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CHARACTERIZATION OF TRACE ELEMENTS IN AUSTRALIAN OIL SHALES

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INTRODUCTION

Australia's most extensive oil shale deposits are located in the state of Queensland (Figure 1), where oil reserves exceed 2000 billion barrels (1). Much of this is of low oil yield and located at considerable depths. A number of deposits are, however, being studied for commercial development, including one at Julia Creek in the north-west part of the large Toolebuc formation containing a Cretaceous oil shale. On the eastern coast, the Condor, Rundle and Nagoorin deposits of Tertiary oil shales have estimated recoverable reserves of 8500, 2000 and 3000 million barrels, respectively (2-4).

The depositional environments of these oil shales are very different. The three eastern deposits appear to be dominated by Pediastrum and other planktonic algae inhabiting what was a shallow lacustrine environment (5), together with high concentrations (up to 50%) of humic material. Julia Creek oil shale was deposited in a marine environment and contains cyanobacteria and other marine algal species, with humic acid comprising only a very small percentage of the organic matter (6). Evidence for these differing origins may be reflected in the trace element contents of the kerogens where elements, such as arsenic which preferentially accumulates in marine algae (7), should be more abundant in the marine deposit.

The trace element content of an oil shale is, however, likely to be dominated more by the mineral matrix binding the kerogen, rather than kerogen-associated elements. These minerals also differ significantly between deposits; in Julia Creek shale, calcite and quartz predominate, whereas the Tertiary shales contain primarily claystone, limestone and sandstone. Comprehensive elemental analyses were, therefore, carried out on the raw shales, to characterize them and to indicate differences in the environmental impact that might be posed by the products of oil shale retorting.

The latter have been more fully investigated in measurements of the partitioning of trace elements between retort waters, shale oils, gases and spent shale. Products for these studies were generated using the Fischer Assay procedure which yields products similar to those of some commercial retorting processes and, thus, provides a comparative product assessment.

While atmospheric emissions of volatile elements, or the accumulation of others in shale oil or retort water, may be undesirable from environmental or processing viewpoints, a further problem is created by those elements remaining in the retorted shale. The retorting process will concentrate non-volatile elements in this residue, while transforming others into soluble species on pyrolysis of the associated organics. Leaching of trace elements from both spent and raw shale storage heaps may pose a further environmental problem, with leaching conditions in the sub-tropical climate of north Queensland quite different to those encountered in the U. S. Column leaching studies on raw and spent shales have been carried out to define the extent of the problem.

Multi-element techniques were applied to the analysis of raw shales, retorted shales, oil, retort waters and leachates. Spark-source mass spectrometry (SSMS) and instrumental neutron activation analysis (INAA) together provided data for 65 elements. More precise data for specific elements were obtained using inductively-coupled plasma emission spectrometry (ICP) and atomic absorption spectrometry (AAS).

EXPERIMENTAL

Bulk samples (1-2 kg) of raw shale, for use in Fischer retorting and leaching studies, were ground to -2 mm particle size and dried at 110°C for 17 h. For chemical analyses, samples were further ground, using a tungsten carbide mill, to -74 µm.

For INAA, 100-200 mg shale samples were irradiated for two days in a thermal neutron flux of $5 \times 10^{12} \text{ n cm}^{-2} \text{ s}^{-1}$ in the Australian Atomic Energy Commission HIFAR reactor. Retort

waters were analyzed after freeze drying, while oils were analyzed directly. High resolution gamma spectrometric measurements were made after cooling periods of 5-7 days and 28-40 days.

Spark-source mass spectrometric analysis of the oil shales was carried out using photo-plate detection for maximum element coverage. Lutetium was added as an internal standard to provide quantitative data. Retort waters were analyzed via this procedure after evaporation onto a graphite substrate.

For partitioning studies, shales were retorted under standard Fischer Assay conditions (8) and the product oil, water and spent shales analyzed for trace element content. Off-gas samples were collected, but not analyzed. Oils for analysis by ICP and AAS were first digested with sulfuric acid-hydrogen peroxide to decompose the organic matter.

Analytical methods were checked for accuracy using the USGS Green River Shale SGR-1 and Coady Shale SC0-1 samples.

