SURFACE GEOCHEMICAL PATTERNS ASSOCIATED WITH URANIUM IN AND BENEATH THE ATHABASCA SANDSTONE, SASKATCHEWAN, CANADA

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ABSTRACT

Major uranium deposits marginal to the Precambrian unmetamorphosed Athabasca Sandstone contain differing suites of associated elements. Dispersion patterns of U, Cu, Ni, Pb, Zn, Co, Mo, V, Mn, Fe, and Cr in lake sediments near mineralization, show considerable variation in concentrations and size of halos: lakes down drainage from Rabbit Lake contain anomalous U for up to 5 km, with weakly associated Cu, V and Mo; U from the Key Lake deposit extends for over 20 km and is in strong association with Ni, Co, and, to a lesser degree Zn. Fluoride in lake waters correlates with U in sediments near Rabbit Lake, but not near Key Lake. Factor analysis of various trace metal populations around the Sandstone emphasizes the variability in trace metal associations, yet discloses certain basic patterns: sediments from lakes on the Athabasca Sandstone have a dominant U and V association, whereas sediments from lakes on the crystalline basement show a predominant U, Ni, and Cu association, sometimes with Mo, and sometimes with Co.

Geochemical patterns are controlled mainly by: (1) different chemical compositions of the ore bodies; (2) composition of crystalline basement adjacent to the Sandstone; (3) basic igneous intrusions: possible traps for U-bearing solutions; (4) paleocurrent systems and possible unconformities within the Sandstone; (5) grain size of the Sandstone; (6) subsurface water movements, past and present; (7) post-Athabasca faulting: perhaps much more significant than previously supposed; (8) glaciation: a major factor in confusing geochemical patterns by (a) covering the bedrock with several different types of glacial deposit, (b) modifying drainage, (c) producing mineralized boulder trains which ultimately may give their own geochemical halos.

Near the northern edge of the Sandstone, U and V patterns appear to be related to faulting and glacial smearing. At Midwest Lake near the eastern edge, U beneath the Sandstone is reflected in the overlying lake sediments; possibly as a result of ionic transport by capillary action in winter.

INTRODUCTION

The Athabasca Formation covers an area of approximately 60,000 km^2, over 90 percent of which is in northern Saskatchewan (Figure 1). Its centre basin thickness exceeds 1500 m. Outcrops are sparse because of the extensive Pleistocene glacial overburden, locally over 90 m thick (Tan, 1977), which gives rise to a physiography of gently rolling plains, accentuated by drumlins and eskers, under a cover of mosses and muskegs between moderately open coniferous woodland typical of boreal forests in a region of discontinuous permafrost (Brown, 1967).

