



Petrography and geochemistry of the San Miguel lignite, Jackson Group (Eocene), south Texas

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Abstract—The San Miguel lignite deposit (late Eocene, lower Jackson Group) of south Texas consists of four or more thin (generally < 1 m thick) lignite benches that are separated by claystone and mudstone partings. The partings are composed of altered volcanic air-fall ash that has been reworked by tidal or channel processes associated with a back-barrier depositional environment. The purpose of this study is to examine the relationship between the ash yield and the petrographic and geochemical characteristics of the San Miguel lignite as mined. Particular attention is given to 12 of the environmentally sensitive trace elements (As, Be, Cd, Cr, Co, Hg, Mn, Ni, Pb, Sb, Se, and U) that have been identified as possible hazardous air pollutants (HAPs) by the United States Clean Air Act Amendments of 1990. A total of 29 rock and lignite samples were collected and characterized by geochemical and petrographic methods. The major conclusions of the study are as follows: (1) The distribution of Mn is inversely related to the ash yield of the lignite samples. This indicates an organic affinity, or an association with finely disseminated minerals in the lignite that contain this element. (2) On a whole-coal basis, the concentration of the HAPs' element Pb is positively related to ash yield in lignite samples. This indicates an inorganic affinity for Pb. (3) Average whole-coal concentrations of As, Be, Sb, and U in the San Miguel samples are greater than published averages for these elements in other U.S. lignites. (4) The upper and lower lignite benches of the San Miguel deposit are both ash- and algal-rich, indicating that these intervals were probably deposited in wetter conditions than those in which the middle intervals formed. (5) The dominance of the euglenite maceral subgroup over the huminite subgroup indicates that the San Miguel lignites were subjected to peat-forming conditions (either biogenic or chemical) that enabled degradation of wood cellular material into matrix gels, or that the plants that formed these lignite benches were less woody and more prone to formation of matrix gels. (6) An inertinite-rich layer (top of the B bed) might have formed from widespread oxidation of the San Miguel peat as a result of a volcanic ash fall which was subsequently reworked. Published by Elsevier Science Ltd

Key words—San Miguel lignite, Jackson Group, Texas, coal petrography, coal geochemistry, volcanic ash, trace elements, Eocene lignite

INTRODUCTION

Recent investigations into the influences of volcanic ash on the physical and chemical character of coal beds have found that the ash may be the source for some coal impurities (Zielinski, 1985; Kendrick, 1985). Some of these impurities can be described as potential environmental pollutants (Crowley *et al.*, 1989, 1994; Ruppert and Moore, 1993). The purpose of this study is to examine the petrographic and geochemical characteristics of a lignite interval that is mined and used for thermo-electric power generation in the U.S. Gulf of Mexico coastal plain. The study seeks to identify relationships among the ash yield, maceral composition, and trace-element concentrations in coal and adjoining rock layers sampled from a major mine. Particular interest is given to the distribution of 12 of the environmentally sensitive trace elements (As, Be, Cd, Cr, Co, Hg, Mn, Ni, Pb, Sb, Se, and U) that have been identified as possible hazardous air pollutants (HAPs) by the United States Clean Air Act Amendments of 1990. The subject of the study is the San Miguel lignite deposit (late

Eocene, lower Jackson Group) of south Texas (Figs 1 and 2).

Previous investigations

The general geology of the San Miguel lignite deposit has been reviewed by McNulty (1978), Snedden (1979), Snedden and Kersey (1981), Tewalt *et al.* (1983), Gowan (1985), and Ayers (1986, 1989). The San Miguel lignite interval consists of four (or more) thin (generally < 1 m thick) lignite benches that are separated by claystone and mudstone partings. The upper bed is designated as the A bed and is underlain by the B, C, and D beds (Gowan, 1985). The rocks associated with the lignite beds are dominated by fine siltstone and claystone with occasional thin layers of gastropod and bivalve shells. The lignite-bearing interval is laterally persistent for more than 40 km and is interpreted to have formed in lagoonal mires landward (west) of a sandstone-dominated barrier island complex (Ayers, 1986, 1989). Jackson Group lignite resources for the south Texas area have been estimated to be about 6 billion short tons (Kaiser *et al.*, 1980). The Keystone

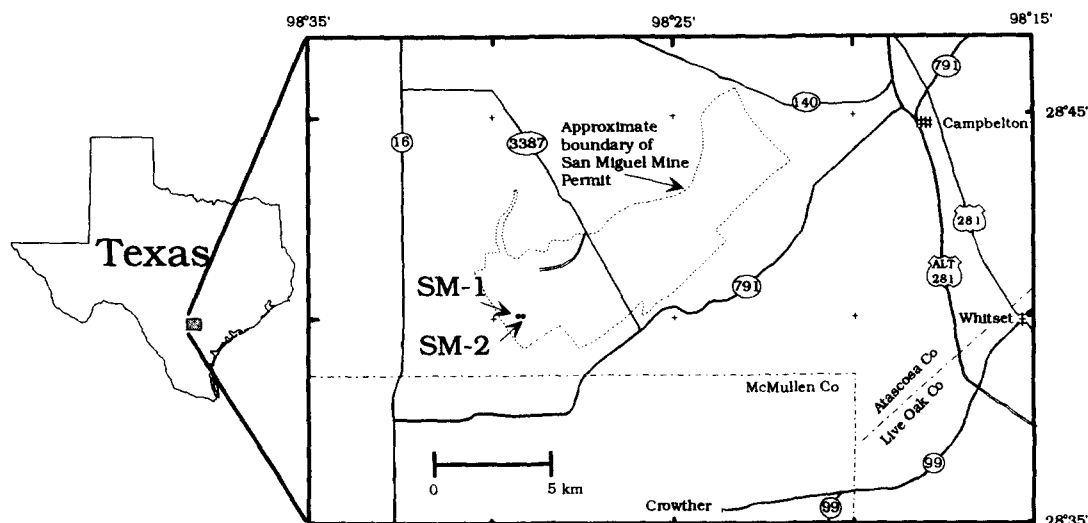


Fig. 1. Index map of the San Miguel Mine area showing towns, roads, and sample sites. Geodetic locations for sample sites are given in Appendix I. Mine outline from the San Miguel Lignite Mine Permit Application, on file at the Texas Railroad Commission in Austin, Texas.

Coal Industry Manual (Maclean Hunter Publishing Company, 1994) reports the total resources for the San Miguel Mine holdings to be 100 million short tons.

Kaiser (1982), Gowan (1985), and Ayers (1986, 1989) suggest that the rock partings within the San Miguel lignite deposit are composed of volcanic air-fall ash that has been reworked by tidal or channel processes. Senkayi *et al.* (1987) examined the partings in detail and found that most contained altered kaolinite and mixed detrital and volcanic quartz grains, thereby supporting the interpretation of a volcanic origin and subsequent detrital mixing of the sediment that forms these layers. Furthermore, Senkayi *et al.* (1987) recognized three layers that contained vermicular kaolinite, opal-CT, and altered glass shards consisting mainly of clinoptilolite. They suggested that these layers represent major volcanic ash falls. The layers identified are: a 25 cm thick layer in the interval below the D bed, the entire parting between the C and D beds, and a thin layer (about 10 cm thick) within the roof rock approximately 30 cm above bed A (Fig. 2). Senkayi *et al.* (1987) also reported that ground water rich in silica derived from the volcanic material in the partings may have provided solutions from which opal-CT and euhedral clinoptilolite precipitated in fossilized plant roots, veinlets, and fractures within underlying strata.

Chemical and physical data obtained from San Miguel lignite samples have been reported on an individual bed basis (5 samples; Mukhopadhyay, 1989) and on a combined bed basis (23 samples; Tewalt, 1986). From these data the dry ash yields of samples range from 25 to 55% (av. 38%; Tewalt, 1986) with the A bed having the greatest average ash yield (39%, Mukhopadhyay, 1989). Equilibrium

moisture values range from 27 to 33% (Tewalt, 1986). Total sulfur contents (on a dry basis) range from 1.5 to 3.1% (Tewalt, 1986). Organic sulfur is the dominant sulfur type. Calorific values (on a moisture-free basis) for the San Miguel samples range from 5384 to 8690 Btu/lb (12.5–20.2 MJ/kg) (Tewalt, 1986). Tewalt (1986) and Mukhopadhyay (1989) report that the rank of the Jackson Group and the San Miguel lignites is lignite A.

Tewalt (1986) also reported major oxide and trace-element data for the San Miguel lignite interval. She found that the San Miguel lignite interval contains greater amounts of Na_2O (av. 3.67%; $N = 66$) as compared to other lignite deposits of Texas (range of averages: 0.41–1.22%), and suggested that this enrichment was either the result of sodium sorption from saline waters during and after deposition or of sodium cation exchange with present-day ground water. Tewalt (1986) reported trace-element concentrations for 15 elements (As, B, Be, Cd, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Se, U, V, Zn) that were obtained from two samples from the San Miguel deposit. Based on the results from other Jackson Group lignites of east Texas, Tewalt suggested that the Jackson lignites contain greater amounts of B, Be, Mn, and Zn than the older Wilcox lignites of eastern Texas.

Mukhopadhyay (1986, 1989) first examined the petrographic characteristics of channel and lithotype samples from each of the four major lignite beds exposed at the San Miguel mine. Mukhopadhyay did not report the geodetic locations for his samples but he reported that the samples were collected from the same mine area as the samples used for this study. Mukhopadhyay's channel sample data indicate that bed A contains greater amounts of liptinite macerals (32%, primarily sporinite and

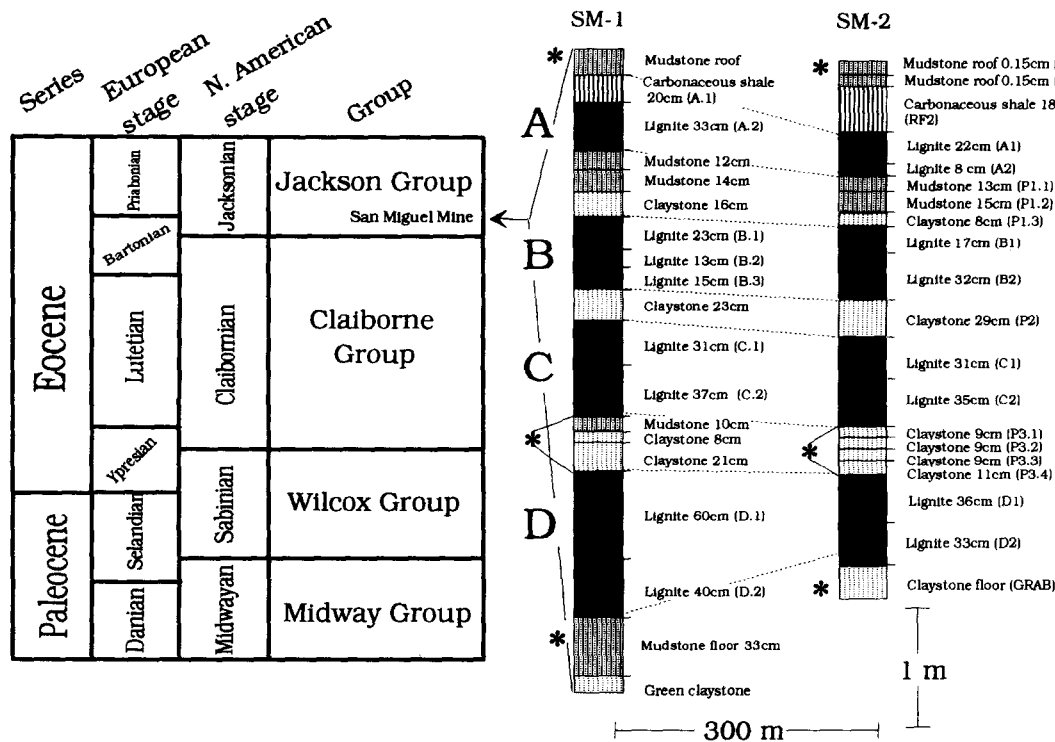


Fig. 2. Generalized stratigraphy and stratigraphic sections of the coal-bearing interval at the San Miguel Mine. Sample numbers in parentheses refer to Table 1, and channel sample sites are shown in Fig. 1. Detailed interval descriptions are given in the Appendix. The approximate positions of the volcanic ash beds identified by Senkayi *et al.* (1987) are indicated by an asterisk. Stratigraphy is after Breyer (1991).

liptodetrinite) than the huminite-rich middle lignite beds. Bed C contains the greatest amount of huminitic material (85%, primarily ulminite and attrinite/densinite) when compared to the other beds. Inertinite content for the beds range from 1 to 4% and is primarily in the form of sclerotinite and fusinite. The D bed contained a few marine dinoflagellates (algal cysts).