Leaching of raw and spent shales (150 g) was carried out in 50 cm x 2.5 cm diameter glass columns under saturated conditions, using distilled water drawn through the bed at 0.5 mL min⁻¹ by a peristaltic pump. Leachates were analyzed by INAA and SSMS using the procedures followed for retort waters. Specific elements were analyzed by ICP and AAS. Dissolved organic carbon was measured on a Beckman Carbon Analyzer, while selected anions were determined using standard wet chemical procedures (9).

RESULTS AND DISCUSSION

Elemental Composition of Raw Shales

Analytical data for raw shales from the four Australian deposits are shown in Table I. For comparison, data for Green River shale (10) and a Devonian eastern U. S. shale (11) are also included. Although it was possible to quantify 65 elements, the tabulated data contain only those elements which most reflected the differences between deposits.

TABLE I
ELEMENTAL COMPOSITION OF RAW SHALES

	(Dry Basis: $\mu\text{g g}^{-1}$ except as shown)					
	Julia Creek	Condor	Rundle	Nagoorin	Green River (10)	Antrim (11)
C(Org)	15.0 \pm 0.1 (%)	10.3 \pm 0.1 (%)	15.4 \pm 0.1 (%)	30.4 \pm 0.1 (%)	26.2 \pm 2.6 (%)	10.0 (%)
C(Inorg)	7.2 \pm 0.1 (%)	0.7 \pm 0.1 (%)	0.8 \pm 0.1 (%)	0.5 \pm 0.1 (%)	3.05 \pm 0.31 (%)	-
Na	0.19 \pm 0.01 (%)	0.47 \pm 0.03 (%)	0.83 \pm 0.05 (%)	0.39 \pm 0.02 (%)	2.36 \pm 0.06 (%)	0.39 (%)
Mg	0.18 \pm 0.01 (%)	0.76 \pm 0.18 (%)	1.86 \pm 0.54 (%)	0.51 \pm 0.03 (%)	2.87 \pm 0.06 (%)	1.14 (%)
Al	0.61 \pm 0.07 (%)	6.79 \pm 0.35 (%)	5.73 \pm 0.32 (%)	3.86 \pm 0.22 (%)	3.41 \pm 0.06 (%)	7.35 (%)
S	1.8 \pm 0.1 (%)	0.6 \pm 0.1 (%)	1.0 \pm 0.1 (%)	1.0 \pm 0.1 (%)	2.54 \pm 0.25 (%)	3.2 (%)
Cl	950 \pm 60	0.57 \pm 0.01 (%)	0.26 \pm 0.01 (%)	0.29 \pm 0.01 (%)	--	-
K	0.16 \pm 0.02 (%)	0.57 \pm 0.06 (%)	0.93 \pm 0.09 (%)	0.21 \pm 0.02 (%)	1.01 \pm 0.2 (%)	3.12 (%)
Ca	23.7 \pm 3.4 (%)	0.24 \pm 0.01 (%)	2.58 \pm 0.45 (%)	1.04 \pm 0.22 (%)	5.72 \pm 0.03 (%)	0.51 (%)
Ti	340 \pm 17	0.39 \pm 0.06 (%)	0.40 \pm 0.08 (%)	0.17 \pm 0.05 (%)	0.11 \pm 0.05 (%)	0.42 (%)
V	0.21 \pm 0.01 (%)	104 \pm 11	79 \pm 10	83 \pm 10	166 \pm 18	156
Cr	97 \pm 5	48 \pm 2	42 \pm 2	25 \pm 2	33.3 \pm 0.7	83
Mn	125 \pm 4	390 \pm 11	650 \pm 20	232 \pm 7	242 \pm 5	195
Fe	0.84 \pm 0.02 (%)	4.97 \pm 0.13 (%)	3.26 \pm 0.09 (%)	2.1 \pm 0.06 (%)	1.94 \pm 0.16 (%)	4.66 (%)
Co	10.8 \pm 0.3	38 \pm 1	17.5 \pm 0.4	12.1 \pm 0.3	13.3 \pm 0.3	24.4
Ni	237 \pm 12	108 \pm 5	53 \pm 10	37 \pm 2	24.2 \pm 3.2	81
Cu	65 \pm 3	32 \pm 2	43 \pm 2	41 \pm 2	51.2 \pm 2.4	79
Zn	1220 \pm 60	100 \pm 5	70 \pm 5	60 \pm 3	69.3 \pm 2.8	39
As	66 \pm 6	9.7 \pm 1.3	7.7 \pm 1.1	14 \pm 1	42.3 \pm 1.7	28
Se	26.7 \pm 0.5	4.2 \pm 0.4	<1	12 \pm 1	2.4 \pm 0.6	2.7
Br	8.2 \pm 2.7	32 \pm 9	10 \pm 3	19 \pm 5	--	-
Mo	295 \pm 30	1.3 \pm 0.4	1.6 \pm 0.4	4.3 \pm 1	31.8 \pm 2.5	114
Cd	28 \pm 3	0.6 \pm 0.2	1.8 \pm 0.4	2.2 \pm 0.5	1.20 \pm 0.06	0.67
Sb	29 \pm 3	0.2 \pm 0.1	0.2 \pm 0.1	0.7 \pm 0.2	2.50 \pm 0.19	4.00
U	38 \pm 3	1.8 \pm 0.9	0.9 \pm 0.4	4.3 \pm 0.9	4.79 \pm 0.05	28
Tl	6.4 \pm 1.5	1.1 \pm 0.2	0.4 \pm 0.2	0.4 \pm 0.2	--	-

