Geochemistry of Minor and Trace Elements of 22 Core Samples from the Monterey Formation and Related Rocks in the Santa Maria Basin, California

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Chapter B

Geochemistry of Minor and Trace Elements of 22 Core Samples from the Monterey Formation and Related Rocks in the Santa Maria Basin, California

By JOEL S. LEVENTHAL

U.S. GEOLOGICAL SURVEY BULLETIN 1581

STUDIES OF URANIUM CONTENT AND GEOCHEMISTRY OF THE MONTEREY FORMATION, CALIFORNIA

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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Geochemistry of Minor and Trace Elements of 22 Core Samples from the Monterey Formation and Related Rocks in the Santa Maria Basin, California

By Joel S. Leventhal

Abstract

Twenty-two samples from the organic carbon rich Monterey Formation and related rocks have been analyzed for major, minor, and trace elements. Relative to averages reported for other organic-rich black shales, these samples are depleted in Al, K, Cu, La, Y, and Pb by about a factor of 2. They are enriched by a factor of 2 in Mg, Na, organic C, Mn, Mo, Ni, and V and by a factor of 3 in Ca and carbonate-C (CO_3–C).

Statistical analysis, using correlation coefficients, was employed to determine affinity of trace elements. Certain trace elements (Sc, Co, Ga, Th, and Pb and rare earths—La, Ce, and Nd) are most associated with the major constituents (Al, Na, K, Fe, and Ti) presumably in clay minerals. Mn and Sr are associated with the Ca and Mg carbonate phase.

Organic carbon and sulfur are correlated in the Monterey Formation sediments as expected for marine organic carbon-rich sediments because of sulfate reduction by bacteria which utilize organic matter to form sulfide compounds. Trace metals—Ni, Cr, Cu, Zn, U, V, Mo, and Cd—are statistically associated with both the organic carbon and sulfur. However, some metals—Cd, V, Mo, and U—show greater statistical association with organic carbon than with sulfur.

INTRODUCTION

Organic carbon rich mudstones often contain larger-than-average contents of metals. The metal content for 20 selected organic carbon-rich rock units has been summarized by Vine and Tourtelot (1970). However, their study did not include the Miocene Monterey Shale, which is more prominent as an oil-source rock than a metal-rich shale, and perhaps because it is not strictly a shale—containing smaller amounts of clay and greater amounts of biogenic silica (Bramlette, 1946; Isaacs, 1980). The Vine and Tourtelot (1970) results also do not include data on sulfur or phosphorus contents of the shales, due to the lack of an available analytical technique when their data was collected. Leventhal and Hosterman (1982) have reported detailed results for Devonian age shales from the Appalachian basin and showed that both organic carbon and sulfur are closely correlated with metals, indicating that sulfur is an important element in black shales.

The purpose of this report is to present new chemical data obtained by modern instrumental techniques and to discuss the metal contents and their geochemical controls and affinities of the organic carbon rich mudstones of the Monterey Formation. Previous work on the Monterey Formation includes the classic study by Bramlette (1946) which reported chemical analyses for major elements. Major element chemistry data were given and discussed by Piper and Fowler (1979). Major and trace element (semiquantititive) chemistry was given by Isaacs (1980); however, only the major elements are discussed. A recent volume (edited by Garrison and Douglas, 1981) includes papers on the depositional environment of the Monterey Formation.

In the present study, a suite of 22 samples from 3 wells from the Santa Maria basin (fig. 1) was analyzed for major (except Si), minor (including S and P), and trace elements to determine the composition of the organic-rich facies of the Monterey Formation. The geology and stratigraphy of the Monterey Formation in general and also for these cores has been summarized by Durham (1987). In his report on the Monterey Formation,

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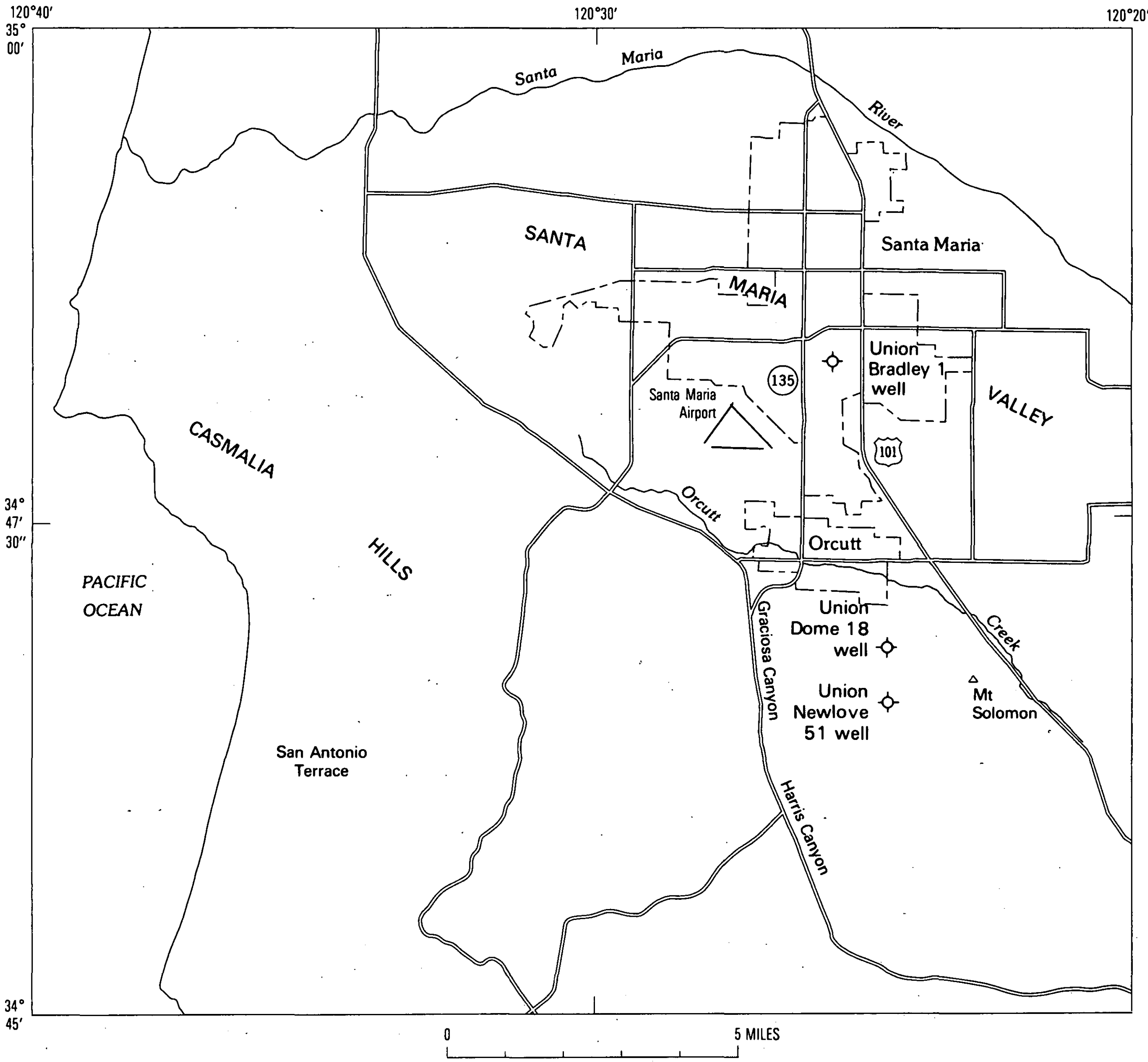