Gennett (1985) and Gennett and Raymond (1986) examined incremental bench samples from a core of the San Miguel lignite and found that the lower D bed had pollen derived from marsh ferns and palms, which suggested a brackish-water influence on the deposition of the D bed paleo-mire. Pollen types found in the overlying beds showed fresh-water associations as indicated by a vertical transition from *Nyssa* (tupelo) to *Engelhardia* (walnut family) and Fagaceous (oak family) types. Mukhopadhyay (1989) reported that beds B and D contain marsh pollen types, and suggested that the San Miguel lignites are dominated by *Engelhardia/Juglandaceae* and herbaceous(?) monocots.

METHODS

Lignite and rock samples for this study were collected from an active opencast pit of the San Miguel lignite mine. Two sites along the highwall, about 300 m apart, were selected for incremental

channels (SM-1 and SM-2, Figs 1, 2 and 3a). Incremental bench samples were collected to determine the vertical and lateral variability of physical and chemical characteristics. The megascopic character of the lignite beds was used to determine the sample-interval size (Fig. 2, Appendix I). The volcanic ash layers identified by Senkayi *et al.* (1987) were not recognized in the field and were not sampled independently; however, the parting samples collected at the SM-2 site (Fig. 2) in our study include the volcanic layers identified by Senkayi *et al.* (1987).

Standard proximate analyses were performed on all lignite samples in accordance with ASTM test methods (ASTM, 1993) and the results are recorded in Table 1 and Fig. 4. As-received moisture content was determined only for the SM-2 lignite sample set (Table 1). Roof, floor, lignite and partings were sampled at SM-2; only lignite was sampled at SM-1. All samples were analyzed for 51 elements and nine oxides (Table 1); analytical methods follow USGS methods (Golightly and Simon, 1989). Elemental chemistry of the lignite and rock samples were determined using inductively coupled plasma atomic emission spectroscopy (Na₂O, SiO₂, Al₂O₃, CaO, MgO, K₂O, Fe₂O₃, TiO₂, P₂O₅, B, Ba, Be, Co, Cr, Cu, Li, Mn, Ni, Sc, Sr, Th, V, Y, Zn, Zr), inductively coupled plasma mass spectroscopy (Ag, As, Au, Bi, Cd, Ce, Cs, Dy, Er, Eu, Ga, Gd, Ge, Hf, Ho, La, Mo, Nb, Nd, Pb, Pr, Rb, Sb, Sm, Sn, Ta, Tb, Te, Tl, Tm,

U, Yb), atomic absorption spectroscopy graphite furnace (Hg), X-ray fluorescence analysis (P), and hydride generation atomic absorption spectroscopy (Se).

Representative microblocks of claystone and mudstone partings from the SM-2 channel sample set were embedded in epoxy, polished, sectioned, and then carbon coated for scanning electron microscopy (SEM) and energy-dispersive X-ray analyses (EDXA).

Representative splits of all lignite samples were ground and cast into pellets and polished for petrographic analyses according to the procedures

outlined by ASTM (1993). The pellets were etched by acidified potassium permanganate (Stach *et al.*, 1982; Pontolillo and Stanton, 1994) which permitted detailed subdivision of the huminite maceral group. An initial petrographic examination of the pellets was made using blue-light fluorescence by counting 1000 point counts on duplicate pellets to determine maceral percentages within the liptinite group. Subsequently, 1000 point counts were made in reflected white light to determine inertinite and huminite maceral percentages. Mineral matter is counted and included in the blue-light analysis of the samples but is not counted during the white-light

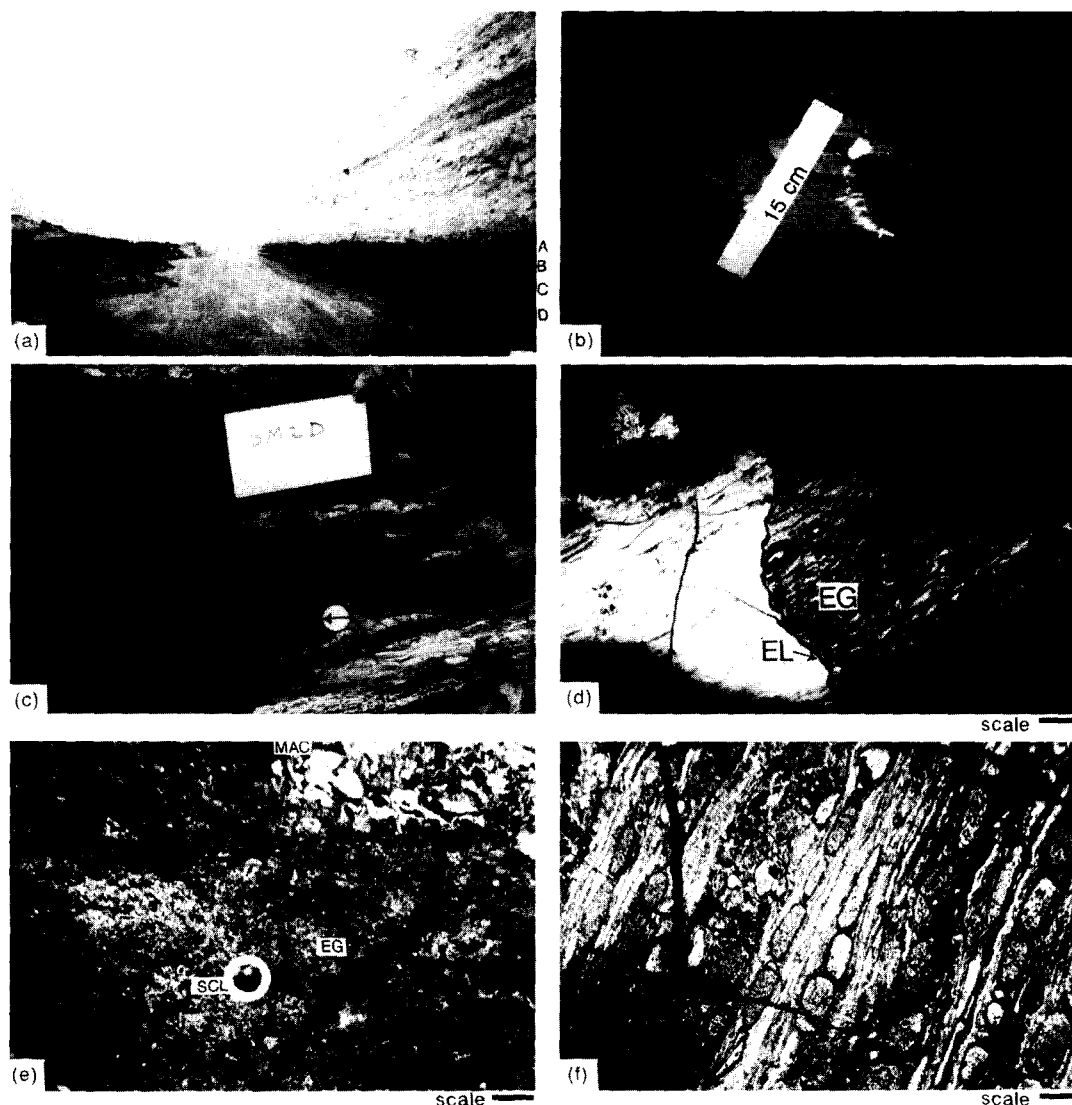


Fig. 3. Representative photographs and photomicrographs of outcrops and samples from the San Miguel lignite interval. (a) View of a highwall with A (upper), B, C, and D beds and the partings. (b) Clay-filled burrows common in the San Miguel lignite. Scale = 15 cm. (c) Arrow points to a compressed log in the D bed. (d) Typical photomicrograph of an etched and unetched surface of a polished pellet of San Miguel lignite. EG = eugelinite, EL = etch line. Scale bar = 25µm. (e) Photomicrograph of an etched surface of a polished pellet of San Miguel lignite. EG = eugelinite, SCL = sclerotinite, MAC = macrinite. Scale bar = 25µm. (f) Cell structure of preserved woody tissue, probably from an angiosperm. Scale bar = 25µm.

Table 1. Proximate, trace element, and major oxide data for the San Miguel (SM) lignite deposit. Sample intervals are shown in Figure 2. Proximate data are percentages on an as-received (AR) and dry basis except BTU (British Thermal Units/lb) and MJ/kg. Trace element data is on an ash basis. S. No. = sample number; Moist = moisture, S = total sulfur; Ss = sulfate sulfur; Sp = pyritic sulfur; So = organic sulfur; ND = no data; Sample locations are shown in Fig. 1