The Julia Creek sample is distinctly different from the others. Calcium, inorganic carbon, zinc, vanadium, arsenic, selenium, thallium, molybdenum, cadmium, antimony and uranium

are all 1-2 orders of magnitude higher in concentration, while aluminium, titanium and iron are by comparison lower. The high calcite and quartz and relatively low clay mineral content explain many of these differences. Results for Sunbury and other U. S. marine-derived shales show similar elevated levels of uranium, molybdenum, zinc and arsenic (12). Vanadium concentrations are also high in these U. S. samples, but not to the extent of the Julia Creek sample.

There is considerable evidence for the uptake of arsenic by marine algae. In low phosphate seawater, arsenate is co-adsorbed by the algae and converted to a range of organoarsenic compounds (7). It has also been suggested that arsenic and selenium may replace sulfur in organo-sulfur compounds (13) and this may also be true for antimony. Antimony is also concentrated by some bacteria.

Uranium in Julia Creek shale is associated mainly with phosphatic fish skeletal remains and high concentrations have been identified in strata rich in fish debris (14). Arrhenius et al. (15) found that concentration of uranium occurs through complexation with phosphate ion after the death of the organism. Phosphate is present as apatite in the skeletal debris. In Chattanooga shales, uranium concentrations as high as 100 mg g⁻¹ have been found, present mainly as the oxide minerals, although some organic association was detected (16).

To examine trace element associations, concentration-depth profiles were studied for two Julia Creek drill core samples. In agreement with the findings of Ramsden (14), cadmium, zinc and thallium were found to be associated with pyritic sulfur, whereas uranium correlated well with organic carbon (17). Vanadium exhibits an association with both the clay and organic fractions. In the shallow core, arsenic, selenium, antimony and molybdenum showed a strong association with both organic sulfur and organic carbon (Figure 2). Data from the deeper core suggest that arsenic and selenium are predominantly associated with pyritic sulfur in the oil shale, but still associated with organic species in the coquinite.

Molybdenum is associated with pyritic sulfur in the coquinite but appears to be associated with organic species in the shale. It is needed by cyanobacteria as a catalyst for nitrogen fixation (18).

Vanadium, while also present as oxides, vanadates and silicates, is present in high concentrations as vanadyl porphyrins (19, 20). A range of both vanadium and nickel porphyrins have been isolated by Ekstrom et al. (21) and evidence has been found indicating a mild thermal history, but possibly a biological transformation from chlorophyll. Both vanadium and nickel form strong complexes with porphyrin-type molecules; however, a high V/Ni complex ratio is favored by oxidizing rather than anoxic conditions. Although the methanogenic bacteria would have created anoxic conditions in the sediments, overlying waters were most likely oxygenated and it is here that complexation would have occurred. Potter et al. (22) explained high V/Ni ratios in Kentucky shales on the basis of low sedimentation rates permitting high vanadium uptake from seawater by organic matter. The ratio of dissolved vanadium to nickel is at least 30 times greater in seawater than in river or lake waters (23). In addition, there are species of tunicates which are efficient concentrators of vanadium and these may have been present amongst the precursor organisms (18).