Fahrig (1961) published the first major survey of the

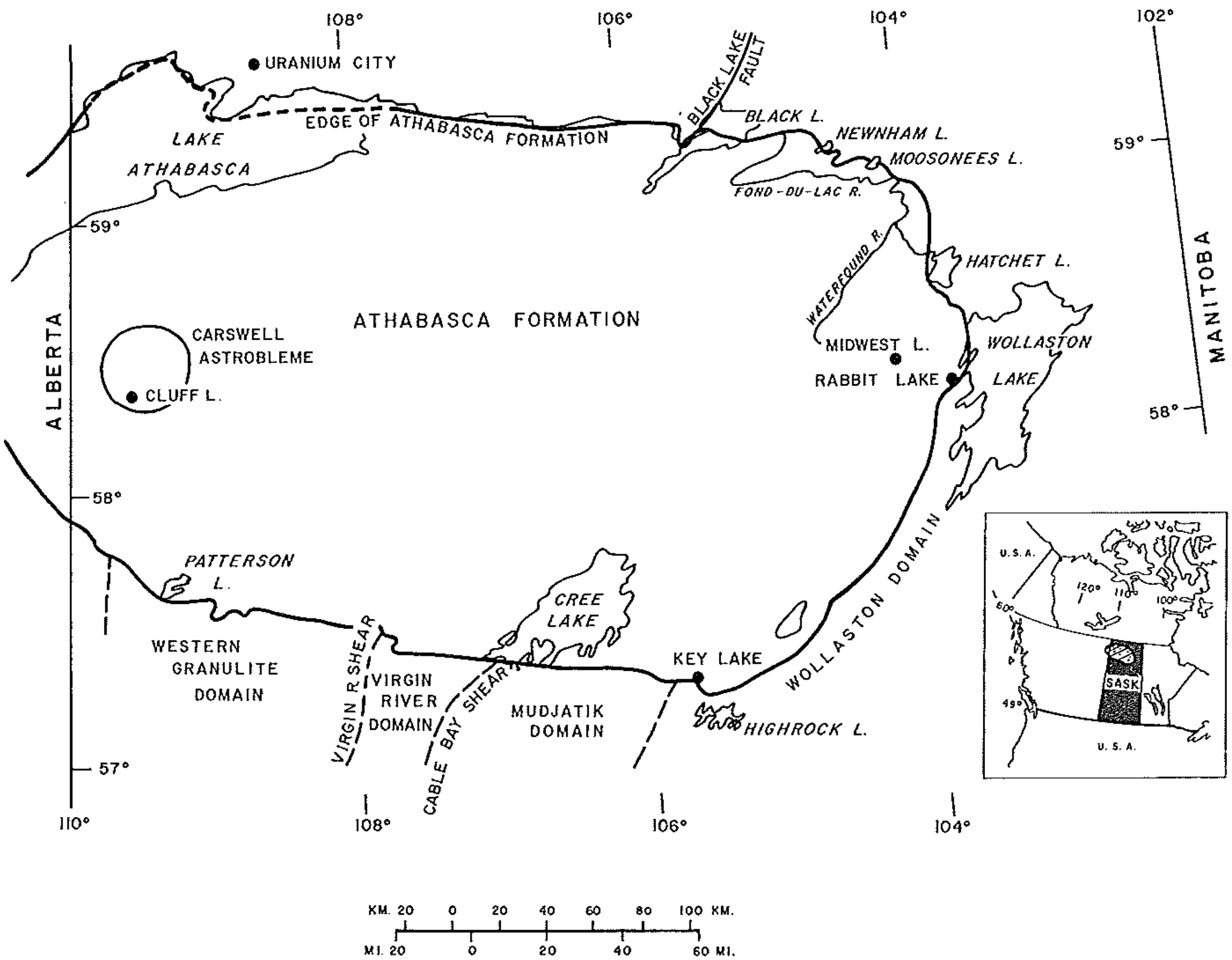

FIGURE 1. Location Map: Athabasca Formation, Northern Saskatchewan.

geology of the Athabasca Formation. Aeromagnetic maps were compiled by Agarwal (1962, 1965a, 1965b), and a seismic study was published by Hobson and MacAulay in 1969. At present a four-year detailed study of the edge of the formation, initiated by the Saskatchewan Geological Survey in 1975, is under way and progress is reported on the geology by Ramaekers (1975, 1976, 1977); on the geochemistry by Dunn (1976, 1977); seismic studies by Suryam (1976, 1977); and in a review by Ramaekers and Dunn (1977). This paper represents an interim report.

GEOLOGY

The Athabasca Formation or Sandstone consists mostly of unmetamorphosed fluviatile sandstones, characteristic of a fast-flowing braided stream environment. Thin clay bands yield a Rb/Sr isochron of 1350 ± 50 m.y. which dates the formation as Neohelikian (Ramaekers and Dunn, 1977). Subjacent Archean and Aphebian (>1700 m.y.) metasediments, ranging from greenschist to granulite facies, and with a regolithic surface locally over 200 m thick, unconformably underlie the Athabasca Formation and constitute the crystalline basement.

Conglomerates usually comprise the basal sediments of the Athabasca Formation. These are overlain by the dominant quartz sandstone, weakly to strongly cemented by quartz and hematite, and containing minor amounts of kaolinite and illite. Abundant bedding features help interpret paleocurrent patterns, and indicate numerous disconformities against which the oxidation and diffusion phenomena of Liesegang rings outlined by reddish hematite or limonite frequently terminate.

GEOCHEMICAL STUDIES

SAMPLE COLLECTION

Trace metals are concentrated in lake sediments (primarily lake centre oozes) and in view of the high density of lakes in the area, these sediments are chosen as the main source materials for outlining and interpreting dispersion patterns.* Sample density is at a minimum of one sample per 7 km^2, or much denser in regions of particular interest. This study is based upon nearly 4000 samples; 3000 of which were collected on a regional basis, and 1000 from detailed sampling.