Figure 1. Index map showing locations of 3 wells in the Santa Maria basin, Calif.

Durham was mainly concerned about anomalous U contents and the source, mobility, and concentration of U. To further consider these questions, a geochemical study of the Monterey Formation organic carbon rich rocks (similar to that by Leventhal, Crock, and Malcolm, 1981) was undertaken and is reported here.

These 22 samples represent portions of three cores from the Santa Maria basin and are not necessarily representative of the whole Monterey Formation, which is quite heterogeneous. The trace elements in these samples are primary (syngenetic) as opposed to the higher uranium values that may be due to secondary (epigenetic) enrichment as reported by Durham (1987).

SAMPLES

The samples (listed in table 1) are from the Union Newlove 51 well (1395–3509 ft depth[1], sec 25, T. 9 N., R. 34 W., samples 1–17), Union Dome 18 well (sec. 24, T. 9 N., R. 34 W., 9868–11,014 ft depth, samples 18–20) and the Union Bradley 1 well (sec. 26, T. 10 N., R. 34 W., 4156 and 4849 ft depth, samples 21 and 22).

[1]Original depths from the drillers' log are given for identification purposes; 1 ft = 0.305 meters.

The samples were all fine grained rocks, which are green, brown, gray, or dark gray in color and include siliceous mudstones, bedded cherts, and cherty shales. Some of the samples have laminations, which indicates a lack of infaunal burrowing and a very low oxygen or anoxic conditions during deposition. Six of the 22 samples are from formations related to the Monterey Formation. In table 1, samples 1 and 2 are from the Sisquoc Formation, and samples 15, 16, and 17 are from the Point Sal Formation. Sample 18 is from the Sisquoc Formation. Some samples showed fractures with yellow staining, indicating subsequent (recent) oxidation and (or) chemical alteration during storage.

ANALYTICAL METHODS

Samples were described, and a representative portion was ground. Major, minor, and trace elements were determined by induction-coupled plasma spectroscopy (Taggart, Lichte, and Wahlberg, 1981) after acid digestion. Certain elements were at or below detection limits (in ppm, in parentheses) and are not listed in the results [Ag (2), As (10), Au (4), Be (1), Bi (10), Sn (4), Ta (40), U (40), Pr (10), Sm (10), Eu (2), Gd (10), Tb (20), Dy (4), Ho (4), Er (4), Yb (4)]. The following elements were not looked for: Si, B, W, Zr, Tm, and Lu. An important element, phosphorus, not reported by Vine and Tourtelot (1970), is reported for these rocks. The precision and accuracy are generally ±10–15 percent.

Uranium was analyzed by the delayed neutron method (Millard, 1976). The precision and accuracy are generally ±5 percent. Thorium results from delayed neutron analysis were not useful due to uranium interference.

Total carbon was analyzed by LECO combustion, organic-carbon by combustion after acid leach, and sulfur by LECO combustion (Leventhal and Shaw, 1980). The precision and accuracy are generally ±5 percent. Several samples were analyzed for elemental sulfur—they showed less than 0.2 percent. Several samples were analyzed for non-pyrite, non-barite sulfur by acid leach (which removes soluble sulfates and sulfides); these values were also less than 0.2 percent.

RESULTS

The analytical results are shown in table 1. In several cases (indicated by an asterisk, *) the qualified (less than) values were changed to "real" values equal to one half the qualified value for purposes of statistical analysis and are listed as "real" values in table 1. Table 2 shows arithimetic mean values and ranges for elemental constituents.

STATISTICAL TREATMENT

Correlation coefficients were run by the U.S. Geological Survey STATPAC statistical routine (VanTrump and Miesch, 1977) on the Data General Corporation ECLIPSE C/330 computer. The matrix array of correlation coefficient results is shown in table 3. For 22 sample pairs a coefficient of correlation (*r*) value of 0.54 or greater is significant at the 99 percent confidence level. Values of 0.49 and 0.42 are significant at the 98 and 95 percent confidence levels, respectively. However, visual inspection of scatter plots is necessary to ascertain the meaning of these results because a few high and low values (non-normal distribution) can result in a high correlation coefficient that is not valid.

DISCUSSION

Major elements in sedimentary rocks, such as shale, occur as oxide minerals—mainly as silica (SiO_2) and clays (such as illite), and as carbonates. Sulfur occurs mainly in pyrite; organic carbon occurs in amorphous organic matter that coats grain surfaces as well as filling interstices; and phosphorus occurs in phosphate. The trace elements are usually associated with one of these major or minor phases.