Trace element abundances in the three Australian Tertiary shales are very similar and approximate the values for average sedimentary shales as reported by Turekian and Wedepohl (24). Differences in minor element content of the shales are associated with slightly differing lithologies. Rundle shale, for example, is higher in calcium and magnesium than either Condor or Nagoorin shales, due to the presence of both calcite and dolomite. Green River shale contains even more carbonate, calcium and magnesium than Rundle shale, with measurably higher concentrations of arsenic, antimony, molybdenum and cadmium.

Trace Element Partitioning

Details of oil and water yields and total weight losses in Fischer Assays are shown in Table II and data for the concentrations of 19 trace elements found in oils and retort waters are given in Table III.

TABLE II
FISCHER ASSAY PRODUCT DETAILS OF OIL SHALES

Sample	Oil Yield (g/100 g Dried Raw Shale)	Water (mL/100 g Dried Raw Shale)	Weight Loss (g/100 g Dried Raw Shale)
Julia Creek	7.62	1.60	12.0
Condor	5.38	9.73	18.7
Rundle	10.64	2.68	21.7
Nagoorin	4.95	7.98	25.7

TABLE III

PARTITIONING OF TRACE ELEMENTS IN SHALE OIL AND RETORT WATERS

Element	Julia Creek			Condor			Rundle		
	Oil $\mu\text{g g}^{-1}$	Water $\mu\text{g L}^{-1}$	Mobility %	Oil $\mu\text{g g}^{-1}$	Water $\mu\text{g L}^{-1}$	Mobility %	Oil $\mu\text{g g}^{-1}$	Water $\mu\text{g L}^{-1}$	Mobility %
Al	37	<1	0.046	153	<1	0.012	25	<1	0.005
As	42	19	5.3	1.3	0.24	0.85	5.7	3.8	9.2
Br	0.3	1.1	0.49	0.12	2.4	0.72	0.18	0.95	0.5
Ca	60	50	0.002	22	19	0.088	35	18	0.016
Cl	66	370	1.15	49	2110	3.7	29	600	0.74
Co	0.16	1.6	0.37	0.42	4.8	1.3	0.26	2.7	0.57
Cr	1.2	0.29	0.093	6.7	1.0	0.96	3.5	0.08	0.88
Cu	0.49	0.08	0.063	0.41	0.27	0.16	0.32	0.57	0.12
Fe	17	0.22	0.015	6.9	5.4	0.002	16	0.7	0.005
K	33	15	0.17	20	10	0.016	26	8.8	0.032
Mg	9	3.2	0.041	14.4	10.7	0.023	22	8.7	0.0001
Mn	0.4	0.07	0.025	0.14	0.52	0.015	0.28	0.12	0.005
Na	3.6	11	0.024	3.9	11	0.028	6.1	6.5	0.01
Ni	1.9	4.2	0.089	3.5	8.4	0.93	1.4	5.2	0.55
Sb	1.8	0.04	0.48	<0.03	<0.03	0	<0.03	<0.03	0
Se	10	12	3.6	0.25	0.05	11.0	0.11	0.2	0.15
Ti	13	0.016	0.29	0.91	0.13	0.002	13.4	0.023	0.035
V	10.2	<0.1	0.037	<0.1	<0.1	<0.01	<0.1	<0.1	<0.01
Zn	5	<0.07	0.031	1.2	0.17	0.09	1.5	0.31	0.24