ANALYTICAL TECHNIQUES

Uranium analyses were performed by activation/delayed neutron counting by Atomic Energy of Canada. Atomic absorption spectrophotometry was used for the determination of Cu, Ni, Pb, Zn, Co, Fe, Mn, Mo, V, Cr, Ag, Cd, Ba, Sr, and As. The geochemistry laboratories of the University of Regina and the Saskatchewan Research Council conducted the work, and close cross-checking of the laboratories has been maintained. Ag, Cd, Ba, Sr, and As are not included in the data analysis, since not all chemical analyses have been received. Water samples were taken at selected sites for analysis of U by fluorometry, and F^- using a selective ion electrode.

DATA HANDLING

The 50,000 to 60,000 items of lake sediment are divided into regional populations. Two main categories are recognized; lakes situated on the Sandstone, and lakes situated on the crystalline basement. Further subdivision is on the basis of lithostructural domains adjacent to the edge of the Sandstone. These domains have been established only for the southern half of the Precambrian Shield (Sibbald *et al.*, 1977). The less-understood area to the north of the Sandstone is subdivided here primarily on the basis of dominant basement lithologies, in order to provide a preliminary basis for grouping geochemical populations (Figure 2):

- Area 1: Black Lake to just east of Moosonees Lake: mainly felsic gneiss;
- Area 2. East of Moosonees Lake to Hatchet Lake: felsic gneiss with medasediments (Whitaker and Pearson, 1972);
- Area 3. Hatchet Lake to southern Wollaston Lake: northern portion of the Wollaston domain, comprising gneisses, schists, calc-silicates and metavolcanics;
- Area 4. Southern Wollaston Lake to the southernmost extension of the Athabasca Sandstone; southern portion of the Wollaston domain, comprising pelitic schists and gneisses;
- Area 5. Cree Lake area: felsic gneisses and thin pelitic supracrustals of the Mudjatik domain;
- Area 6. Virgin River area: schists, gneisses, amphilolites, calc-silicates and possible metavolcanics of the Virgin River domain;
- Area 7. Patterson Lake area: granulite facies gneisses of the Western Granulite domain.

Basic statistics for these regional subdivisions of geochemical populations are given in Table 1. Sampling is incomplete in the Virgin River domain, and the lakes sampled are on the gneissic rocks comprising the eastern two-thirds of the domain. No samples have been collected yet from lakes on the basement in the Patterson Lake (Area 7) region.

Cumulative frequency histograms and chi-square tests show that only loss on ignition (LOI), Zn and Cr commonly exhibit distributions approaching normality. The skewed distributions of the other elements indicate that a log transform of the data should be conducted prior to the generation of correlation coefficients and R-mode factor analysis matrices. The factor analysis chosen is the orthogonal varimax rotation of a principal component matrix (Kaiser, 1958; Spencer, 1966), followed by the generation of factor score coefficients. The rotated matrix is the stage considered here for interpretation of elemental suites. The eigenvalue cut-off is taken at 0.5 (cf. Spencer, 1966) and factor loadings below 0.3 in the varimax rotated matrix are disregarded. In factor analysis studies of geochemical data factor loadings down to 0.2 are commonly interpreted (e.g. Hitchon *et al.*, 1971); Cameron and Ballantyne (1977) adopted 0.25 as the minimum value considered; in the experience of one of us (CED) 0.3 is a more restrictive and useful limit.

*About 2000 till samples collected near the eastern margin of the Sandstone, from Black Lake in the north to Virgin Lake in the south, provide an additional and effective medium for outlining mineralization, but are excluded from the present considerations.