Elements Associated With The Clay Mineral Fraction

From the correlation coefficient (*r*) results (table 3) the major elements Al, K, Fe, and Ti are all interrelated. For example, Fe versus Ti (fig. 2) is typical, showing a high (> 0.88) *r* value. Na is less highly correlated to these four elements ($r < 0.78$). (These 5 elements are mainly contained in clay minerals.) Associated with these major elements are the trace elements Sc, Co, Ga, Th, Pb, La, Ce, Nd, and Nb. For example, Sc shows *r* of 0.84 or greater with the 5 major elements (table 3; fig. 3). In addition, Co and Ga show *r* values in the range of 0.72 to 0.90 (for example, fig. 4, Co versus K) with the major elements. Th and Pb show low *r* values, only in the range 0.52 to 0.66 for Ti, Al, and K. The rare earth elements, La and Ce, show *r* values in the range 0.61 to 0.78 with Al, K, and Ti. Nd shows lower *r* values of 0.55 and 0.57 with Ti and K. The rare earth elements, La and Ce, are more closely correlated with each other ($r = 0.87$) than with the major elements as is to be expected. This is because La, Ce, and Nd are in the

Table 1. Elemental abundance in 22 core samples from the

[Values: %, indicates values given in weight percent; all other values are in parts per million; *, asterisk indicates a value which was less than

No.	Depth, ft	Fe%	Mg%	Ca%	Ti%	Mn	Ba	Cd	Co	Cr	Cu	La	Mo	Nb	Ni	Pb
1	1395-1416	2.6	1.1	1.2	0.24	240	600	3	5	71	15	13	1*	6	31	2*
2	1783-1798	3.2	1.1	1.3	.32	290	620	4	7	85	19	19	4	8	40	10
3	1937-1955	1.8	.5	4.9	.18	160	400	8	5	90	27	15	15	6	73	2*
4	1980-2002	1.4	.84	5.9	.18	160	400	9	5	100	34	16	19	5	87	5
5	1980-2002	1.5	.74	3.9	.19	170	150	8	4	100	28	16	18	5	66	5
6	2018-2033	1.1	1.1	17.0	.12	300	730	10	4	82	28	8	20	2*	70	2*
7	2119-2137	1.8	.81	2.3	.22	210	310	15	5	130	45	20	23	9	100	8
8	2154-2165	1.5	.57	2.1	.20	130	430	11	5	110	37	15	14	7	76	4
9	2240-2267	2.3	.96	6.0	.28	250	460	14	8	190	67	23	23	8	130	8
10	2262-2276	2.4	.84	2.2	.28	210	190	12	6	150	57	24	28	9	100	5
11	2435-2443	1.6	2.4	6.9	.18	200	240	18	5	300	130	18	62	5	250	8
12	2625-2641	2.2	2.1	7.9	.22	220	330	10	6	270	83	18	34	6	200	7
13	2660-2677	3.2	.91	4.3	.28	320	150	8	8	210	69	24	24	8	180	7
14	2677-2696	2.5	1.7	3.0	.23	270	270	7	7	170	41	6	18	5	130	7
15	3451-3460	3.2	1.8	2.1	.28	370	390	6	11	140	30	18	3	6	100	8
16	3475-3491	2.8	1.8	2.5	.25	340	410	7	9	130	29	19	8	6	89	7
17	3491-3509	3.4	1.8	1.5	.30	370	380	7	11	140	34	19	6	7	100	7
18	9868-9875	3.2	1.2	1.3	.31	260	340	4	6	91	18	20	1*	7	36	10
19	10,105-10,114	1.2	.5	5.6	.14	150	290	16	3	110	45	15	66	4	89	5
20	10,889-10,900	.97	5.0	12.0	.06	700	370	1*	2	52	10	7	6	2*	21	2*
21	4840-49	2.2	.63	12.0	.19	230	240	7	7	270	120	14	30	5	260	5
22	4156-65	1.9	4.9	9.5	.17	800	290	9	4	71	21	17	24	8	51	9

rare earth element family (in fact all 3 are light rare earths), and it is expected that their chemistry will be very similar based on their identical valence electron configuration. Relative to average values reported for other organic carbon rich shales, the Monterey samples are depleted in Al and K and enriched in Si, Mg, and Na.

Elements in Carbonate Minerals

The elements Mg, Ca, Mn, and Sr are often correlated with carbonate (CO_3–C); for example, Ca versus CO_3–C (fig. 5). The substitution of Mn and Sr in the carbonate lattice has been reported for sedimentary rocks (Leventhal and Hosterman, 1982). However, these results show Sr (fig. 6) associated with Ca (but not statistically significantly with Mg), and Mn associated with Mg (not statistically significantly with Ca). Ba is not significantly correlated with any major constituents but does show a low *r* value (not statistically significant) with Sr and CO_3–C. Relative to average organic carbon rich shales, these Monterey Formation samples are enriched in CO_3–C and Mn.

Organic Carbon and Sulfur

Organic carbon and sulfur are highly correlated ($r=0.87$) (fig. 7) as has been noted for modern marine sediments (Goldhaber and Kaplan, 1974). This relationship is due to the sulfate reduction by bacteria to produce sulfide and the fact that these bacteria use organic matter as a food source. Because these bacteria can only metabolize a portion of the organic matter, the remaining organic carbon is preserved along with the a qualified number that was changed to real values equal to one-half the qualified value for statistical analysis, for example, <4=2*]