Element	Nagoorin			Green River (10)		
	Oil $\mu\text{g g}^{-1}$	Water $\mu\text{g L}^{-1}$	Mobility %	Oil $\mu\text{g g}^{-1}$	Water $\mu\text{g L}^{-1}$	Mobility %
Al	24	<1	0.003	9.7	<1	0.0062
As	9	1.5	4.1	4.1	3.4	3.8
Br	0.67	1.32	0.74	-	-	-
Ca	32	180	0.15	<1	6	0.003
Cl	240	1050	3.3	-	-	-
Co	0.78	4.9	3.6	2.0	0.21	3.8
Cr	1.2	0.36	0.36	0.22	0.01	0.38
Cu	0.46	0.12	0.073	<0.7	<0.1	0.27
Fe	23	18	0.012	60	1.2	0.084
K	8	83	0.34	5	5	0.023
Mg	7.1	95	0.16	8.2	<17	0.021
Mn	0.26	0.32	0.017	0.16	<0.10	0.056
Na	26	18	0.07	51.5	1360	0.19
Ni	1.3	11.4	2.6	4.1	1.3	4.7
Sb	0.4	<0.03	2.9	0.005	0.15	0.28
Se	0.58	0.37	0.5	0.81	1.25	5.1
Ti	2.4	0.43	0.009	<0.5	<0.6	0.009
V	<0.1	<0.1	<0.02	0.60	<0.07	0.11
Zn	1.6	0.80	0.23	0.69	0.09	0.27

On the basis of these data, mobilities of elements into the oil and water phases were calculated as the percentage by weight of the element transferred to these phases from the raw shale (Table III). Data for Green River shale are included for comparison (11).

During retorting, aluminium, arsenic, chromium, iron, titanium and zinc partitioned predominantly into the oil fraction. Vanadium was found in Julia Creek oil and antimony in both Julia Creek and Nagoorin oil. Cobalt, nickel and chlorine partitioned mainly in the retort waters in each case. Arsenic and selenium are the most mobile elements in all shales. Cobalt and nickel (except in Julia Creek shale) were also mobilized to greater than 1%, into the retort water. Apparent anomalies, such as the low mobilities of zinc, nickel and chromium in Julia Creek shale and the high mobilities of antimony in Nagoorin and titanium in Julia Creek shales, are the result of higher or

lower concentrations, respectively, of the element in the raw shale, when compared with the value for an average sedimentary shale (24).

Preferential mobility in the oil phase must be interpreted as arising from organic association of the element; this has already been demonstrated for vanadium, uranium, molybdenum, arsenic, selenium and antimony in Julia Creek Shale. The possibility that a small fraction of elements in either phase may result from the carryover of shale fines cannot be discarded.

Elements soluble in retort waters may be volatile organic complexes or inorganic species, including fines, which preferentially dissolve on contact with the weakly basic retort water. Typical analyses of these waters (Table IV) showed them to be primarily dilute solutions of ammonium carbonate, with high concentrations of chloride and thiosulfate ion. Dissolved organic carbon concentrations are also high, especially in the Nagoorin sample and are due to the presence of a plethora of metal-binding organic species, principally carboxylic acids, but also phenols, aromatic amines and heterocyclic bases.

In assessing the potential environmental impact posed by trace elements in retort waters and oils, it is their ultimate concentration rather than their mobility which is important. On the basis of recommended "safe" environmental concentration limits for waters (25) considerable treatment would be required to remove elements such as arsenic, selenium, cobalt, nickel and other heavy metals, in addition to toxic organic species, before discharge to a waterway would be permissible.

The chemical form and concentration of elements remaining in the spent shale will also be of concern, especially if the retorting process has rendered them readily leachable from the spent shale storage heaps. Concentrations of all but the mobile elements are altered little from those in the raw shale, but depending on retorting temperatures and conditions, non-volatile organic complexes may well be decomposed, while carbonates and other non-refractory minerals are transformed to oxides.