Proximate data (as-received basis)													
S. No.	Moist	Ash	S	Ss	Sp	So	BTU	Mj/kg					
SM-2-A1	29.49	26.33	1.61	0.02	0.19	1.4	5562	13					
SM-2-A2	30.15	24.17	1.96	0.02	0.14	1.53	5728	13					
SM-2-B1	32.93	18.41	2.05	0.07	0.49	1.49	6073	14					
SM-2-B2	34.17	12.48	1.78	0.05	0.29	1.44	6804	16					
SM-2-C1	36.53	11.03	1.75	0.06	0.29	1.4	6520	15					
SM-2-C2	32.3	12.71	1.86	0.06	0.47	1.33	6953	16					
SM-2-D1	37.44	9.86	1.54	0.04	0.32	1.18	6582	15					
SM-2-D2	34.11	17.99	1.71	0.07	0.29	1.35	5942	14					
Proximate data (dry basis)													
S. No.	Ash	S	Ss	Sp	So	BTU	Mj/kg						
SM-1A.1	67.25	2.05	0.17	0.65	1.23	3962	9						
SM-1A.2	43.49	3.01	0.31	0.62	2.08	7028	16						
SM-1B.1	37.39	2.89	0.18	0.59	2.12	7591	18						
SM-1B.2	27.8	3.25	0.26	0.78	2.21	8823	21						
SM-1B.3	22.11	3.03	0.25	0.38	2.4	9633	22						
SM-1C.1	23.82	2.81	0.26	0.45	2.1	9173	21						
SM-1C.2	25.97	2.54	0.25	0.35	1.94	9032	21						
SM-1D.1	25.66	2.65	0.37	0.37	1.91	8922	21						
SM-1D.2	41.65	3.18	0.64	0.46	2.08	6673	16						
SM-2-A1	37.34	2.29	0.03	0.27	1.99	7888	18						
SM-2-A2	34.6	2.81	0.03	0.59	2.19	8201	19						
SM-2-B1	27.45	3.06	0.11	0.74	2.21	9055	21						
SM-2-B2	18.96	2.71	0.08	0.44	2.19	10336	24						
SM-2-C1	17.38	2.76	0.09	0.45	2.22	10273	24						
SM-2-C2	18.77	2.75	0.09	0.7	1.96	10270	24						
SM-2-D1	15.77	2.46	0.06	0.51	1.89	10521	24						
SM-2-D2	27.3	2.6	0.11	0.44	2.05	9019	21						
Trace element data (ash basis, in parts per million)													
S. No.	As	Au	B	Ba	Be	Bi	Ce	Cd	Co	Cr	Cs	Cu	
SM-1A.1	20	< 3	350	1200	10	0.9	50	0.7	2	9	1.8	7	
SM-1A.2	50	< 3	540	1000	15	1.2	80	< 0.2	4	24	4	28	
SM-1B.1	39	< 3	950	1300	5	1	80	2.2	11	26	1.9	28	
SM-1B.2	45	< 3	1300	1900	6	1	100	0.9	12	18	1.8	25	
SM-1B.3	43	< 3	1600	3300	10	1.1	120	0.5	8	32	1.8	40	
SM-1C.1	42	< 3	1600	2100	11	1	170	3.2	9	33	2	28	
SM-1C.2	42	< 3	1500	1100	11	1.1	150	0.6	3	22	2.9	26	
SM-1D.1	83	< 3	1400	3900	9	0.8	70	1.4	5	18	1.8	25	
SM-1D.2	51	< 3	640	1100	7	0.8	80	1.1	6	24	5.1	31	
SM2-RF1T	4	< 10	100	1000	2	< 2	60	< 0.8	< 2	38	4	4	
SM2-RF1B	6	< 10	150	1100	5	< 2	50	< 0.8	< 2	76	4	15	
SM2-RF2	10	< 10	120	1600	6	< 2	70	1	5	86	2	12	
SM-2-A1	20	< 10	680	1900	24	< 2	100	1	7	4	2	16	
SM-2-A2	30	< 10	760	1700	19	< 2	80	< 0.8	6	39	3	40	
SM2 P1.1	10	< 10	88	1200	3	2	80	< 0.8	< 2	68	3	24	
SM2 P1.2	8	< 10	110	1100	4	3	70	2	4	48	2	45	
SM2 P1.3	20	< 10	200	2000	3	< 2	100	2	13	21	2	33	
SM-2-B1	30	< 10	1300	1800	9	< 2	170	1	15	42	2	20	
SM-2-B2	55	< 10	2100	1500	16	< 2	130	< 0.8	10	47	2	27	
SM2 P2	< 4	< 10	190	1100	< 2	2	50	< 0.8	< 2	53	1	16	
SM-2-C1	99	< 10	2100	1400	20	< 2	260	2	14	28	1	28	
SM-2-C2	40	< 10	2000	1400	21	< 2	260	< 0.8	7	19	1	28	
SM2 P3.1	30	< 10	110	1800	< 2	< 2	90	< 0.8	< 2	70	4	5	
SM2 P3.2	< 4	< 10	160	1400	< 2	< 2	20	0.9	< 2	27	2	< 2	
SM2 P3.3	< 4	< 10	140	1200	< 2	< 2	60	< 0.8	< 2	71	2	4	
SM2 P3.4	5	< 10	160	1600	< 2	< 2	70	1	< 2	18	2	23	
SM-2-D1	40	< 10	2700	1500	18	< 2	200	0.9	11	53	1	33	
SM-2-D2	63	< 10	1000	870	12	< 2	110	1	7	33	6	41	
SM-2 GRAB	< 4	< 10	95	140	< 2	< 2	40	< 0.8	9	80	16	12	
S. No.	Dy	Er	Eu	Ga	Ge	Gd	Hf	Hg	Ho	La	Li	Mn	Mo
SM-1A.1	7	6	0.8	22	30	5	9	0.08	2	20	51	120	20
SM-1A.2	11	7	2	27	19	10	10	0.4	2	40	39	340	21
SM-1B.1	9	5	2	23	7.1	8	10	0.4	2	40	75	290	12
SM-1B.2	11	6	2	14	6.3	10	10	0.36	2	50	41	390	8.9
SM-1B.3	15	9	3	25	7.1	10	20	0.14	3	60	47	530	14
SM-1C.1	17	10	4	31	8.6	20	30	0.18	3	90	40	480	14
SM-1C.2	16	10	3	30	7	20	20	0.1	3	70	31	490	14
SM-1D.1	10	5	2	15	7.1	9	9	0.17	2	40	21	540	12
SM-1D.2	8	5	1	26	8.8	7	7	0.14	2	50	77	380	22
SM2-RF1T	3	2	0.5	38	< 2	3	10	0.11	0.6	40	44	58	9.9
SM2-RF1B	5	4	0.6	47	2	4	10	0.1	1	30	81	76	7.7
SM2-RF2	7	5	1	42	4	5	10	0.03	1	40	84	67	9.7
SM-2-A1	16	11	2	41	81	10	10	0.15	3	50	45	240	11
SM-2-A2	15	9	2	50	14	10	20	0.47	3	40	66	370	12
SM2 P1.1	5	3	1	42	< 2	5	10	0.03	1	40	98	100	6.7
SM2 P1.2	7	4	1	56	< 2	6	10	< 0.01	1	40	150	140	10

continued overleaf

Table 1—*continued*

SM2 P1.3	6	3	1	35	2	6	10	0.01	1	50	61	130	7.8
SM-2-B1	13	7	3	32	6.7	10	10	0.39	2	90	49	310	9.7
SM-2-B2	20	11	3	35	6.2	20	30	0.2	4	60	60	510	12
SM2 P2	3	2	0.7	46	< 2	3	10	0.1	0.6	30	110	58	3
SM-2-C1	29	15	5	34	7.6	30	30	0.21	5	130	56	650	18
SM-2-C2	29	17	5	32	7.7	30	20	0.21	5	130	40	550	12
SM2 P3.1	5	3	1	44	< 2	6	10	0.13	0.9	50	40	58	6.3
SM2 P3.2	1	0.8	0.3	54	< 2	1	9	0.13	< 0.5	10	45	32	2
SM2 P3.3	3	1	0.6	53	< 2	3	7	0.06	< 0.5	30	66	38	3
SM2 P3.4	5	3	1	48	< 2	5	10	0.07	1	40	42	57	5.9
SM-2-D1	23	13	4	24	7	20	20	0.12	4	100	37	640	13
SM-2-D2	12	8	2	32	4.6	10	10	0.1	2	60	62	440	16
SM-2 GRAB	3	2	0.7	26	< 2	3	8	0.05	0.6	30	44	120	2
S. No.	Nb	Nd	Ni	Pb	Pr	Rb	Sb	Sc	Se	Sm	Sn	Sr	Tb
SM-1A.1	31	20	5	40	5	80	1.7	7	1.4	4	6	860	0.7
SM-1A.2	26	40	9	26	9	77	4	15	4.3	9	11	830	2
SM-1B.1	18	40	12	26	9	82	5.2	17	3.7	8	9	1300	1
SM-1B.2	16	50	15	14	12	98	3.2	17	3.1	11	6	1400	2
SM-1B.3	23	60	16	14	13	93	8.8	32	3.2	14	42	1500	2
SM-1C.1	110	80	17	20	19	89	6.2	31	3.2	18	18	1400	3
SM-1C.2	68	80	13	24	18	96	4.5	21	3.1	16	11	1400	3
SM-1D.1	24	40	11	7	9	95	4.4	13	3.2	8	7	1500	1
SM-1D.2	23	40	17	22	9	71	2.6	12	4.1	7	6	910	1
SM2-RF1T	62	30	6	40	7	76	< 2	8	1.7	4	10	440	< 0.5
SM2-RF1B	74	20	9	40	5	72	< 2	10	4.5	4	10	450	0.8
SM2-RF2	20	30	4	60	8	77	4	8	3.9	6	< 10	740	1
SM-2-A1	59	50	< 4	30	12	95	5.2	21	2.6	11	10	1100	2
SM-2-A2	30	40	12	30	9	88	6.7	25	4.7	10	10	1100	2
SM2 P1.1	30	30	5	54	8	82	4	9	8.4	6	10	540	0.8
SM2 P1.2	42	30	8	92	8	43	4	15	16	7	10	540	1
SM2 P1.3	10	40	12	46	11	60	4.1	10	7.4	8	< 10	960	1
SM-2-B1	20	70	7	20	20	72	5.2	21	3	15	< 10	1100	2
SM-2-B2	30	70	13	20	16	63	6.1	37	3.4	16	< 10	1300	3
SM2 P2	30	20	4	73	5	51	2	9	7.8	4	< 10	440	0.5
SM-2-C1	86	120	21	20	31	57	5.6	44	5.1	27	< 10	1400	5
SM-2-C2	60	120	15	20	31	51	3	30	2.7	26	< 10	1200	4
SM2 P3.1	30	40	< 4	30	10	100	2	6	6.2	7	< 10	740	0.9
SM2 P3.2	30	9	< 4	55	2	65	< 2	< 4	1.5	2	10	500	< 0.5
SM2 P3.3	43	20	< 4	30	6	70	< 2	5	3.1	4	< 10	480	0.5
SM2 P3.4	20	30	9	43	8	74	< 2	7	10	7	< 10	700	0.9
SM-2-D1	30	100	13	20	24	53	3	23	2.2	21	< 10	1500	3
SM-2-D2	30	50	14	30	13	90	2	19	4.4	11	< 10	900	2
SM-2 GRAB	20	20	15	10	5	210	< 2	14	0.6	3	< 10	130	< 0.5
S. No.	Ta	Te	Th	Tm	Tl	U	V	W	Y	Yb	Zn	Zr	
SM-1A.1	2	< 0.5	19	1	4	12	31	10	53	8	51	300	
SM-1A.2	2	< 0.5	25	1	4.7	11	78	20	79	7	32	310	
SM-1B.1	1	0.6	23	0.6	5.2	8.8	88	10	41	5	92	370	
SM-1B.2	1	0.5	18	0.9	3.8	6	67	20	53	6	50	270	
SM-1B.3	1	1.3	28	1	0.6	17	110	10	76	8	56	570	
SM-1C.1	10	0.8	56	1	2	20	160	10	92	9	130	880	
SM-1C.2	3	< 0.5	32	1	< 0.5	14	81	6	91	10	46	570	
SM-1D.1	1	0.5	16	0.8	1.8	6.5	66	8	70	5	82	280	
SM-1D.2	2	< 0.5	15	0.8	1.3	5.4	71	4	55	5	46	230	
SM2-RF1T	4	< 2	13	< 0.5	< 2	9.2	78	10	13	3	22	260	
SM2-RF1B	5	< 2	27	0.7	< 2	11	73	9	35	5	29	330	
SM2-RF2	3	< 2	27	0.7	2	9	52	4	39	5	130	400	
SM-2-A1	3	< 2	29	2	< 2	11	84	10	99	10	100	520	
SM-2-A2	2	< 2	50	1	2	20	130	10	88	8	67	550	
SM2 P1.1	3	< 2	28	< 0.5	< 2	6.4	83	5	27	3	27	320	
SM2 P1.2	4	< 2	27	0.6	< 2	8.2	160	7	32	4	61	400	
SM2 P1.3	1	< 2	15	< 0.5	3	7.5	68	4	25	3	110	280	
SM-2-B1	2	< 2	22	0.9	2	10	88	10	61	6	110	370	
SM-2-B2	2	< 2	39	2	< 2	17	160	10	97	10	98	980	
SM2 P2	2	< 2	30	< 0.5	< 2	9	47	3	12	2	26	250	
SM-2-C1	6	< 2	51	2	< 2	26	150	9	150	15	99	810	
SM-2-C2	4	< 2	41	3	3	14	100	10	150	17	82	720	
SM2 P3.1	2	< 2	20	< 0.5	< 2	4.9	31	2	21	2	35	320	
SM2 P3.2	3	< 2	< 8	< 0.5	< 2	4	15	3	4	0.7	160	160	
SM2 P3.3	3	< 2	15	< 0.5	< 2	4	24	3	11	1	20	140	
SM2 P3.4	2	< 2	22	< 0.5	< 2	8.5	26	1	23	3	100	310	
SM-2-D1	2	< 2	27	2	3	10	92	10	130	12	98	470	
SM-2-D2	2	< 2	24	1	< 2	7.9	110	4	88	7	43	320	
SM-2 GRAB	2	< 2	11	< 0.5	< 2	4.1	110	2	13	2	74	180	