No.	Sc	Sr	V	Y	Zn	Al%	Na%	K%	P%	Ce	Ga	Th	Nd	U	Org C%	S%	CO_3-C%
1	10	170	85	11	99	4.9	1.5	1.0	0.13	20	9	2	9	2.8	0.86	0.70	0.38
2	12	250	100	14	73	6.6	1.8	1.4	.15	29	13	8	16	4.3	.91	1.27	.22
3	9	310	180	12	140	3.5	1.2	.95	.13	15	7	2*	12	11.6	3.45	1.60	.62
4	8	410	220	14	100	3.5	1.2	.89	.15	21	6	2*	10	14.5	4.15	1.53	.98
5	7	330	210	15	77	3.7	1.3	.99	.25	21	7	5	15	12.2	3.85	1.43	.59
6	4	750	250	8	69	2.2	.78	.62	.15	9	2*	2*	13	8.1	4.53	1.00	3.75
7	8	220	360	17	120	4.7	1.1	1.3	.18	30	10	8	13	13.1	9.26	2.40	.38
8	7	210	250	13	130	4.1	1.1	.97	.11	20	7	5	15	13.1	7.47	2.20	.80
9	12	330	420	19	270	5.1	1.1	1.5	.26	30	9	8	20	20.6	7.24	2.85	.93
10	9	210	390	20	140	5.2	1.2	1.5	.19	37	10	9	21	15.8	6.40	2.80	.05
11	8	210	600	25	310	3.3	.66	1.1	1.10	13	2*	6	17	32.2	12.7	3.80	2.29
12	7	260	510	27	260	3.7	1.0	1.1	2.00	11	5	2*	21	16.5	9.48	3.90	2.10
13	11	210	360	29	300	5.7	1.1	1.6	1.50	33	9	2*	27	14.0	7.85	4.70	.34
14	8	73	250	6	150	4.6	1.1	1.3	.13	4	6	5	6	3.0	4.05	3.20	1.35
15	14	180	150	17	140	6.7	1.8	1.7	.10	25	11	6	16	3.8	2.22	1.05	.53
16	12	200	160	17	120	6.4	1.8	1.6	.10	31	11	6	17	4.1	2.11	.90	.63
17	16	160	180	19	110	7.1	1.9	1.8	.11	32	13	6	17	4.1	1.87	.92	.23
18	13	200	110	16	74	6.5	1.4	1.5	.32	32	13	6	20	4.5	.74	.92	.40
19	4	310	390	15	96	2.7	.52	.78	.19	14	6	5	9	17.1	2.13	1.50	1.62
20	1*	300	260	6	86	1.1	.37	.28	.11	2*	2*	2*	10	2.9	1.39	.43	5.50
21	6	600	240	22	320	3.6	.87	1.2	1.40	9	2*	5	13	13.4	14.4	5.06	.87
22	6	240	160	13	80	3.7	1.3	1.0	.21	22	7	5	16	8.4	3.44	1.55	4.72

newly produced sulfide. If the proportion of metabolizable organic matter is constant, the sedimentation rate constant, and the amount and reactivity of iron constant—then the organic C versus S correlation is obtained.

A variant on this organic carbon and sulfur relationship is the presence of a sulfur (non-zero) intercept of the linear least-squares-fit line (Leventhal, 1983). This effect has been observed for sediments from the Black Sea and is interpreted to indicate the presence of the H_2S laden water producing iron sulfide in the water column (as well as within the sediments). From the organic carbon and S data on the Monterey Formation (fig. 7), it appears that these samples fall into this category, which implies an H_2S laden water above the sediments of the Monterey Shale of the Santa Maria basin that was an offshore basin at the time of deposition. The magnitude of the intercept is less than the Black Sea; thus, the H_2S layer was thinner than the Black Sea or more likely there were times of no H_2S in the overlying water but only anoxic conditions.

Association and Abundance of Trace Elements

Trace metals are associated with other trace metals in terms of highest correlation coefficients (*r* values); however, their geochemical control is with organic carbon and/or sulfur. Ni, Cr, Cu, and Zn are very highly correlated with S and organic carbon (r >0.82). Figures 8 through 12 show some of these relationships. V, Mo, U, and Cd are less highly correlated with organic carbon and S (figs. 13–16) than are Ni, Cr, Cu, and Zn. Phosphorus, which can form a phosphate mineral phase, such as apatite, that can contain certain metals, is correlated with Cr (0.81), Ni (0.80), Zn (0.80), Y (0.77), and Cu (0.76). From these statistical results it is not possible to determine if these elements are really associated with P, or if it is the association of P with organic C (r = 0.70) and S (0.80) that gives these high correlations. However, because these metals show higher *r* values with both C and S than with P, only a fraction of these metals may reside in the phosphate minerals.

Table 2. Mean abundance values and ranges of constituents of 22 core samples from the Monterey Formation and related rocks, Santa Maria basin, California

Major constituents expressed as an element	Mean abundance (weight percent)	Range (weight percent)	Major constituent expressed as oxides[1]	Mean abundance (weight percent)
Al	4.48	(1.1 - 7.1)	Al_2O_3	8.46
Fe	2.18	(0.97 - 3.4)	Fe_2O_3	3.12
Mg	1.51	(0.50 - 5.0)	MgO	2.50
Ca	5.25	(1.2 - 17.0)	CaO	7.34
Na	1.19	(0.37 - 1.9)	Na_2O	1.60
K	1.19	(0.28 - 1.8)	K_2O	1.43
P	.41	(0.11 - 2.0)	P_2O_5	.94
Ti	.22	(0.17 - .31)	TiO_2	.37
orgC	5.4	(0.74 - 14.4)	Organic Matter[1]	7.0
CO_3-C	1.2	(0.22 - 4.7)	Carbonate	6.0
S	2.1	(0.7 - 5.1)		

Trace elements	Mean abundance (parts per million)	Range (parts per million)	Trace elements	Mean abundance (parts per million)	Range (parts per million)
Mn	298	(130 - 800)	Mo	20	(<2 - 66)
Ba	363	(150 - 730)	Y	16	(6 - 29)
Sr	279	(73 - 750)	Cd	8.8	(<2 - 18)
V	265	(85 - 600)	Co	6.0	(2 - 11)
Zn	148	(69 - 320)	Nb	6.1	(<4 - 9)
Cr	139	(52 - 300)	Pb	6.0	(<4 - 10)
Ni	104	(21 - 260)	Sc	8.7	(<2 - 16)
Cu	45	(10 - 130)	Ga	7.6	(<4 - 13)
Ce	21	(<4 - 37)	Th	4.9	(<4 - 8)
La	17	(6 - 24)	U	11	(2.8 - 32.2)
Nd	15	(6 - 27)			

[1]Organic matter is orgC x 1.3

CONCLUSION

Relative to the average chemical element values for black shales given by Vine and Tourtelot (1970), these Monterey Formation samples are enriched in Mo, Ni, and V by about a factor of 2. However, they are also enriched in organic carbon by a factor of 2, and thus actually are rather similar to typical black shale in their enrichment. These Monterey samples show less enrichment in all metals than some black shales, such as the Chattanooga Shale (Vine and Tourtelot, 1970; Leventhal and Hosterman, 1982), probably because of the greater sedimentation rate (Garrison and Douglas, 1981) of the Monterey Formation and also because of the relatively larger silica content (Durham, 1987), both of which dilute the metal content.