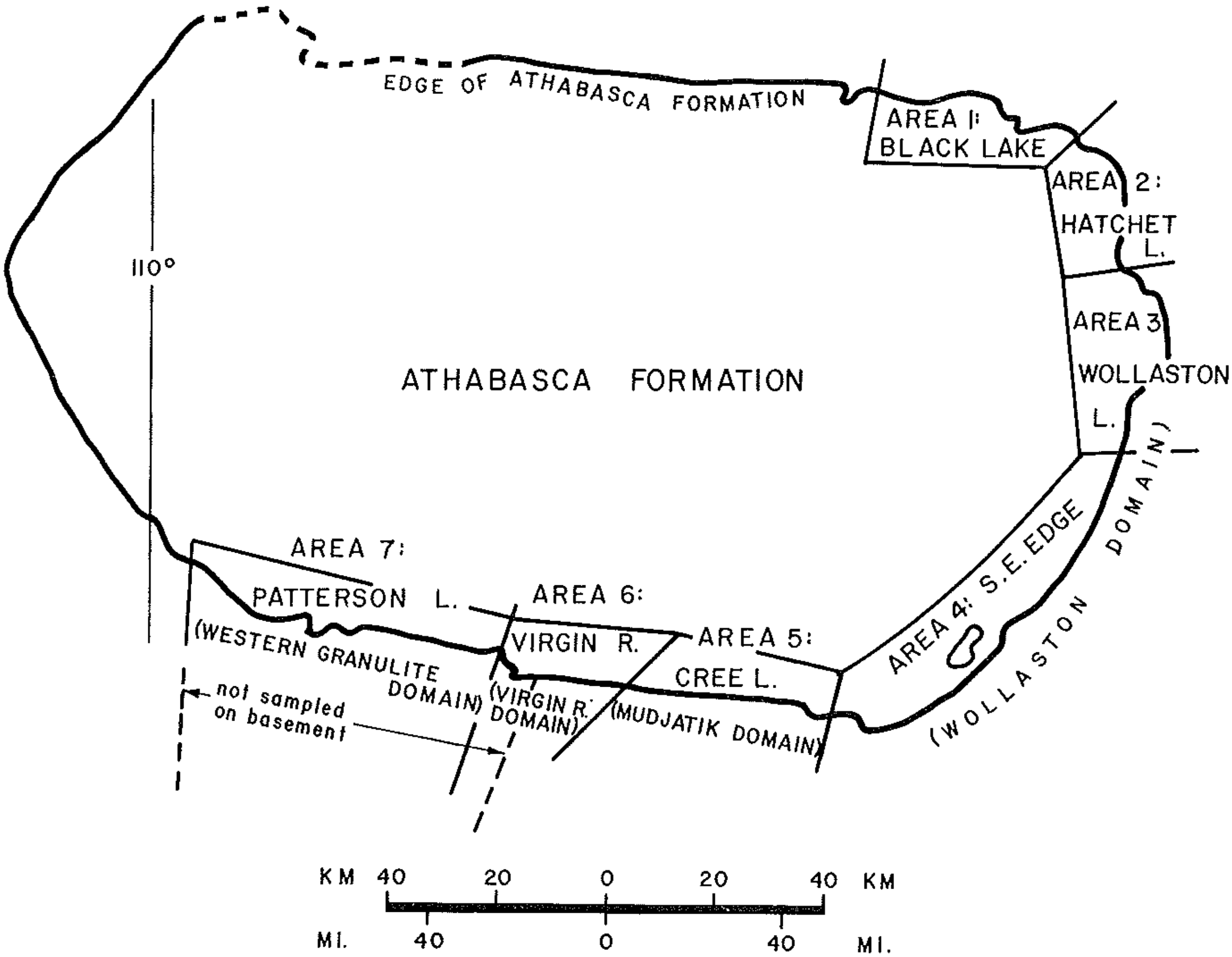

FIGURE 2. Areas of the Athabasca Formation Margin Selected for Subdivision of Lake Sediment Populations.

DATA ANALYSIS RESULTS

The data (Table 2) shows unusually high U, Ni and Co concentrations in Area 4, reflecting dispersion from the Key Lake ore bodies. Lakes on the basement in Area 1 have a geometric mean concentration of U equal to that of the Key Lake area, and higher mean Ni, Cu and Zn values than elsewhere around the Sandstone. No ore body has been found in Area 1, despite the good potential. In Areas 2 and 6 the high U values are not all isolated and have associated anomalous trace metal concentrations, implying possible existence of ore bodies. Data from Area 3 do not include values from Rabbit Lake (up to 1110 ppm U), and at first sight the U potential of the region looks low. However, broad anomalies do exist, particularly on the Sandstone, emphasizing that whereas regional data analysis gives useful information, careful examination of metal values at individual sample sites remains of fundamental value in assessing the more subtle indicators of mineralization.