continued

Table 1—continued

Major oxide data (ash basis, in percent)											
S. No.	Al ₂ O ₃	CaO	FeTO ₃	K ₂ O	MgO	Na ₂ O	P ₂ O ₅	SiO ₂	So ₃	TiO ₂	USGS Ash
SM-1A.1	17	2	2.1	2.1	0.35	3.3	< 0.02	64	3.34	0.32	67.43
SM-1A.2	11	4	3.6	1.6	0.45	3.4	0.02	68	6.51	0.7	43.5
SM-1B.1	16	4.9	3.6	2	0.43	5.1	< 0.02	57	7.97	0.48	36.84
SM-1B.2	12	6.6	5.5	1.9	0.47	5.8	< 0.02	53	11.2	0.45	28.62
SM-1B.3	12	8.7	4.5	1.8	0.59	6.7	0.02	50	13.6	0.59	22.36
SM-1C.1	13	7.9	4.3	1.8	0.57	6.3	0.03	48	13.7	0.64	24.11
SM-1C.2	14	7.3	3.7	1.9	0.58	6	0.03	52	11.3	0.71	26.13
SM-1D.1	11	6.8	5	2	0.54	6.6	< 0.02	50	12.6	0.45	25.44
SM-1D.2	15	3.8	5.1	1.9	0.77	3.7	< 0.02	59	7.38	0.69	42.83
SM2-RF1T	17	0.8	0.62	1.6	0.54	2	0.02	72	0.69	1.2	93.33
SM2-RF1B	25	1.2	1.2	1.9	0.7	2	0.03	72	1.18	1.2	84.2
SM2-RF2	21	1.4	1.7	2	0.33	2.8	< 0.02	65	1.99	0.55	77.16
SM-2-A1	13	4.3	1.3	1.9	0.39	4.4	< 0.02	58	8.28	0.49	36.6
SM-2-A2	12	5.2	2.8	1.5	0.47	4.5	< 0.02	57	10.2	0.71	33
SM2 P1.1	20	1.6	1.2	2.2	0.35	2.1	0.02	68	2.3	1.1	71.48
SM2 P1.2	25	2	0.84	1.1	0.41	1.8	0.03	62	2.65	1.9	65.85
SM2 P1.3	17	2.8	3.7	1.8	0.35	3.3	< 0.02	59	4.98	0.75	51.2
SM-2-B1	14	5.8	5.2	1.4	0.48	4.9	0.02	51	11.6	0.63	26.76
SM-2-B2	13	8.8	4.3	1.2	0.6	6.2	0.02	40	18.3	0.78	21.28
SM2 P2	29	1	0.41	1.6	0.36	1.6	0.03	62	1.36	1.1	80.52
SM-2-C1	12	9.6	5.4	1.1	0.63	7	0.04	34	21.1	0.64	17.16
SM-2-C2	14	9.1	6.2	0.94	0.63	6.2	0.04	40	18.5	0.91	18.52
SM2 P3.1	19	1.1	7.4	2.7	0.36	2.4	0.02	59	3.1	0.69	78
SM2 P3.2	31	0.72	0.53	1.6	0.39	1.9	< 0.02	64	0.59	0.56	88.52
SM2 P3.3	27	0.71	0.43	1.9	0.37	1.8	0.02	60	0.64	0.7	88.16
SM2 P3.4	26	1.3	0.89	1.7	0.28	2.3	< 0.02	58	1.78	0.43	73.85
SM-2-D1	13	10	6	0.99	0.74	8	0.02	34	22.2	0.73	15
SM-2-D2	16	5.8	4.2	1.7	1	4.6	0.02	49	12.1	0.92	26.2
SM-2 GRAB	19	0.76	5.9	2.3	2.4	1.7	< 0.02	68	0.8	0.75	94.48

analysis. This procedure requires that the blue-light data be adjusted to a mineral-matter-free (mmf) basis in order to be comparable to the white-light data. The sulfur content and ash yield of each sample is used in the Parr Mineral Matter Formula (ASTM, 1993) to calculate the mineral matter content of the sample. The calculated mineral matter content allowed the adjustment of the blue-light counts to obtain mineral-matter-free values. These values were used to determine percentages of each maceral counted. A total of 23 maceral types was counted and their percentages are given on an dry ash-free basis (Table 2). The low-rank coal petrography terms used in this paper follow the nomenclature described in ICCP (1963, 1971), Stach *et al.* (1982), and Warwick and Stanton (1988). The use of "crypto" to denote macerals identified on etched pellet surfaces has not been used in this paper for the sake of readability.

RESULTS

Physical and chemical characteristics

As described by Gowan (1985), the San Miguel lignite interval has been extremely reworked by burrowing organisms. This is apparent from the lithologic descriptions of the channel sample sites of this study (Appendix). Some of the burrows near the top of the A lignite bed were identified as gyrolithes by Gowan (1985) and probably were formed by organisms that lived in the sea water that encroached over the top of the peat deposit. The burrows are usually filled with a mixture of organic material and

kaolinitic claystone which is one source of ash in the lignite beds (Fig. 3b). Individual lignite beds generally exhibit a dull, somewhat massive texture near their base, which grades upwards into attrital-rich lignite with increasing xylinitic bands (3–4 cm thick) towards the top of the individual bed. Xylinitic bands can compose up to 30% of the sample interval (for example, see interval 9, sample SM-1-C.1 Appendix). Occasionally, compressed logs are exposed in cross-section on the exposed face of the lignite bench (Fig. 3b). The middle lignite beds (B and C) appear to contain the greatest percentage of xylinitic banding when compared to the upper and lower beds (A and D) (Appendix).

Proximate analyses of the 17 lignite samples collected from the San Miguel deposit indicate that dry ash yields average 30.16%; total dry sulfur content averages 2.76% (dominated by organic sulfur, 2.04%); and dry calorific values average 8611 Btu/lb (20 MJ/kg) (Table 1 and Fig. 4). As-received moisture content averages 33.4% for the SM-2 channel sample set. At both sample sites, ash yields were greatest from the upper and lower lignite benches. Total sulfur content is fairly uniform both within and between each sample site (Fig. 4, Table 1).

Trace element data from both channel sample sites are listed in Table 1 and the distribution of the 12 HAP elements (on an dry, ash basis) for both sample sites are plotted in Fig. 5. Visual analysis of the SM-2 bar graphs shows that some of the HAP elements are concentrated in the organic-rich (or lignite) samples. Linear correlations between ash yield and the concentrations of the HAP elements on an ash basis for those samples containing less than 50% ash (i.e.

what is normally mined) showed that only Mn has a strong negative ($r < -0.5$) relationship to sample ash yield. On a whole-coal basis (for those samples containing less than 50% ash), a strong positive correlation ($r > 0.5$) was found between ash and Pb, Se, and Na_2O (Fig. 6).

Bar graphs were plotted for both San Miguel rock and lignite samples to show the vertical distribution of elements that may be associated with volcanic ash partings. Mean concentrations are: Ce, 117 ppm; Nb, 36 ppm; Ta, 2.4 ppm; Th, 29 ppm; and Zr, 477 ppm (all concentrations in coal on an ash basis) (Fig. 7).

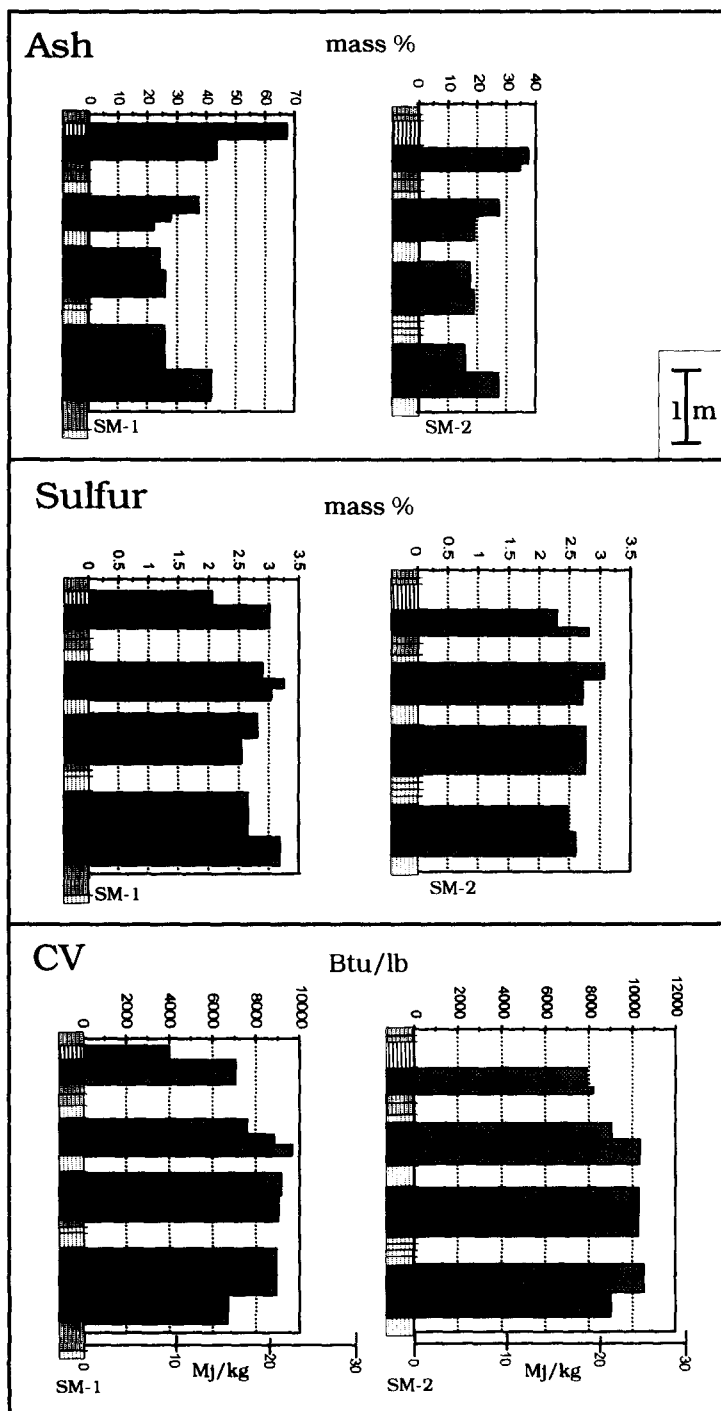


Fig. 4. Bar graphs showing concentrations of ash, total sulfur, and calorific value (CV, dry basis) for the sample sets SM-1 and SM-2. Location of samples are shown in Fig. 1 and lithologic symbols are the same as used in Fig. 2. Distance between sample sites is about 300 m.

Table 2. Petrographic data for the San Miguel lignite zone. Data are shown as percent averages on an ash-free basis. Sample locations are shown in Fig. 1; sample intervals are shown in Fig. 2. "Crypto"-macerals: HM = humotelinite, EC = "eu"-corpohuminites, PC = "pori"-corpohuminites in attritus, PG = "pori"-corpohuminites in humotelinite, EG = euglenite, DG = detrogelinite, ECG = "eu"-corpohuminites in attritus, PCG = "pori"-corpohuminites in attritus. Other macerals: FUS = fusinite, SF = semifusinite, ITD = inertodetrinite, SCL = sclerotinite, MAC = macrinite, SPR = sporinite, CUT = cutinite, RES = resinite, RSD = resinite in attritus, SUB = suberinite, EXD = exsudatinites, BIT = bituminites, FLR = fluorinite, ALG = alginate, LPD = lipodetrinite, T-HUM = total huminites, T-INR = total inertinites, T-LIP = total lipinites, ave = average. T = trace (< 5 counts/1000).