Table 3. Correlation coefficient matrix listing r values for analyses of 22 core samples from the Monterey Formation and related rocks

	Fe	Mg	Ca	Ti	Mn	Ba	Cd	Co	Cr	Cu	La	Mo	Nb	Ni	Pb	Sc	Sr	V	Y	Zn	Al	Na	K	P	Ce	Ga	Th	Nd	U	orgC	S
Mg	--	1.0																													
Ca	-.61	--	1.0																												
Ti	.91	--	-.73	1.0																											
Mn	--	.91	--	--	1.0																										
Ba	--	--	--	--	--	1.0																									
Cd	--	--	--	--	-.41	--	1.0																								
Co	.83	--	-.45	.77	--	--	--	1.0																							
Cr	--	--	--	--	--	-.45	.45	--	1.0																						
Cu	--	--	--	--	--	-.44	.56	--	.95	1.0																					
La	.51	--	-.48	.68	--	--	--	.45	--	--	1.0																				
Mo	-.46	--	--	--	--	-.42	.81	--	.55	.68	--	1.0																			
Nb	.57	--	-.64	.75	--	--	--	.42	--	--	.80	--	1.0																		
Ni	--	--	--	--	--	-.46	.47	--	.97	.96	--	.59	--	1.0																	
Pb	--	--	--	.63	--	--	--	.47	--	--	.57	--	.58	--	1.0																
Sc	.88	--	-.70	.91	--	--	--	.86	--	--	.61	-.43	.60	--	.54	1.0															
Sr	-.50	--	.80	-.49	--	--	--	--	--	--	--	--	-.51	--	-.43	-.41	1.0														
V	--	--	--	--	--	-.40	.77	--	.71	.74	--	.80	--	.67	--	--	--	1.0													
Y	--	--	--	.42	--	-.48	--	.41	.78	.72	.75	.41	.44	.73	.42	--	--	.56	1.0												
Zn	--	--	--	--	--	-.40	--	--	.92	.90	--	.46	--	.92	--	--	--	.65	.75	1.0											
Al	.93	--	-.75	.95	--	--	--	.84	--	--	.61	-.46	.68	--	.62	.95	-.53	--	--	--	1.0										
Na	.77	--	-.66	.76	--	--	--	.72	--	--	.40	-.64	.53	--	.41	.84	-.41	-.62	--	--	.87	1.0									
K	.88	--	-.64	.92	--	--	--	.89	--	--	.70	--	.70	--	.67	.90	-.47	--	.52	--	.93	.72	1.0								
P	--	--	--	--	--	--	--	--	.81	.75	--	.43	--	.80	--	--	--	.56	.77	.80	--	--	--	1.0							
Ce	.62	--	-.64	.77	--	--	--	.51	--	--	.87	--	.81	--	.50	.74	--	--	.40	--	.78	.65	.75	--	1.0						
Ga	.77	--	-.82	.85	--	--	--	.59	--	.43	.61	-.52	.71	-.40	.53	.83	-.57	-.44	--	--	.90	.83	.76	--	.85	1.0					
Th	--	--	-.45	.54	--	--	--	--	--	--	.52	--	.60	--	.62	.41	--	--	--	--	.52	--	.58	--	.57	.51	1.0				
Nd	.49	--	--	.55	--	--	--	.41	.40	--	.80	--	.56	--	.47	.45	--	--	.77	.43	.46	--	.57	.49	.63	--	--	1.0			
U	--	--	--	--	-.42	--	.84	--	.64	.77	--	.82	--	.65	--	--	--	.85	.58	.64	--	-.51	--	.47	--	-.41	--	--	1.0		
orgC	--	--	--	--	--	-.40	.57	--	.82	.91	--	.56	--	.87	--	--	--	.70	.60	.82	--	-.44	--	.70	--	-.49	--	--	.73	1.0	
S	--	--	--	--	--	-.53	.44	--	.87	.87	--	.52	--	.89	--	--	--	.64	.67	.89	--	--	--	.80	--	--	--	--	.60	.87	1.0
CO_3-C	-.59	.80	.77	-.76	.71	--	--	-.56	--	--	-.55	--	-.56	--	--	-.71	--	--	--	--	-.71	-.58	-.70	--	-.62	-.65	--	--	--	--	--
	Fe	Mg	Ca	Ti	Mn	Ba	Cd	Co	Cr	Cu	La	Mo	Nb	Ni	Pb	Sc	Sr	V	Y	Zn	Al	Na	K	P	Ce	Ga	Th	Nd	U	orgC	S

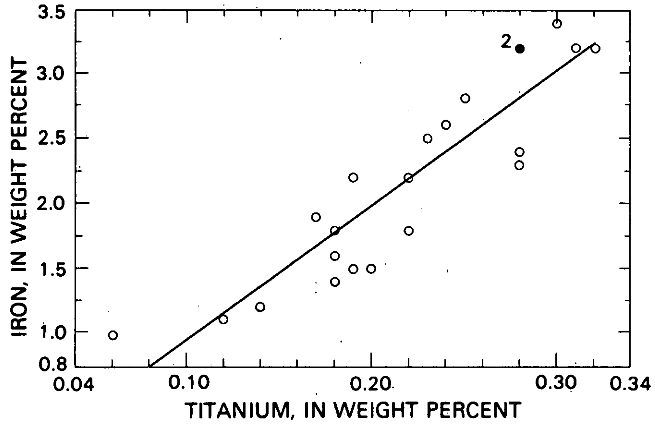

Figure 2. Plot of Ti versus Fe, correlation coefficient $r=0.91$, for 22 core samples from the Monterey Formation and related rocks listed in table 1. (Two samples plot at the solid symbol marked "2.")