TABLE IV
CHEMICAL ANALYSIS OF RETORT WATERS

	<u>Julia Creek</u>	<u>Condor</u>	<u>Rundle</u>	<u>Nagoorin</u>
pH	8.4	9.5	8.6	8.8
Organic C, g L ⁻¹	2.3	4.1	2.2	7.4
Ammonia, g L ⁻¹	1.3	5.0	29	8.6
Alkalinity, g L ⁻¹ (CaCO ₃)	1.6	11.5	2.6	17.1
S ₂ O ₃ ⁼ , g L ⁻¹	1.1	0.01	0.3	0.05
SO ₄ ⁼ , mg L ⁻¹	72	100	26	212
SCN ⁻ , mg L ⁻¹	97	22	29	50
CN ⁻ , mg L ⁻¹	24	10	4	7
Phenolics, mg L ⁻¹	58	29	41	37

Leaching Studies

There have been many differing approaches to the study of leaching characteristics (26, 27) and standard batch leach tests have now been devised and accepted by the U. S. Environmental Protection Agency as a basis for the comparison of samples (28). Batch tests are, however, sensitive to the solution-to-solids ratio, give only a total leachable quantity and fail to reflect adequately the compositional changes that may occur in the leachate with time. More realistic data can be obtained by column testing, ideally conducted under non-saturated flow for extended periods of up to six months or more; however, data obtained from saturated flow experiments over a few days of continuous flow provide a useful estimate of potential pollutant release. In the present studies, the latter approach was adopted to enable a comparison of raw and spent shales from the four Australian deposits, since stockpiles of either will be potentially leachable.

The distribution of major ions in leachates from the raw and spent shales was similar to that reported previously for some U. S. shales (29) and for Rundle shale (30). The salt release was disturbingly high; the first pore volumes released from the Condor sample contained approximately 0.3 M sodium and chloride, accompanied by a high sulfate concentration (0.01 M). The

concentrations of these ions were lower in the other deposits, although they exhibited higher calcium concentrations consistent with its elevated levels in the shales.

The rate of trace element release was initially rapid except for calcium and sulfate whose solubility was a limiting factor in some shales. In most instances, the concentrations of trace elements in the leachates reduced to acceptable levels after the passage of 4-5 pore volumes. The pH values, however, diminished little. Values for raw shale leachates were near 7 (Table V); however, the Rundle and Julia Creek spent-shale leachates were more basic as a consequence of oxides, formed during retorting, which undergo partial hydrolysis during leaching.

TABLE V
COMPOSITION OF THE FIRST PORE VOLUME OF COLUMN LEACHATES

	Julia Creek		Condor		Rundle		Nagoorin	
	Raw	Retorted	Raw	Retorted	Raw	Retorted	Raw	Retorted
pH	7.7	10.7	6.5	6.1	7.5	9.7	5.2	7.5
Na, g L ⁻¹	1.4	1.3	6.7	5.0	3.7	2.3	1.2	3.6
Ca, g L ⁻¹	1.0	0.9	0.6	0.4	1.0	0.8	0.8	0.7
Cl ⁻ , g L ⁻¹	1.8	0.9	12.0	14.2	3.6	3.5	1.9	5.8
SO ₄ ⁼ , g L ⁻¹	5.5	2.3	7.4	2.5	7.1	2.9	5.4	2.2
Organic C, mg L ⁻¹	252	36	12	2	680	36	168	10
Mn, mg L ⁻¹	0.1	0.1	1.0	0.4	2.6	2.5	1.8	0.9
Ni, mg L ⁻¹	1.2	0.1	0.7	0.6	0.2	0.2	0.1	0.1
Cu, mg L ⁻¹	0.4	0.2	2.6	1.4	1.7	0.1	0.3	0.1
Zn, mg L ⁻¹	2.3	0.3	2.6	1.2	1.5	1.0	4.0	0.2
Cd, mg L ⁻¹	0.5	0.4	0.2	0.1	0.6	0.1	0.7	0.5
As, mg L ⁻¹	0.8	0.4	1.4	0.5	0.6	0.1	4.0	0.2
CN ⁻ , mg L ⁻¹	1.0	1.0	0.1	0.1	0.1	0.1	0.1	0.5
S ₂ O ₃ ⁼ , mg L ⁻¹	5.5	56	15.4	96	7.3	47	0.8	11.4

Leachates from Green River retorted shale are also basic (pH 8.2-9.5 (27)); however, those from Kentucky shales, both raw and retorted, are acidic (31). This acidity results from high pyrite yet low carbonate concentrations, unlike that of Julia Creek shale. Mobilization of trace elements during leaching will be pH dependent. Most heavy metals will be more readily leached under acidic conditions, while molybdenum, arsenic and selenium are more soluble in basic conditions. Low concentrations of these latter elements were found in leachates of Kentucky shales (31), but cadmium, zinc, copper and manganese concentrations were environmentally significant. Arsenic and molybdenum levels were higher in leachates of Green River shale (27, 32).