S. No.	HM	EC	PC	EG	PG	DG	ECG	PCG	FUS	SF	ITD	SCL	MAC	SPR	CUT	RES	RSD	SUB	EXD	BIT	FLR	ALG	LPD	T-HUM	T-INR	T-LIP
SM-1-A.1	7	T	0	53	T	2	1	0	0	0	T	T	0	1	1	2	6	0	2	4	T	10	11	63	T	37
SM-1-A.2	7	T	T	68	T	2	1	T	0	0	0	T	0	1	T	1	4	0	1	1	T	4	9	78	T	22
SM-1-B.1	11	1	1	70	1	1	1	T	1	0	1	T	4	1	T	T	T	T	T	1	0	2	3	86	6	8
SM-1-B.2	14	T	1	74	T	2	1	1	0	0	T	T	0	1	0	0	T	0	T	1	0	1	2	94	T	6
SM-1-B.3	5	T	1	84	2	1	T	T	0	0	0	T	0	1	T	0	T	0	T	1	0	T	3	94	T	6
SM-1-C.1	7	T	1	81	1	2	1	T	T	0	T	T	T	1	T	T	T	0	0	1	T	1	3	93	T	7
SM-1-C.2	10	T	1	80	1	2	1	1	0	0	T	T	0	1	0	T	T	0	T	0	0	1	2	94	T	5
SM-1-D.1	10	1	1	77	T	3	1	T	T	0	T	1	T	1	0	0	T	0	0	T	0	T	3	94	2	5
SM-1-D.2	8	T	T	77	T	5	1	T	T	0	0	T	T	1	T	0	T	0	0	2	0	1	3	92	T	7
ave	9	T	T	74	1	2	1	T	T	0	T	T	T	1	T	T	1	T	T	1	T	2	4	88	1	11
SM-2-A1	7	T	T	80	T	3	1	T	T	0	1	T	0	1	1	T	1	0	T	0	0	1	4	91	1	8
SM-2-A2	7	T	T	80	0	3	2	T	T	0	0	T	T	1	0	T	T	0	0	1	T	T	4	92	T	7
SM-2-B1	18	1	T	66	T	4	2	T	1	0	T	1	1	1	T	0	1	0	T	1	0	T	3	91	2	7
SM-2-B2	16	T	T	67	T	3	3	1	T	0	T	T	T	1	T	0	T	0	T	1	0	1	5	89	T	10
SM-2-C1	18	1	T	67	0	3	3	T	T	0	T	T	T	0	1	0	T	0	T	1	0	2	4	91	T	8
SM-2-C2	14	1	0	71	T	3	1	T	T	0	T	T	1	1	T	T	1	0	T	T	T	1	4	91	1	8
SM-2-D1	22	1	T	65	T	4	4	0	T	T	T	T	T	1	T	0	T	0	T	T	0	T	3	97	T	5
SM-2-D2	4	1	T	77	0	4	1	T	0	0	T	T	1	1	T	0	T	0	T	1	0	1	6	88	1	11
ave	13	1	T	72	T	3	2	T	T	T	T	T	T	1	T	T	T	T	T	1	T	1	4	91	1	8
Total ave	11	1	T	73	T	3	1	T	T	T	T	T	T	1	T	T	1	T	T	1	T	2	4	89	1	10

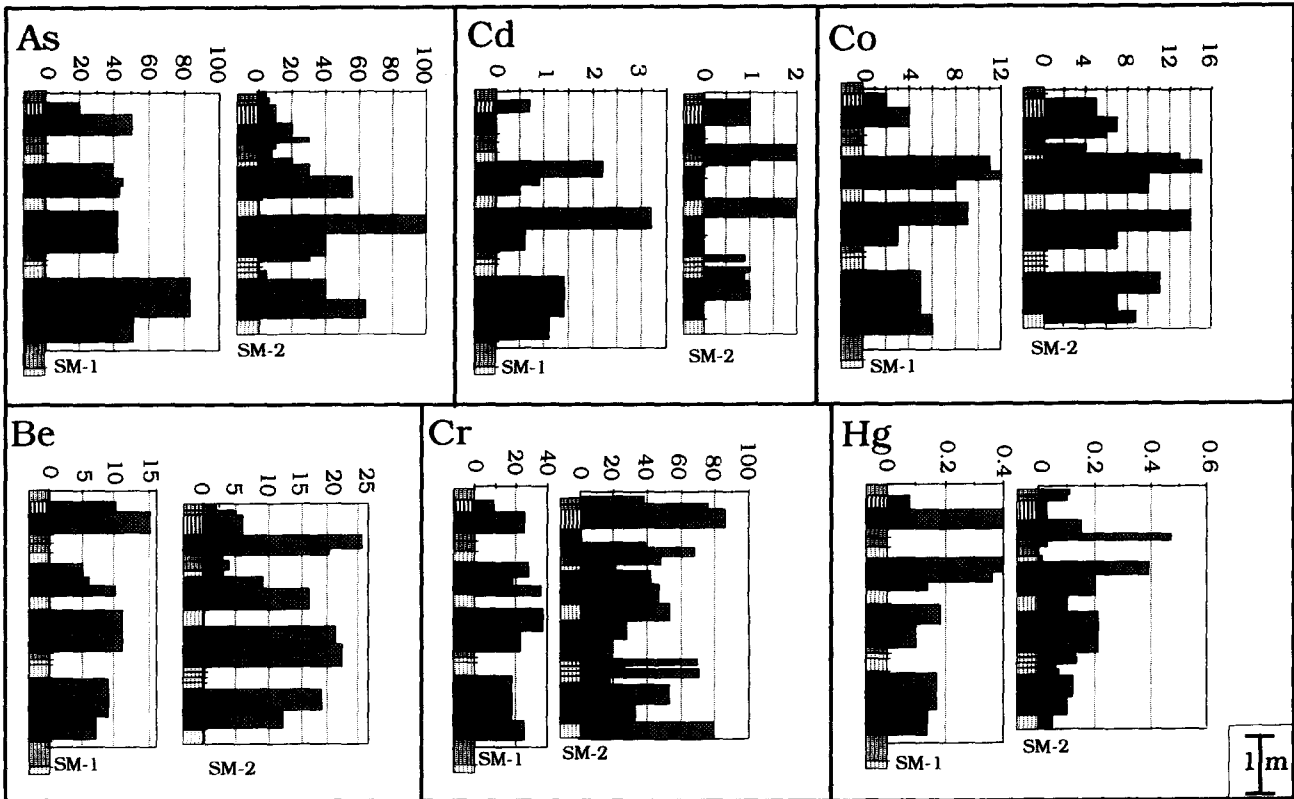


Fig. 5.

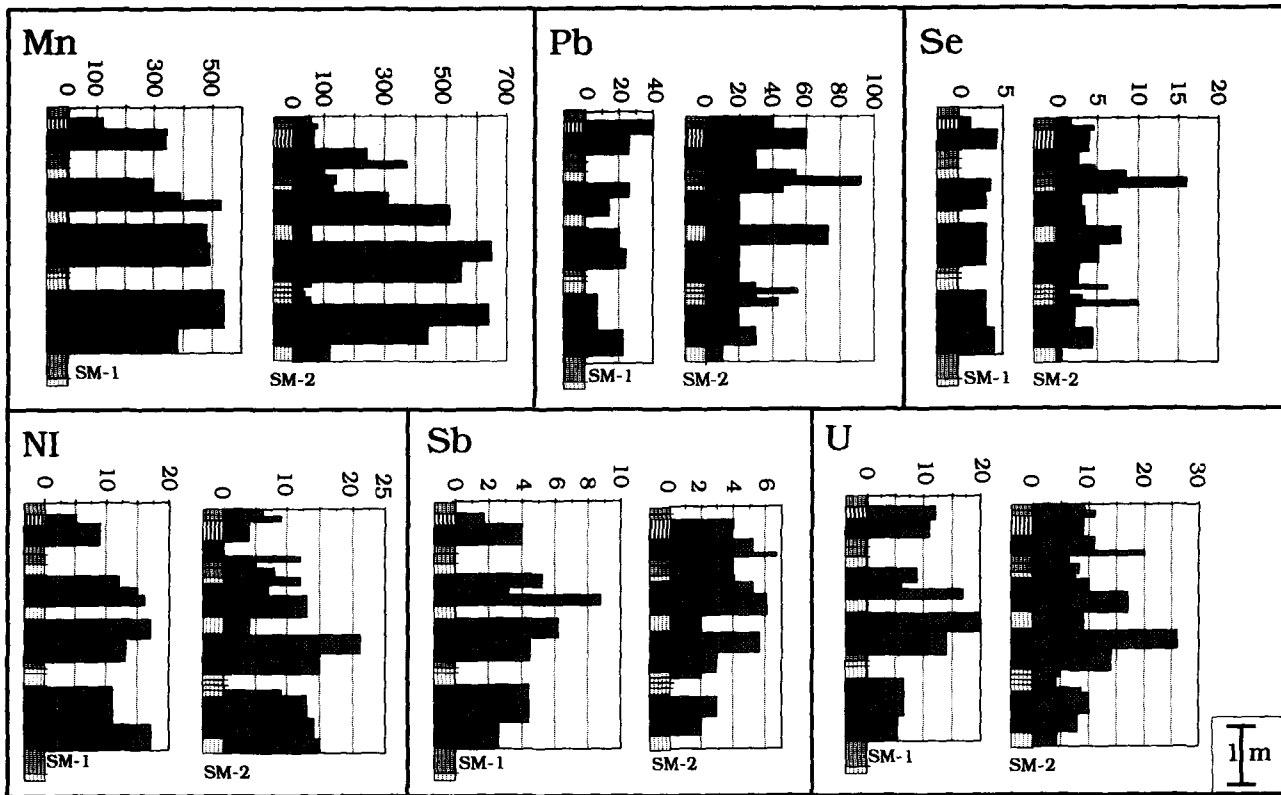


Fig. 5. Bar graphs showing the distribution of trace element concentrations (dry USGS ash basis) for the 12 potential HAPs identified by the 1990 U.S. Clean Air Act. Locations of samples are shown in Fig. 1 and lithologic symbols are the same as used in Fig. 2. All values are parts per million (ppm).

Concentrations of these elements are generally enriched in the B and C lignite beds. Previous work has indicated that concentrations of these elements in coal can be enriched by incorporation of volcanic ash in peat or by leaching from volcanic ash beds (Zielinski, 1985; Crowley *et al.*, 1989). In coal samples from intervals adjacent to altered volcanic ash partings in the Cretaceous C coal bed of Utah, Crowley *et al.* (1989) reported mean concentrations (on an ash basis) of elements having a volcanic origin as follows: Zr (752 ppm), Nb (57 ppm), Th (60 ppm), and Ce (246 ppm). Although the mean concentrations of these elements in the San Miguel samples do not reach the reported averages for the Utah C coal bed, specific samples from SM-1 and SM-2 exceed the Utah averages for Zr, Nb, and Ce.

Na₂O has a strong positive correlation with ash yield (Fig. 6). Tewalt (1986) reported that in Texas, the average concentrations of Na₂O (3.67%) are generally greater in San Miguel lignites than those found in the lignites of the Wilcox Group (range 0.41–0.84%) (Fig. 2).

Mineralogy of San Miguel partings

Preliminary examination of San Miguel rock

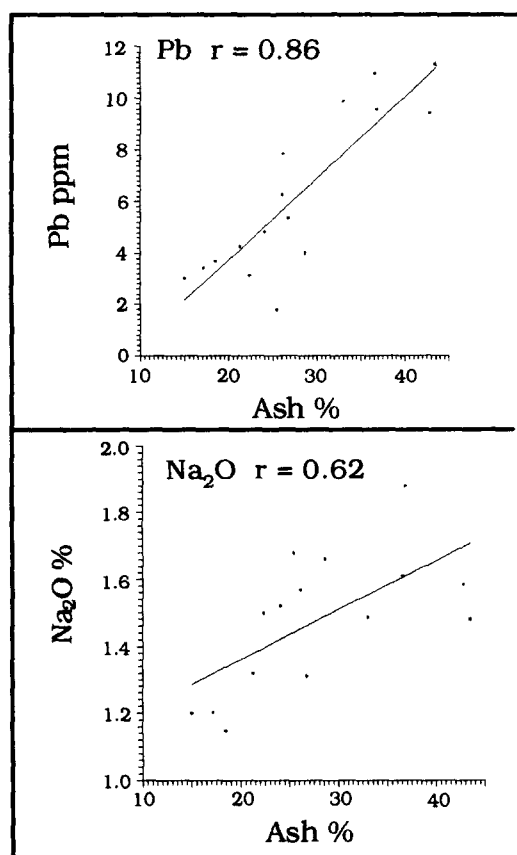


Fig. 6. Linear correlation plots of concentrations (whole-coal basis) of Pb and Na₂O. Data from coal samples (< 50% ash yield, Table 1) were used for the plots. r = correlation coefficient.

parting samples by scanning electron microscopy (SEM) and energy-dispersive X-ray analyses (EDXA) revealed that the upper part of the mudstone parting (SM-2 P1.1, Fig. 2) below the A bed is composed primarily of kaolinite with some mixed-layer clay present. Vermicular kaolinite is present throughout the sample as are small (< 50 μ m) K-feldspars. Isolated plagioclase, quartz, barite, framboidal pyrite, anatase, and a single Al-phosphate were also observed. The mudstone is very organic-rich. Individual organic stringers are rare; however, irregular pieces of coaly material are found throughout the sample.

The matrix of the claystone below the B bed (sample SM-2 P2, Fig. 2) is composed primarily of mixed-layer clay and abundant organic material. Both alkali and plagioclase feldspars are observed throughout the sample but they are rare. Quartz, pyrite, and Ca-Al phosphate (crandalite group?) are present in trace amounts.