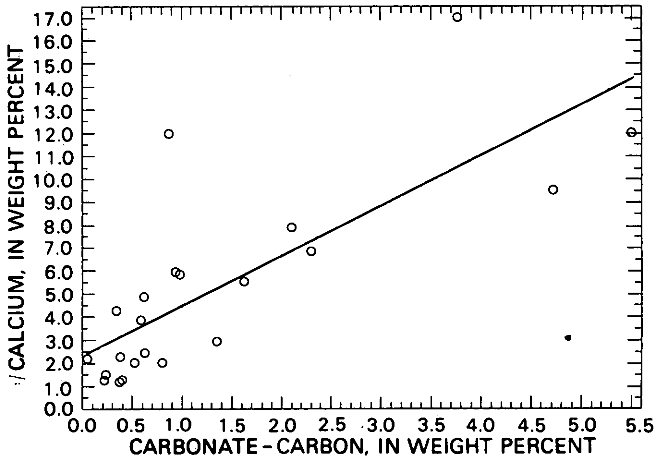

Figure 5. Plot of CO_3–C versus Ca, correlation coefficient $r=0.77$, for 22 core samples from the Monterey Formation and related rocks listed in table 1.

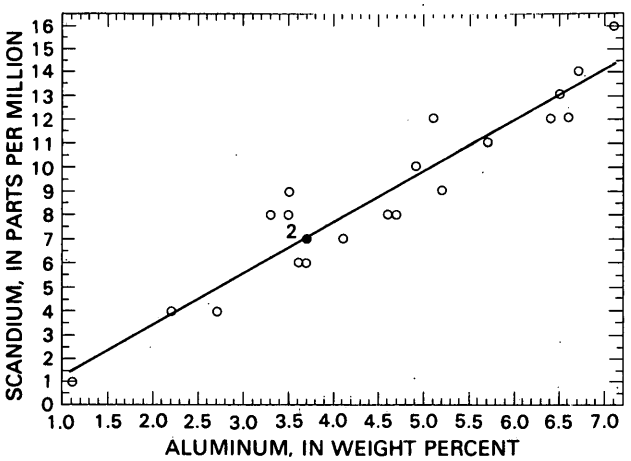

Figure 3. Plot of Al versus Sc, correlation coefficient $r=0.95$, for 22 core samples from the Monterey Formation and related rocks listed in table 1. (Two samples plot at the solid symbol marked "2.")

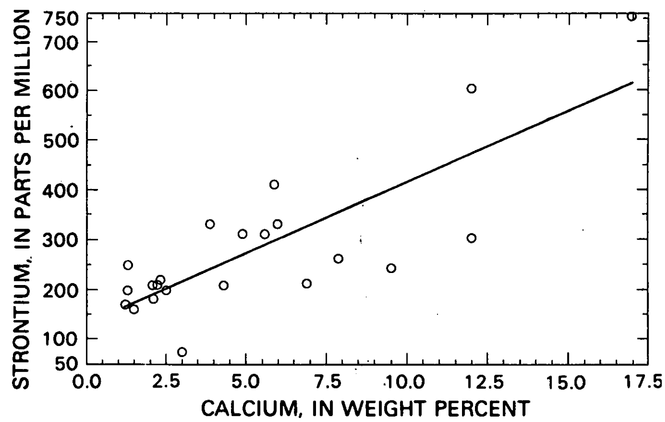

Figure 6. Plot of Ca versus Sr, correlation coefficient $r=0.80$, for 22 core samples from the Monterey Formation and related rocks listed in table 1.

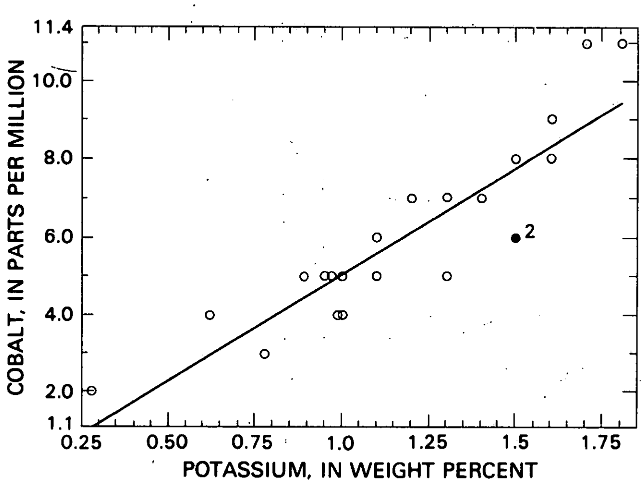

Figure 4. Plot of K versus Co, correlation coefficient $r=0.89$, for 22 core samples from the Monterey Formation and related rocks listed in table 1. (Two samples plot at the solid symbol marked "2.")

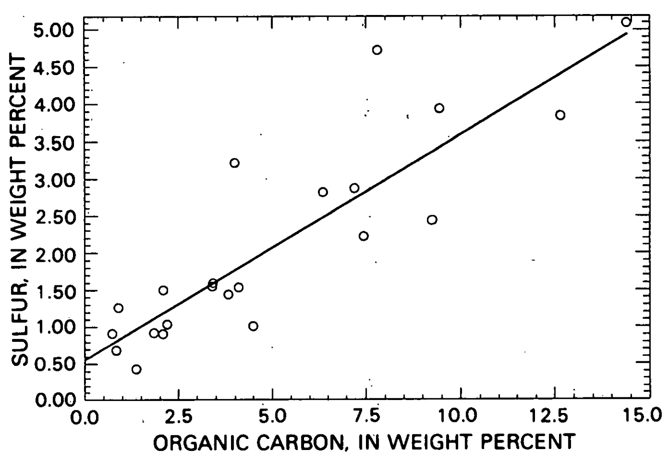

Figure 7. Plot of C org versus S, correlation coefficient $r=0.87$, for 22 core samples from the Monterey Formation and related rocks listed in table 1.

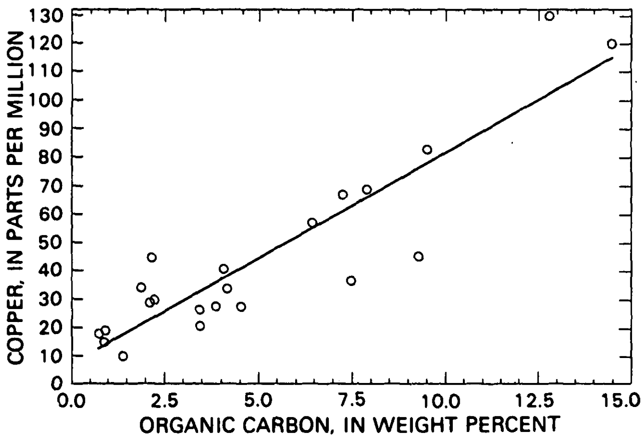

Figure 8. Plot of C org versus Cu, correlation coefficient r=0.91, for 22 core samples from the Monterey Formation and related rocks listed in table 1.

