.687	1.75	3.89	6.87
5	12.0	4.74	0.547	<0.030	12.9	123.	0.661	1.81	4.38	2.87

Table 6. Major-, minor-, and trace- element data for 23 Chilean coal samples calculated to a dry, whole-coal basis—continued.

Field Number	Cu (µg/g)	Ga (µg/g)	Ge (µg/g)	Hg (µg/g)	Li (µg/g)	Mn (µg/g)	Mo (µg/g)	Nb (µg/g)	Ni (µg/g)	Pb (µg/g)
6	11.3	5.88	1.08	0.022	11.3	109.	0.855	1.54	6.70	4.91
Pecket #1	27.6	7.34	3.47	0.022	14.7	203.	0.655	1.85	5.04	6.03
Pecket #2	31.1	6.89	1.16	0.057	22.5	219.	0.568	1.59	2.65	6.19

Table 6. Major-, minor-, and trace- element data for 23 Chilean coal samples calculated to a dry, whole-coal basis—continued.

Field Number	Rb (µg/g)	Sb (µg/g)	Sc (µg/g)	Se (µg/g)	Sn (µg/g)	Sr (µg/g)	Te (µg/g)	Th (µg/g)	Tl (µg/g)	U (µg/g)
Chile-3	0.679	0.0554	0.841	1.8	<0.230	95.2	0.0133	<0.600	0.0435	0.103
Manto Alto Lebu	1.44	0.0160	1.14	1.3	<0.200	88.1	0.00766	<0.520	0.0294	0.156
Manto Chico Lebu	0.180	0.0290	0.490	1.0	<0.083	44.3	0.00438	<0.220	0.0268	0.0468
Manto Chiflon Lebu	2.34	0.239	2.96	1.1	<1.10	85.8	<0.0360	<2.90	0.182	0.549
Manto Huitrero Lebu	0.279	0.0104	0.361	0.50	<0.290	62.3	<0.00950	<0.760	0.0285	0.0285
Lebu #1	0.0799	0.0104	0.289	0.29	<0.0670	62.4	0.00932	<0.180	0.00688	0.0422
Lebu #2	0.913	0.0333	1.57	0.73	<0.260	83.9	0.0137	<0.690	0.0205	0.230
Chile-1	4.76	0.0817	3.52	0.27	0.364	209.	0.0342	2.30	0.0446	0.632
Mulpún 3004	130.	0.293	13.6	0.51	4.90	129.	0.0993	9.98	0.580	2.16
Mulpún 3005	22.5	0.306	8.52	3.1	1.63	92.9	0.0618	8.06	2.73	1.42
Milahuillín	1.18	0.210	1.19	<0.20	.0960	43.2	0.00483	0.262	0.139	0.197
Malihue	28.0	0.333	19.4	<0.20	<3.00	478.	<0.0980	<7.90	0.499	1.14
Mulpún 3006	23.2	0.147	6.78	0.40	1.82	146.	0.0530	5.44	0.144	1.16
Chile-2	1.13	0.0945	3.60	0.39	0.726	219.	0.0928	1.52	0.0506	0.608
1	2.07	0.255	3.65	0.52	1.54	247.	0.210	1.92	<0.0220	0.586
2A	5.94	0.309	5.06	0.71	1.15	255.	0.135	3.48	0.0727	0.812
2B	5.42	0.233	5.98	0.75	<0.770	246.	0.0690	3.12	0.046	0.636
3	3.31	0.120	4.29	0.58	<0.920	269.	0.0460	<2.50	0.497	0.564
4	8.37	0.292	5.87	0.61	0.812	193.	0.0584	3.70	0.108	0.698
5	0.764	0.0686	4.47	0.48	0.851	190.	0.0436	1.22	0.0218	0.432

Table 6. Major-, minor-, and trace- element data for 23 Chilean coal samples calculated to a dry, whole-coal basis—continued.

Field Number	Rb (µg/g)	Sb (µg/g)	Sc (µg/g)	Se (µg/g)	Sn (µg/g)	Sr (µg/g)	Te (µg/g)	Th (µg/g)	Tl (µg/g)	U (µg/g)
6	1.89	0.253	5.74	0.41	0.751	158.	0.0364	2.26	0.0208	0.503
Pecket #1	5.29	0.225	4.95	0.58	2.08	253.	0.114	<2.30	0.0939	0.626
Pecket #2	5.22	0.219	4.76	0.46	<0.820	227.	0.0973	<2.20	0.0676	0.676

Table 6. Major-, minor-, and trace- element data for 23 Chilean coal samples calculated to a dry, whole-coal basis—continued.

Field Number	V (µg/g)	Y (µg/g)	Zn (µg/g)	Zr (µg/g)
Chile-3	6.42	1.08	9.37	8.27
Manto Alto Lebu	8.11	1.85	5.10	5.71
Manto Chico Lebu	3.07	1.60	2.18	3.45
Manto Chiflon Lebu	23.4	8.09	5.84	21.2
Manto Huitrero Lebu	4.14	0.779	2.47	2.20
Lebu #1	1.72	0.992	2.84	2.29
Lebu #2	10.5	2.59	6.68	5.77
Chile-1	23.0	5.95	9.59	8.47
Mulpún 3004	106.	15.3	83.6	125.
Mulpún 3005	56.4	21.1	148.	66.9
Milahuillín	8.66	4.39	10.7	3.10
Malihue	156.	22.9	102.	85.1
Mulpún 3006	47.7	9.81	32.6	30.3
Chile-2	21.6	3.63	12.5	46.1
1	24.2	7.35	7.46	40.2
2A	39.4	12.5	7.39	36.1
2B	64.9	18.2	7.69	38.8
3	37.1	14.0	14.1	34.3
4	55.9	13.4	8.7	35.3
5	37.4	8.85	6.73	32.1

Table 6. Major-, minor-, and trace- element data for 23 Chilean coal samples calculated to a dry, whole-coal basis—continued.

Field Number	V (µg/g)	Y (µg/g)	Zn (µg/g)	Zr (µg/g)
6	54.6	15.0	11.5	31.4
Pecket #1	60.9	12.0	13.0	50.7
Pecket #2	38.7	12.2	11.6	37.0