Examination of samples from the claystone parting between the C and D beds (P3.1, P3.2, P3.3, and P3.4, Fig. 2), which was described as a major ash bed by Senkayi *et al.* (1987), shows that the matrices are composed primarily of mixed-layer clays. Kaolinite is present as cell-fillings, vermicular clasts, and rarely as matrix material. Accessory grains are uncommon. The dominant accessory minerals are subhedral, and often etched, alkali feldspars. Plagioclase is also present but not as abundant as the alkalis. Barite and pyrite, and rare subrounded quartz and euhedral zircons were observed in each of the examined samples.

Organic petrography

The San Miguel lignite deposit is dominated by the huminite maceral group (89%) followed by the liptinite (10%), and inertinite (1%) maceral groups (Table 2 and Figs 3d–f and 8). The three dominant huminite maceral subgroups in decreasing order of abundance are: euglenite (73%), humotelinite (11%), and detrogelinite (3%). The liptinite maceral group is dominated by liptodetrinite (4%), followed by alginite (2%) and resinite in attritus (1%). The inertinite maceral group is composed of macrinite, sclerotinite, and fusinite.

Vertical and lateral variations in maceral composition can be observed in the petrographic data (Table 2 and Fig. 8). Channel sample set SM-1 contains similar amounts of huminite macerals as found in SM-2 samples, but SM-1 samples have markedly less liptinite and inertinite components. Vertical trends in the petrographic data include slightly increased liptodetrinites in samples from the top and bottom of the lignite interval, and a sharp increase in inertinite (primarily macrinite and fusinite, Fig. 8) in the lignite samples directly below the parting between the A and B beds. Humotelinite content increases, although slightly, in the upper part of each bed. This finding is in agreement with

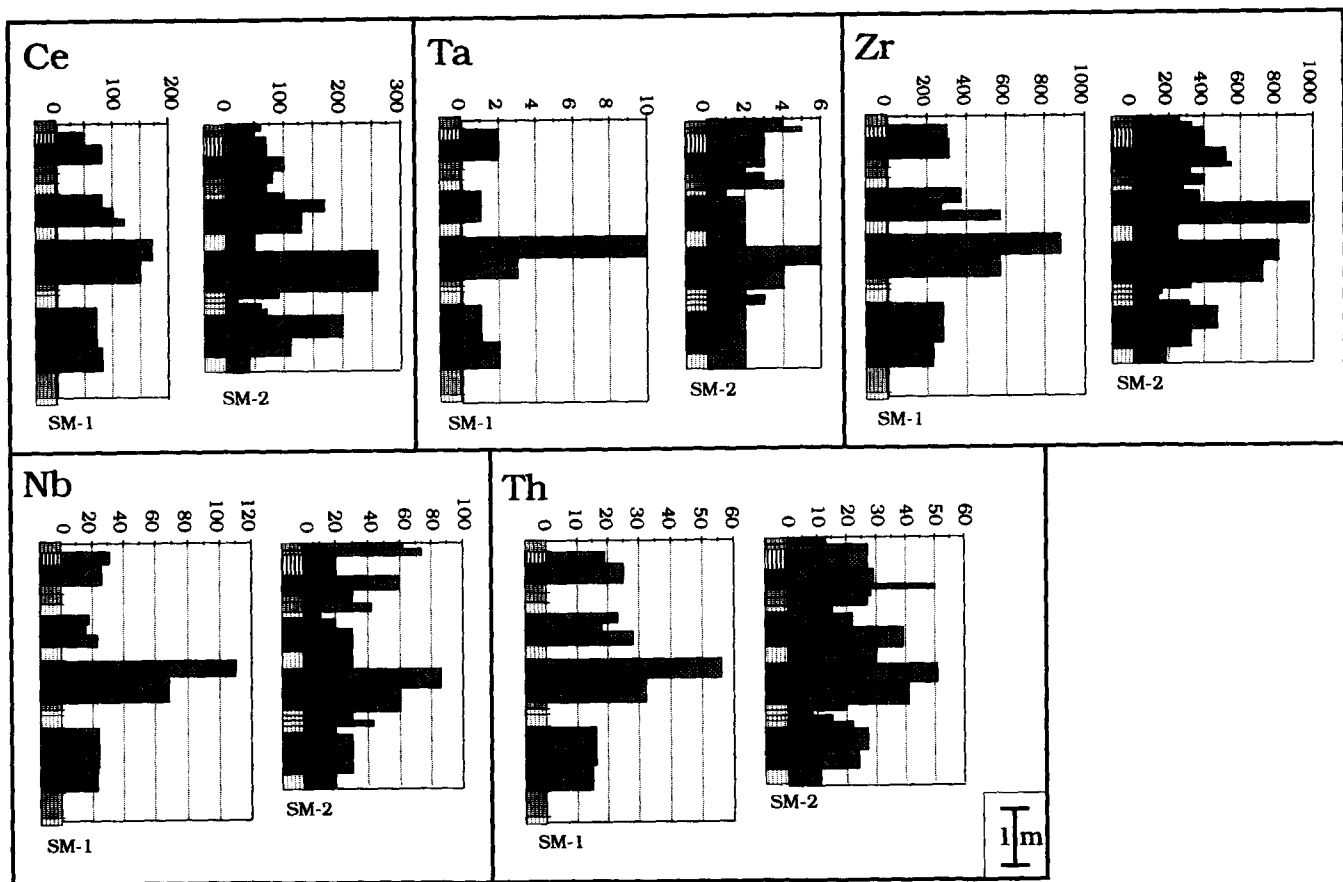


Fig. 7. Bar graphs showing the distribution of trace element concentrations (dry USGS ash basis) for those elements inferred to be derived from volcanic ash. Locations of samples are shown in Fig. 1 and lithologic symbols are the same as used in Fig. 2. All values are parts per million (ppm).

megascopic descriptions of the coal in the field (Appendix).

Cluster analysis

Data that included elemental concentrations on a whole-coal basis, major oxide percentages, major petrographic groups, and ash yield percentages were

grouped by cluster analysis (Fig. 9). Three major clusters were formed by the analysis. In Group I, Se clusters with organic sulfur, huminite, and rare earth elements. In Group II, Hg, Cr, Co, and Cd cluster with pyritic sulfur and inertinites. In Group III, Mn, As, Ni, Pb, Be, Sb, U, and Th cluster with ash yield and most of the oxides (TiO_2 , MgO , Na_2O , P_2O_5 ,

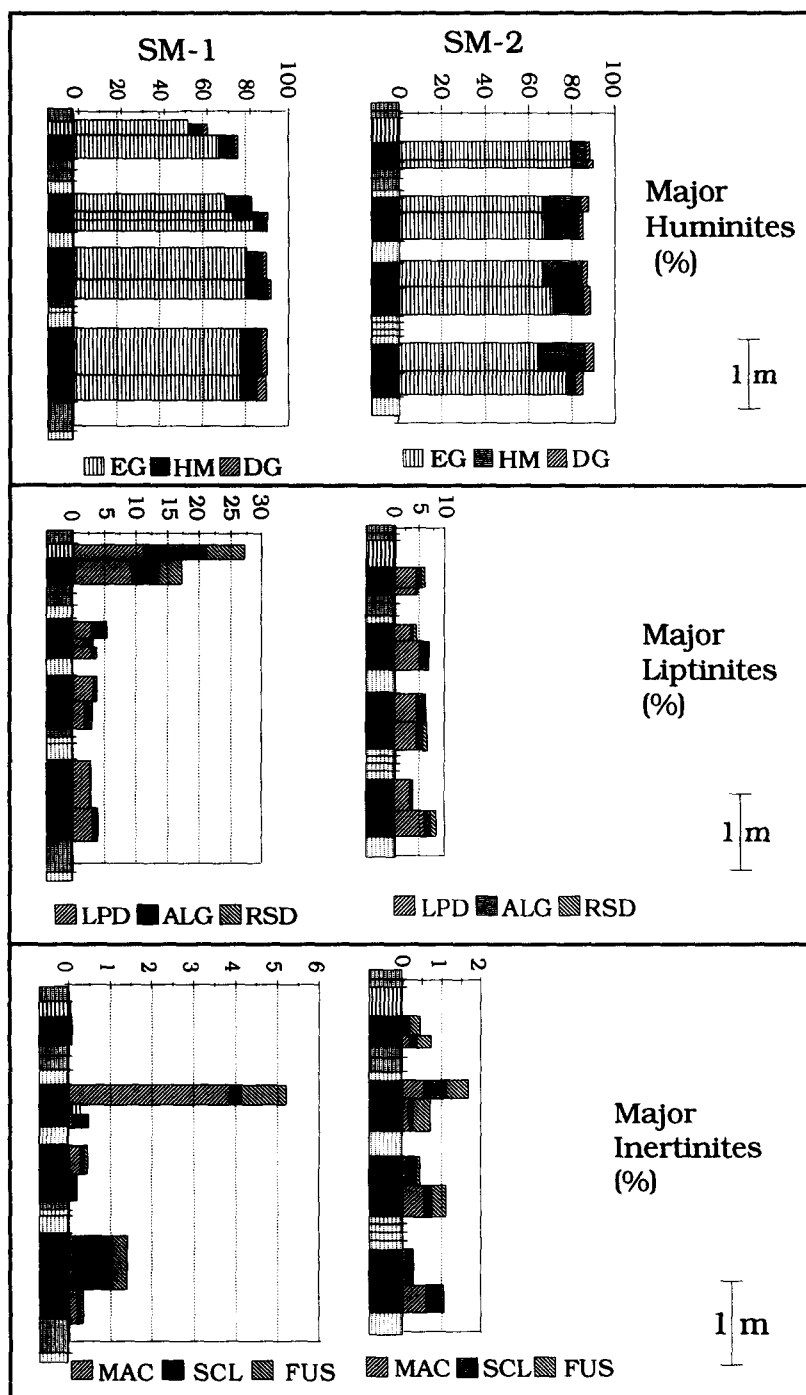


Fig. 8. Bar graphs of the major petrographic constituents for the channel sample sets SM-1 and SM-2. Locations of samples are shown in Fig. 1 and lithologic symbols refer to Fig. 2. Abbreviations are the same as used in Table 1.

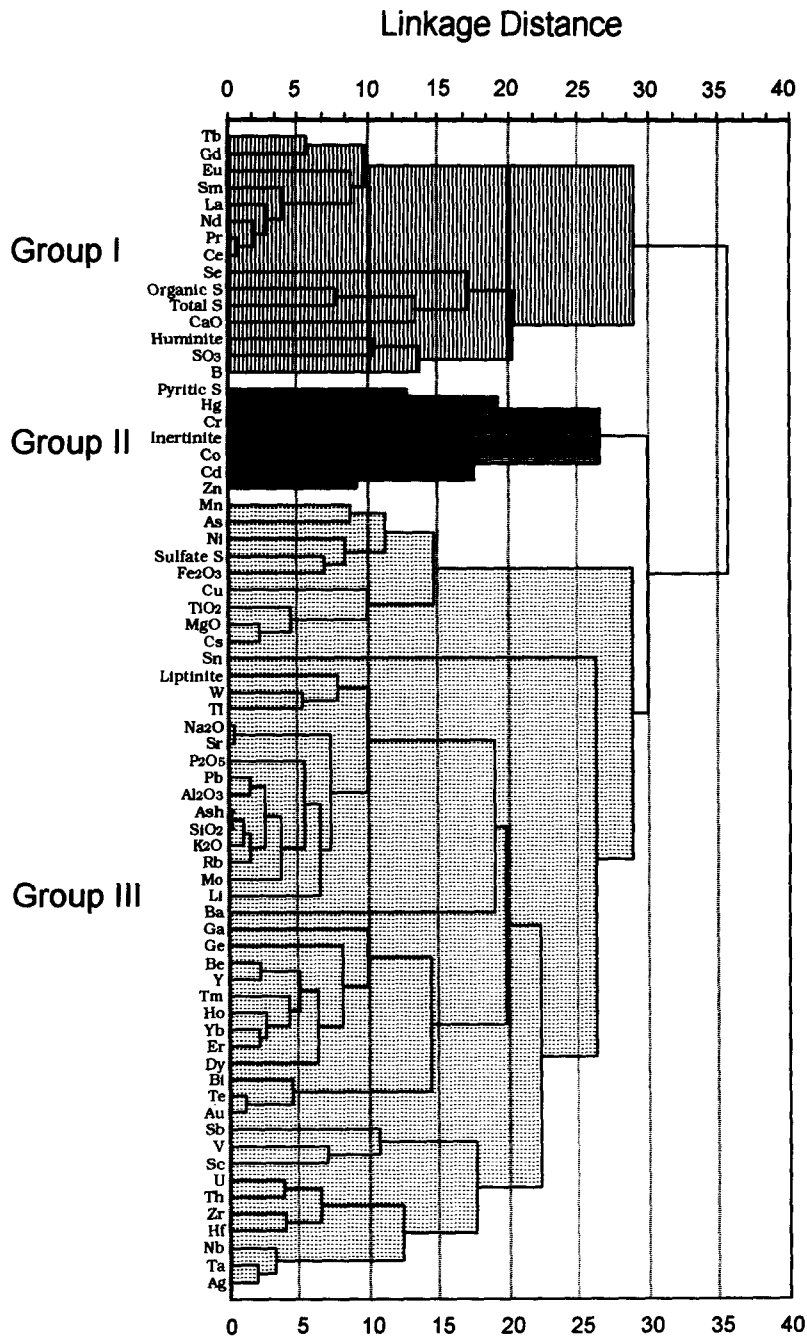


Fig. 9. Correlation diagram for 69 variables using unweighted pair-group average squared Euclidean distances. All values are standardized and trace element concentrations are on a whole-coal basis. Proximate data and oxide data are on a dry basis.