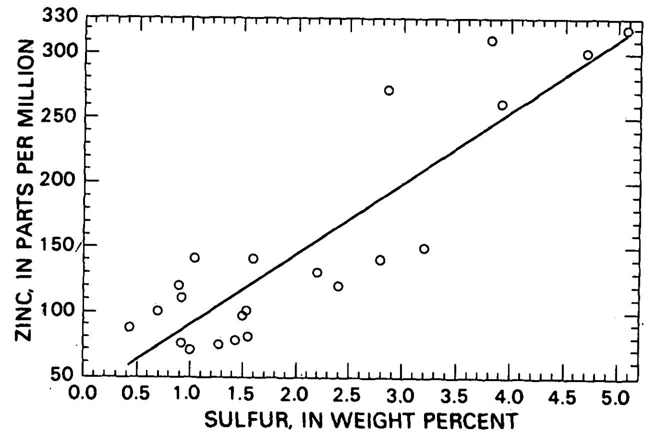

Figure 11. Plot of S versus Zn, correlation coefficient r=0.89, for 22 core samples from the Monterey Formation and related rocks listed in table 1.

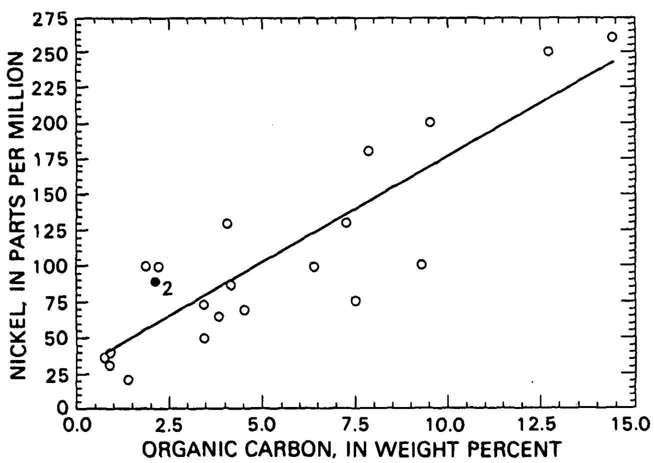

Figure 9. Plot of C org versus Ni, correlation coefficient r=0.87, for 22 core samples from the Monterey Formation and related rocks listed in table 1. (Two samples plot at the solid symbol marked "2.")

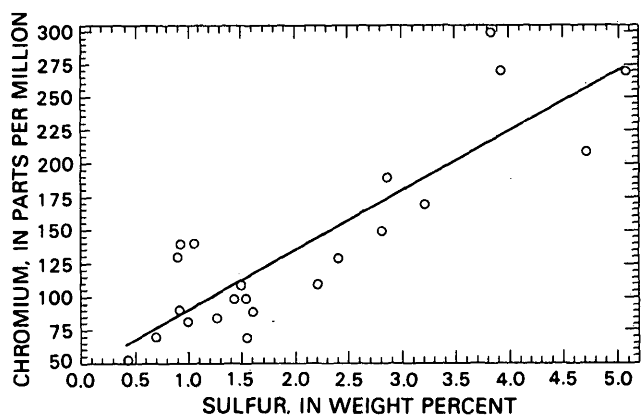

Figure 12. Plot of S versus Cr, correlation coefficient r=0.87, for 22 core samples from the Monterey Formation and related rocks listed in table 1.

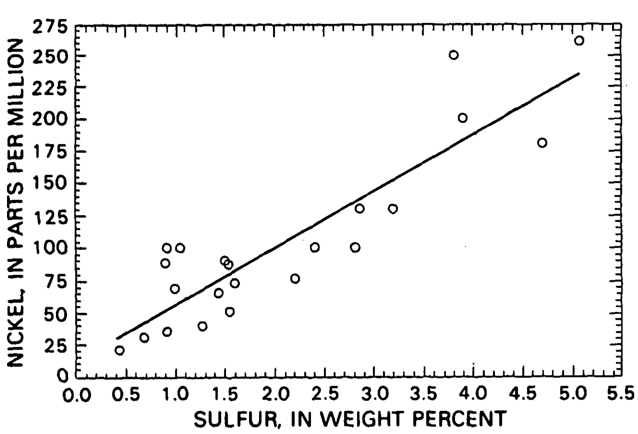

Figure 10. Plot of S versus Ni, correlation coefficient r=0.89, for 22 core samples from the Monterey Formation and related rocks listed in table 1.

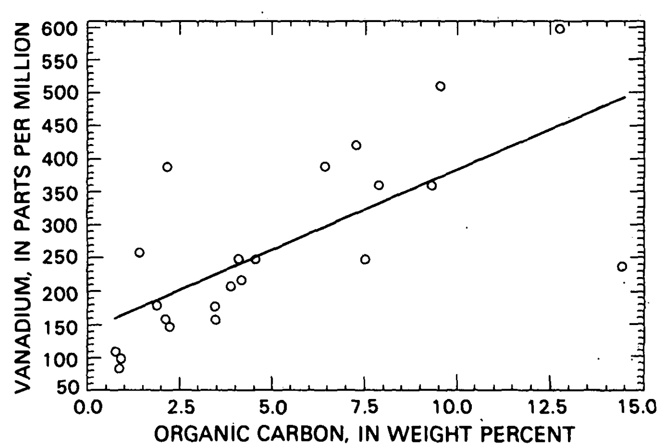

Figure 13. Plot of C org versus V, correlation coefficient r=0.70, for 22 core samples from the Monterey Formation and related rocks listed in table 1.