For the Australian shales, arsenic, cadmium, copper, nickel, zinc and manganese were found to exceed the recommended environmental limits (25) in the first pore volumes of leachates. Changes in the distributions of these species in the leachates depend not only on pH, but also on ionic strength and chemical form. Phenols and carboxylic acids, which are more soluble in basic solutions, are likely metal-binding agents. Preliminary results indicate that up to 60% of nickel and copper are in bound forms.

It was noticeable that cyanide and thiosulfate levels were also high for leachates from some of the retorted shales. The retorting process causes high concentrations of thiosulfate and ammonia to be driven off in the retort waters, together with cyanide, sulfide and thiocyanate (Table IV). Residues of these species may be released from the spent shale by aqueous leaching.

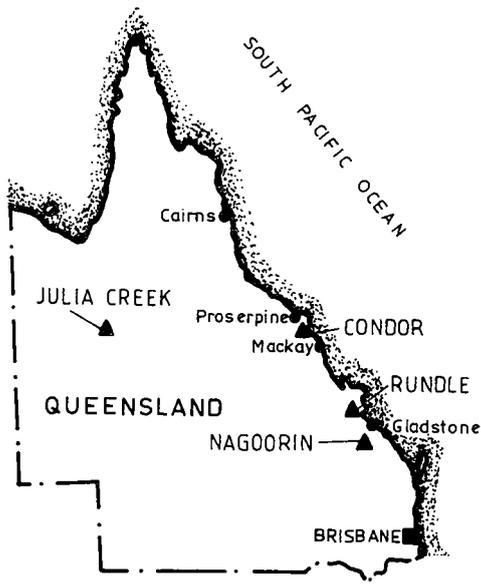


Figure 1. Major oil shale deposits in Queensland, Australia.

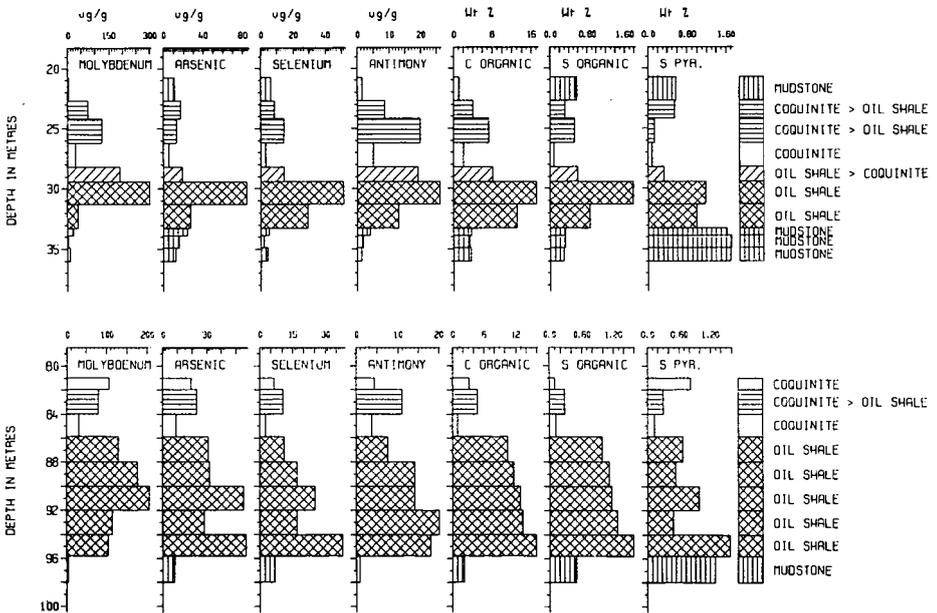


Figure 2. Concentration-depth profiles in Julia Creek drill core samples.

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