Al_2O_3 , SiO_2 , and K_2O). Also, within Group III, Sb, U, and Th cluster with several elements having a possible volcanic origin (Zr, Hf, Nb, and Ta).

DISCUSSION

Several observations can be made about trends in the data and correlations between ash yield, bed

chemistry, and petrography in the San Miguel deposit. The San Miguel lignite deposit contains a large amount of ash (mean ash yield is 31%, dry basis) that tends to be concentrated in the upper and lower beds. The variation of sulfur content does not appear to be correlated with the variation of ash yield (Fig. 4). Visual inspection of the HAP trace-element distribution (ash basis, Fig. 5) indicates that most of

these elements (with the exception of Pb and Se) are enriched in the lignite beds rather than the rock partings and have an organic affinity. An important observation to note here is that trace element concentration varies both vertically and horizontally within the different lignite beds of the San Miguel deposit and that the concentration of the trace elements in the lignite that is actually delivered to the power plant is an average of these variations.

Concentrations of some elements (Ce, Nb, Ta, Th, Zr) in coal might be enriched in the lignite by incorporation of volcanic ash in peat or by leaching of volcanic ash layers (Crowley *et al.*, 1989; Zielinski, 1985). Some of these elements appear to be enriched in the middle lignite benches (Fig. 7). Although Nb and Th are generally considered to be relatively immobile during low-temperature alteration (Wedepohl, 1978), these elements may have been leached from the parting material and concentrated in the underlying and overlying lignite benches possibly as a result of organic complexing as described by Langmuir and Herman (1980). Mixing of the volcanic ash and peat by burrowing organisms might also account for the enrichment of these elements in the lignite beds.

Our preliminary observations support the conclusions of Kaiser (1982), Gowan (1985), and Ayers (1986, 1989) who propose that the parting material within the San Miguel lignite deposit contains altered, reworked, volcanic ash. The gradational contacts below some of the parting layers (unit 5, SM-1; and unit 4, SM-2; Appendix) are not indicative of direct-fall ash beds in coal (see Bohor and Triplehorn, 1993). The channel-form features found in the partings of the San Miguel deposit (described by Ayers, 1986) were observed during our mine visits and indicate that the partings have been reworked by flowing water. The rounded quartz grains found in the partings by SEM and EDXA may be indicative of water-borne transport and a detrital origin. The lateral discontinuity and merging of the lignite benches and their partings observed from drill hole data, as reported by Tewalt *et al.* (1983), Gowan (1985), and Ayers (1986, 1989), further support the

idea that the San Miguel partings are not undisturbed ash-fall layers. A cross-section of the San Miguel lignite deposit (Fig. 47, Tewalt *et al.*, 1983) shows that the parting between the C and D beds (identified as a volcanic ash by Senkayi *et al.*, 1987) has a very irregular thickness and thickens laterally into clastic sediments. Because of the difficulty in distinguishing between undisturbed volcanic ash falls and reworked, detritally mixed volcanic material in Gulf Coast lignites (Ruppert *et al.*, 1994, 1995), careful attention must be given to the mineralogy of the layers and the mineral associations. The layers identified by Senkayi *et al.* (1987) (Fig. 2) as volcanic ash beds may have been deposited in a part of the mire that was not subsequently affected by surface-water movement; however, our samples suggest that the San Miguel partings have both volcanic and detrital components.

Average whole-coal concentrations of the elements As (13.5 ppm), Be (3.4 ppm), Sb (1.3 ppm), and U (3.4 ppm) are greater than published average concentrations for these elements in other U.S. lignites (see Tewalt, 1986; Tewalt *et al.*, 1992; Gluskoter *et al.*, 1977). In this study, the average concentration for U (3.3 ppm) is similar to that reported by Tewalt (1986).

The average calorific value of the lignite samples collected in this study (8612 Btu/lb or 20 MJ/kg) can be used to estimate the pounds per million Btu (lb/MBtu or kg/MJ) of any of the HAP elements that might be delivered to the power plant (Table 3). The result of such calculations must be used with caution because they reflect the original concentrations of these elements in coal without the consideration of coal beneficiation (not currently utilized at the San Miguel mine) and combustion characteristics. As pointed out by Akers and Dospoy (1994) and Meij (1994), coal cleaning prior to burning, and postcombustion cleaning devices such as electrostatic precipitators and wet scrubbers, can greatly reduce the amount of atmospheric discharge of most trace elements released from the burning of coal fuel in electric power plants. Of major concern would be the proper disposal of the ash produced from coal combustion. The fly ash is of particular interest because the HAPs are relatively volatile and would tend to concentrate more in the fly ash rather than the bottom ash.

Some inferences can be drawn from the petrographic data. The dominance of the euglenite maceral subgroup over the huminite subgroup indicates that all San Miguel lignites were subjected to peat-forming conditions (either biogenic or chemical) that enabled degradation of wood cellular material into matrix gels. An alternative possibility is that the plants that formed these lignite benches were less woody and more prone to formation of matrix gels. The latter possibility is preferred and is supported by the work of Gennett (1985), Gennett and Raymond (1986), and Mukhopadhyay (1989), who suggested that the pollen in the San Miguel mires

Table 3. Estimated amount of San Miguel HAP trace elements that might be delivered to a coal-fired power plant. Estimates based on average whole-coal ppm concentrations and an average dry Btu/lb of 8611 (20 MJ/kg)

HAPs element	Average ppm	lb/M Btu	kg/MJ
As	13.5	0.00157	0.675
Be	3.4	0.00039	0.170
Cd	0.3	0.00003	0.015
Cr	10.3	0.00120	0.515
Co	2.2	0.00026	0.110
Hg	0.1	0.00001	0.005
Mn	111.8	0.01298	5.590
Ni	3.4	0.00039	0.170
Pb	7.2	0.00084	0.360
Sb	1.3	0.00015	0.065
Se	1.2	0.00014	0.060
U	3.4	0.00039	0.170

was derived in part from marsh ferns, palms, and herbaceous monocots.

The upper and lower lignite benches of the San Miguel deposit are both ash- and algal-rich, indicating that these intervals were probably deposited in wetter conditions than the conditions in which the middle intervals formed. Megascopic descriptions of the lignite beds (Appendix) indicated that the upper and lower beds contain less preserved xylinitic material than found in the middle benches, further indicating that a more robust vegetation comprised the paleo-mires of the B and C beds.

Another interesting trend found in the petrographic data is that the upper sample interval of the B bed is rich in inertinite. The occurrence of inertinites (particularly semifusinite) adjacent to volcanic ash partings in coal has been observed in other coal beds (Crowley *et al.*, 1989, 1994). In the C coal bed of central Utah, semifusinite and fusinite precursors were inferred to have formed as a result of chemicals (such as sulfuric acid) that charred the original vegetation, or as a result of pH changes which created an environment favorable to the formation of degradosemifusinite precursors (Crowley *et al.*, 1994). Although semifusinite is not the predominant inertinite maceral found in the San Miguel lignites, it is possible that fusinite and macrinite may have formed in a manner similar to inertinite macerals in the C coal bed. On the other hand, the inertinite may have been formed by wide-spread oxidation of the B bed paleo-mire by emplacement of hot volcanic ash which formed the parting between the A and B beds (Fig. 2). As discussed above, the mineral associations found in the parting suggest that the ash that formed the parting was subsequently reworked and mixed with detrital sediments.

From the cluster analysis, we can interpret possible modes of occurrence for several of the environmentally sensitive trace elements. However, further microscopic examination is necessary to definitely determine the mode of occurrence of any of these trace elements. Because Se clusters with organic sulfur and huminite (Group I), we infer that it may occur in organic complexes or as very fine-grained minerals. Finkelman (1994) reports that the bulk of Se in most coals is associated with organic constituents. If the Se in the San Miguel lignite is organically bound, then physical coal cleaning would not be effective in reducing the Se concentration. In contrast, Hg, Cr, Co and Cd cluster with pyritic sulfur (Group II). The occurrence of Hg in solid solution in pyrite has been documented in previous studies (Finkelman, 1994). Because pyritic sulfur has been shown to be removed fairly readily during conventional coal cleaning processes (Berkowitz, 1979; Ward, 1984), perhaps Hg would be easily removed from feedstock to power plants. Finkelman (1994) reports that 25–50% of Hg is removed from coal by conventional coal-cleaning procedures.

Although Swaine (1990) reports on the occurrence of Cd in pyrite, Cd commonly occurs in sphalerite in many coals and exhibits a wide range of behavior in coal-cleaning studies (Finkelman, 1994). Cobalt has been reported to be associated with pyrite and coal cleaning-studies indicate that 50–75% can be removed from coal (Finkelman, 1994). The rest of the environmentally sensitive trace elements (Mn, As, Ni, Pb, Be, Sb, U, and Th) identified in the 1990 Clean Air Act Amendments occur in a large cluster (Group III) that includes ash yield and most of the oxides (Fe_2O_3 , TiO_2 , MgO , Na_2O , P_2O_5 , Al_2O_3 , SiO_2 , and K_2O). In addition, U and Th cluster with several elements (Zr, Hf, Nb, and Ta) that are probably associated with reworked volcanic materials. The environmentally sensitive elements in Group III are probably associated with detrital input to the peat that formed the San Miguel lignite. If these elements occur close to rock partings in the coal bed, they perhaps can be eliminated during selective mining processes. These elements may also possibly be removed during coal beneficiation.

CONCLUSIONS

The following conclusions can be made about the geochemistry, petrography, and geology of the San Miguel lignite deposit:

1. In coal ash, the distribution of the HAP trace element Mn is inversely related to the ash yield of the lignite and rock samples. This indicates an organic affinity for Mn, or an association to finely disseminated minerals in the lignite that contain these elements. Finkelman (1994) also suggested Mn has an organic affinity particularly in low-rank coals.

2. For the lignite samples (on a whole coal basis), the distributions of Na_2O and the HAP trace element Pb are positively related to ash. These preliminary results might help predict Pb concentrations in the San Miguel or similar lignite deposits. The association of Na_2O with ash may be explained by the presence of analcite and Na-K feldspars in the rock partings.

3. Average whole-coal concentrations of As, Be, Sb, and U are greater than published averages for these elements in other lignites in the United States. These elements might be largely removed from the fly ash emitted from coal-fired power plants if coal beneficiation or postcombustion cleaning methods were used. However, further research on characterization of fly ash is necessary to make this determination.

4. Our observations support the conclusions of Kaiser (1982), Gowan (1985), and Ayers (1986, 1989), who propose that the parting material within the San Miguel lignite deposit contains altered, probably reworked, volcanic ash. The lateral discontinuity of the lignite benches and their partings, as reported by Tewalt *et al.* (1983), Gowan (1985) and Ayers (1986, 1989), further support the idea that the San Miguel partings are not relict ash-fall layers.