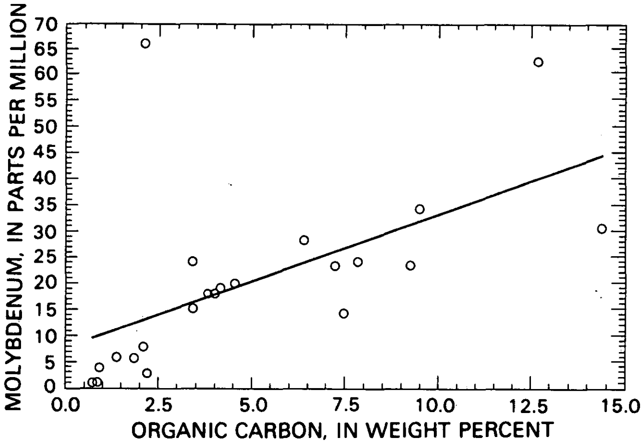

Figure 14. Plot of C org versus Mo, correlation coefficient r=0.56, for 22 core samples from the Monterey Formation and related rocks listed in table 1.

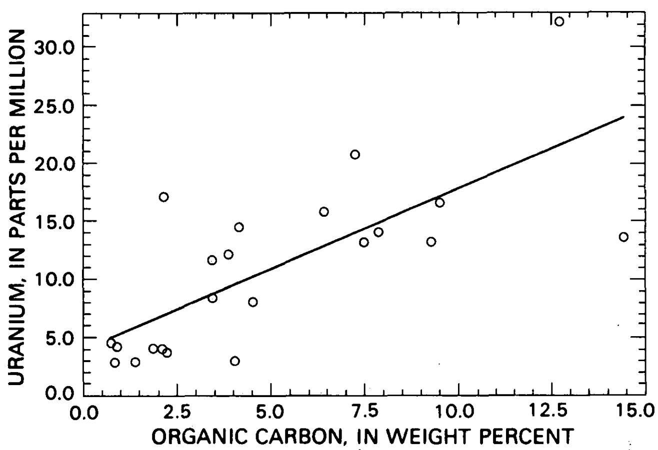

Figure 15. Plot of C org versus U, correlation coefficient r=0.73, for 22 core samples from the Monterey Formation and related rocks listed in table 1.

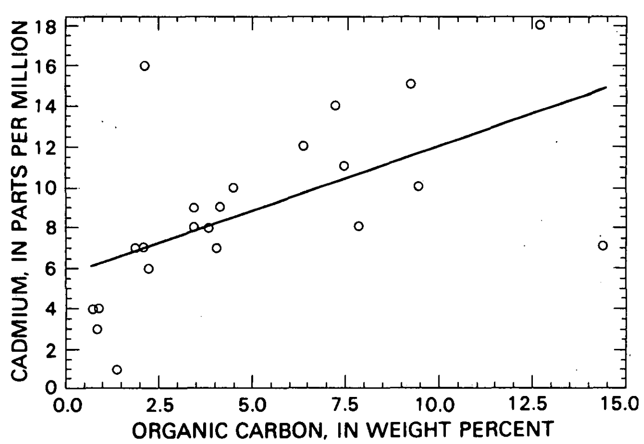

Figure 16. Plot of C org versus Cd, correlation coefficient r =0. 57, for 22 core samples from the Monterey Formation and related rocks listed in table 1.

ACKNOWLEDGMENTS

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REFERENCES CITED

Bramlette, M. N., 1946, Monterey Formation of California and the origin of its siliceous rocks: U.S. Geological Survey Professional Paper 212, 57 p.

Durham, D. L., 1987, Uranium in the Monterey Formation of California: U.S. Geological Survey Bulletin 1581–A, 29 p.

Garrison, R. E., and Douglas, R. G., editors, 1981, The Monterey Formation and related siliceous rocks of California: Society of Economic Paleontologists and Mineralogists Symposium, Pacific Section, SEPM, Los Angeles, 374 p.

Goldhaber, M. B., and Kaplan, I. R., 1974, The sulfur cycle, *in* E. Goldberg, editor, The Sea, v. 5, p. 569–655.

Isaacs, C. M., 1980, Diagenesis in the Monterey Formation examined laterally along the coast near Santa Barbara, Calif.: Ph.D. Thesis Stanford University, 329 p. and U.S. Geological Survey Open-File Report 80–606.

Leventhal, J. S., 1983, An interpretation of carbon and sulfur relationships in Black Sea sediments as indicators of environment of deposition. Geochimica et Cosmochimica Acta, v. 47, p. 133–138.

Leventhal, J. S., Crock, J. G., and Malcolm, M. J., 1981, Geochemistry of trace elements and uranium in Devonian shales of the Appalachian basin: U.S. Geological Survey Open-File Report 81–778, 73 p.

Leventhal, J. S., and Hosterman, J. W., 1982, Chemical and mineralogical analysis of Devonian black shale samples from Martin County, KY, Carroll and Washington Counties, OH, Wise County, VA and Overton County, TN, U.S.A.: Chemical Geology, v. 37, p. 239–264.

Leventhal, J. S. and Shaw, V. E., 1980, Organic matter in Appalachian Devonian black shale: Comparison of techniques to measure organic carbon: Jour. Sedimentary Petrology, v. 50, p. 77–81.

Millard, H. T., Jr., 1976, Determination of uranium and thorium in USGS standard rocks by delayed neutron technique, *in* F. Flanigan, editor, Descriptions and analyses of eight new USGS rock standards: U.S. Geological Survey Professional Paper 840, p. 61–66.

Piper, D. Z. and Fowler,B. L., 1979, Sediment Chemistry, *in* H. E. Cook, editor, Geologic Studies of the Point

Conception Well, southern Calif.: U.S. Geol. Survey-Open File Report 79–1218, p. 97–108.

Taggart, J. E., Lichte, F. E., and Wahlberg, J. S., 1981, Methods analysis using X-ray fluorescence and inductively coupled plasma spectroscopy, *in* P. Lipman and D. Mullineaux, editors, The 1980 Eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 683–692.

VanTrump G., Jr., and Miesch A. T., 1977, U.S. Geological Survey RASS–STATPAC system for management and statistical reduction of geochemical data: Computer and Geoscience, v. 3, p. 475–488.

Vine, J. D. and Tourtelot, E. B., 1970, Geochemistry of black shale deposits—A summary report: Economic Geology, v. 63, p. 253–272.

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Studies of Uranium Content and Geochemistry of the Monterey Formation, California

This volume was published as separate chapters A and B

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CONTENTS

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(B) Geochemistry of Minor and Trace Elements of 22 Core Samples from the Monterey Formation and Related Rocks in the Santa Maria Basin, California: by Joel S. Leventhal

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