The volcanic layers identified by Senkayi *et al.* (1987) were not recognized in the field or laboratory. It must be emphasized that a more detailed examination of these layers should be undertaken to reconfirm that they are undisturbed volcanic ash layers. Perhaps in the San Miguel paleo-mire, local streams or tidal channels (as mapped by Gowan, 1985) reworked and chemically altered parts of these volcanic ash layers and left other areas intact, preserving their exclusive volcanic mineralogy as reported by Senkayi *et al.* (1987).

5. Concentrations of some elements (Ce, Nb, Ta, Th, and Zr) in coal beds are inferred to be enriched in the lignite by incorporation of volcanic ash in peat or by leaching of volcanic ash layers (Zielinski, 1985; Crowley *et al.*, 1989). A plot of the concentration of these elements (on an ash basis, Fig. 7) indicated that they are enriched in the middle lignite benches of the San Miguel deposit.

6. The upper and lower lignite benches of the San Miguel deposit are both ash- and algal-rich, indicating that these intervals were probably deposited in wetter conditions than the conditions in which the middle intervals formed. Megascopic descriptions of the lignite beds show that these beds are less woody and more massive.

7. The dominance of the euglenite maceral subgroup over the huminite subgroup indicates that all lignites were subjected to peat-forming conditions (either biogenic or chemical) that enabled degradation of wood cellular material into matrix gels, or that the plants that formed these lignite benches were less woody and more prone to formation of matrix gels. The latter scenario is suggested because palynological studies (Gennett, 1985; Gennett and Raymond, 1986; Mukhopadhyay, 1989) suggest that parts of the San Miguel paleo-mires were inhabited by marsh and herbaceous plants.

8. There is a distinct increase in inertinite in the lignite directly below the parting between the A and B lignite beds. The inertinite may possibly have originated from widespread oxidation of the San Miguel peat as a result of volcanic ash falls, which were subsequently reworked. Chemical charring of the original vegetation or pH changes created an environment favorable to the formation of degradosemifusinite precursors in a manner similar to inertinite maceral formation in the C coal bed of Utah (Crowley *et al.*, 1994).

9. Cluster analysis of the data (Fig. 9) suggests possible modes of occurrence for several of the environmentally sensitive trace elements. Se appears to have an affinity to organic sulfur and huminite and may be difficult to remove during coal cleaning processes. In contrast, Hg, Cr, Co and Cd cluster with pyritic sulfur and may be easily removed by coal preparation from feedstock to power plants. The rest of the environmentally sensitive trace elements (Mn, As, Ni, Pb, Be, Sb, U, and Th) identified in the 1990 Clean Air Act Amendments occur in a large cluster

that includes ash yield and most of the oxides. In addition, U and Th cluster with several elements (Zr, Hf, Nb, and Ta) that are probably associated with reworked volcanic materials.

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APPENDIX

SAN MIGUEL MEASURED SECTIONS ATASCOSA COUNTY, TEXAS

SM-1

Detailed measured section and sample interval description for the SM-1 channel sample. The section is located in an active pit of the Atascosa Mining Company San Miguel Mine, Atascosa County, south Texas. The pit location is about 2.5 km south-east of the office/plant complex. Location for the section is latitude 28°40'50"N and longitude 98°33'50"W. There is a regional dip of about 2° SE. Samples numbers refer to Fig. 2 and Table 1. The mine location is shown in Fig. 1. The section was measured and samples collected on May 18, 1992.

Interval thickness
(m)

19. Mudstone (roof), light grey, silty, generally massive, but laminated at places, noncalcareous, some burrowing, scattered organic debris..... 3.00 + 18.

Lignite (A bed upper), brown, fine detritus, one 1–2 cm thick elongate lens of xylinitic material about 15 cm from the top, top part burrowed, burrows 1–2 cm in diameter, up to 10 cm long, sample SM-1-A.1..... 0.20

17. *Lignite* (A bed lower), brown, massive, dull, no bright bands, attrital, sample SM-1-A.2..... 0.33

16. *Mudstone* (P1 parting upper), medium grey, silty, gradational lower contact, sharp upper contact, burrowing at the bottom, sample SM-1-P1.1..... 0.12

15. *Mudstone* (P1 parting middle), dark grey, clay rich, silty, lignitic, pyrite oxidized along bedding, burrowing at places, sample SM-1-P1.2..... 0.14

14. *Claystone* (P1 parting lower), medium grey, gradational contact at top and base, with very thin white disks about 1 cm diameter that look like small shells, however probably secondary mineralization, sample SM-1-P1.3..... 0.16

13. *Lignite* (B bed upper), brown, dull, attrital, with burrows 2–3 cm diameter and up to 10 cm long, burrows filled with kaolinitic? clay, contact between B.1 and B.2 has layered pyrite along bedding, small white disks described in above parting are present, sample SM-1-B.1..... 0.23

12. *Lignite* (B bed middle), brown, dull, same as above except without burrows, sample SM-1-B.2..... 0.13

11. *Lignite* (B bed lower), brown, dull in general, with laminae of vitrain 1 cm thick, xylem gellified, slickensided at base, sample SM-1-B.3..... 0.15

10. *Claystone* (P2 parting), medium grey to brown, clay at base, some silt at top, massive, slickensided at top, thin lignitic layers at places, sample SM-1-P2.1..... 0.23

9. *Lignite* (C bed upper), brown, xylinite rich, about 30% xylinite layers, layers up to 2 cm thick, layered pyrite in xylinite beds, a few burrows in top 3–4 cm, sample SM-1-C.1..... 0.31

8. *Lignite* (C bed lower), brown, xylinite poor, about 10% xylinite layers, clay-rich attritus in 2 bands about 5 cm thick, with layered pyrite, lower part more ash rich, with a wispy discontinuous ash parting about 0.5 cm thick at the contact of SM-1-C.1 and SM-1-C.2, sample SM-1-C.2..... 0.37

7. *Mudstone* (P3 parting upper), medium brown, massive, few thin (0.5 cm thick) layers of xylinitic attritus at top, pyrite along contact with P3.2 and in lignitic layers, sample SM-1-P3.1..... 0.10

6. *Claystone* (P3 parting middle), bleached light brown, scattered xylinitic material, rooted?, sample SM-1-P3.2..... 0.08

5. *Claystone* (P3 parting lower), medium brown, sideritic, massive, roots? at top, base gradational—detrital?, sample SM-1-P3.2..... 0.21

4. *Lignite* (D bed upper), brown, contains about 20% xylinitic layers that are about 2 cm thick, in a clay-rich attritus, layering not well developed, attritus layers about 8–10 cm thick, burrowing in top 3–4 cm, little or no pyrite, sample SM-1-D.1..... 0.60

3. *Lignite* (D bed lower), dark brown, attritus rich, clay rich, with some thin pyrite lenses at bottom 10 cm, sample SM-1-D.2..... 0.40

2. *Mudstone* (floor), medium brown, silty, massive..... 0.30

1. *Claystone*, greenish grey, massive, pyritic, noncalcareous, base not exposed..... 1.00

SM-2

Detailed measured section and sample interval description for the SM-2 channel sample. The lignite-bed section is located in Mining Area E of the Atascosa Mining Company San Miguel Mine, Atascosa County, south Texas. The pit location is about 2.5 km south east of the office/plant complex. Location for the section is latitude 28°40'2"N and longitude 98°29'15"W. Samples numbers refer to Fig. 2 and Table 1. The mine is location is shown in Fig. 1. The section was measured and samples collected on April 16, 1993.

Interval thickness
(m)

20. *Mudstone* (Roof-lower) grayish orange pink (5 YR 7/2) massive, structureless, upper 5 cm lighter colored, kaolinitic(?), all in reworked by burrows, sample SM-2-RF1T..... 0.15

19. *Mudstone* (Roof-middle) grayish orange pink (5 YR 7/2) massive, structureless, with horizontal and vertical burrows, some burrows have carbonaceous rims, burrows continue up into highwall, darkens toward base as organic content increases, rooted, carbonaceous blebs throughout, non-calcareous, sample SM-2-RF1B..... 0.15

18. *Carbonaceous shale* (Roof-lower), transitional into lignite, dusky yellowish brown (10 YR 2/2), contains xylinitic lenses (0.5 cm thick and up to 15 cm long inclined 45° to bedding), non-calcareous, contains an up to 3 cm thick, discontinuous parting near base (10 YR6-2), highly burrowed with horizontal and semi-vertical burrows, parting may be reworked by burrowing organisms because it appears to be discontinuous, sample SM-2-RF2..... 0.18

17. *Lignite* (A bed upper), dull attrital, approximately 9% (xylinitic bands up to 2 cm thick, scattered 1 cm diameter burrows in upper 15 cm with 4 out of 5 intervals contain burrows filled with soft clay material, lower 8 cm contains wispy laminae of inorganic material with occasional sand grains, sample SM-2-A1..... 0.22

16. *Lignite* (A bed lower), dull attrital, differs from other units in breakage characteristics, hard, few burrows, undulating contact at base, irregular and gradational base with underlying parting, sample SM-2-A2..... 0.8

15. *Siltstone* (Parting P1 upper), grayish brown (5 YR3/2), upper part rooted, contains xylinitic material (8%): contains lenses of light clay material up to 18 cm long, at 25 cm (5 cm at base) contained abundant white blebs with individual white grains, looks like small shells, sample SM-2 P1.1..... 0.13

14. *Siltstone* (Parting P1 middle), dark gray (5 YR3/2) to pale yellowish brown (10 YR6/2), rooted, rare burrows, xylinitic organic stringers (up to 2 cm thick, comprises about 20% of interval), counted three 1-cm-thick stringers in the 15 cm interval, sample SM-2 P1.2..... 0.15

13. *Claystone* (Parting P1 lower), silty grayish-brown (5 YR3/2), burrowed at top, xylinitic fragments up to 2 cm thick, unit is discontinuous, ends within a few meters of section, unit is approximately 3–4 m wide, lens shaped (may be channel), sample SM-2 P1.3..... 0.08

12. *Lignite* (B bed upper), with > 50% xylinitic (lenses up to 6 cm thick and 35 cm wide, occasional wispy lenses of white grains, burrowed but not as abundant as in parting above, sample SM-2-B1..... 0.17

11. *Lignite* (B bed lower), dull, attrital, blocky fracture, dulls toward base, less xylinitic but more abundantly burrowed than SM-2-B1 above, contains scattered white clay (?) lenses up to 1 cm thick, at base small dikes from lower parting, sample SM-2-B2..... 0.32

10. *Claystone* (Parting P2), pale yellowish brown (10 YR 6/2), massive, organic stringers, top contact gradational with SM-2-B2 and lower contact wavy, sample SM-2 P2..... 0.29

9. *Lignite* (C bed upper), xylinitic fragments up to 2 cm thick, (4 cm out of 15, or 27% xylinitic material), burrowed, contains approximately 1 cm thick, continuous, wispy white parting near base (can follow across mine wall), sample SM-2-C1..... 0.31

8. *Lignite* (C bed lower), dull, attrital, less xylinitic than overlying facies, xylinitic lenses up to 0.5 cm thick, scattered burrows filled with white material, wispy layers (white clay?), gradational base, sample SM-2-C2..... 0.35

7. *Claystone* (Parting P3 upper), pale yellowish brown (10 YR 6/2) claystone, rooted, hard, sample SM-2 P3.1..... 0.09

6. *Claystone* (Parting P3 middle upper), white (N9), massive, laterally continuous, roots extending from upper clay present, sample SM-2 P3.2..... 0.09

5. *Claystone* (Parting P3 middle lower), light brown gray (5 YR 6/1), massive, sample SM-2 P3.3..... 0.09

4. *Claystone* (Parting P3 lower), light brown gray (5 YR 6/1), lower part contains abundant carbonaceous stringers, coal stringers increase towards base, gradational contact with underlying lignite, sample SM-2 P3.4..... 0.11

3. *Lignite* (D bed upper), xylinitic layers up to 2 cm thick and 15 cm long (11% xylinitic), burrowed in upper part, gradational contact with parting above, scattered white wispy layers, sample SM-2-D1..... 0.36

2. *Lignite* (D bed lower), dull, more clay-rich than SM-2-D1 above, contains wispy clay zones and two xylinitic lenses up to 6 cm thick and 19 cm wide, (40% xylinitic), sample SM-2-D2..... 0.33

1. *Claystone* (Floor), dusky brown (5 YR 2/2), rooted, contains thin xylinitic stringers, sample SM2 GRAB..... not measured