In order to reduce to manageable proportions the large volume of data obtained from the factor analysis of each sub-set of data, a summary is given (Table 2) of the elemental suites associated with urànium. Full details will be published later in a Saskatchewan Department of Mineral Resources report.

Table 2 shows a prominent association between U and V, particularly in the Sandstone environment. Lakes on the basement, however, show a dominant association of U with Ni, and/or Cu. The association of U with Mo is restricted to the northern region, and

TABLE 1

STATISTICS FOR ELEMENTS IN LAKE SEDIMENTS FROM LAKES SITUATED NEAR THE MARGIN OF THE ATHABASCA SANDSTONE

Area No.	Location	n	U ppm Max.	U ppm Mean	U ppm S.D.	U ppm Med.	Ni ppm Max.	Ni ppm Mean	Ni ppm S.D.	Ni ppm Med.	Cu ppm Max.	Cu ppm Mean	Cu ppm S.D.	Cu ppm Med.	Co ppm Max.	Co ppm Mean	Co ppm S.D.	Co ppm Med.	Pb ppm Max.	Pb ppm Mean	Pb ppm S.D.	Pb ppm Med.	Zn ppm Max.	Zn ppm Mean	Zn ppm S.D.	Zn ppm Med.
1	Black Lake (S/stn)*	391	61	6.0	7	4.0	81	15	10	13	52	12	7	10	110	7	8	5	37	6	4	6	382	71	44	61
1	Black Lake (Bsmt†)	278	191	20.0	29	11.0	41	18	7	17	70	19	11	17	42	9	6	7	20	8	5	7	430	84	57	71
2	Hatchet L. (S/stn)	154	61	4.5	6	2.7	33	10	5	9	43	5	5	4	46	8	7	6	44	16	8	14	167	48	27	43
2	Hatchet L. (Bsmt)	101	197	10.0	21	4.5	22	12	5	13	33	9	6	9	35	9	5	8	45	15	7	13	141	58	28	58
3	Wollaston L. (S/stn)	305	20	2.5	2	1.9	46	10	6	9	24	6	4	6	45	10	8	8	52	10	10	7	223	67	36	58
3	Wollaston L. (Bsmt)	115	15**	4.3	3	3.7	32	7	7	5	42	5	6	3	48	9	8	6	55	13	11	12	142	45	29	39
4	S.E. Edge (S/stn)	304	29	2.0	3	1.5	220	13	20	10	32	7	5	6	70	14	10	13	27	7	6	6	177	58	30	57
4	S.E. Edge (Bsmt)	83	1787	164.0	350	11.0	638	62	121	21	29	6	5	6	93	18	18	13	25	5	5	2	239	62	46	47
5	Cree Lake (S/stn)	109	3	1.0	0.5	1.0	37	14	7	13	10	5	2	5	29	9	5	7	22	4	4	1	82	36	19	36
5	Cree Lake (Bsmt)	79	10	1.1	2	<1	57	19	11	15	58	13	10	10	44	11	7	8	14	7	3	7	239	64	45	53
6	Virgin River (S/stn)	313	6	0.6	1	<1	56	12	8	10	32	9	5	8	70	7	7	6	34	7	3	6	320	71	44	61
6	Virgin River (Bsmt)	218	52	2.7	5	1.0	77	17	11	15	56	14	9	12	54	12	10	9	20	8	4	7	247	70	36	63
7	Patterson L. (S/stn)	527	8	1.3	0.8	1.1	122	16	14	13	62	8	5	7	65	8	7	5	28	8	5	7	422	63	48	53

Area No.	Location	n	Fe % Max.	Fe % Mean	Fe % S.D.	Fe % Med.	Mn (ppm) Max.	Mn (ppm) Mean	Mn (ppm) S.D.	Mn (ppm) Med.	V (ppm) Max.	V (ppm) Mean	V (ppm) S.D.	V (ppm) Med.	Mo (ppm) Max.	Mo (ppm) Mean	Mo (ppm) S.D.	Mo (ppm) Med.	Cr (ppm) Max.	Cr (ppm) Mean	Cr (ppm) S.D.	Cr (ppm) Med.	LOI % Max.	LOI % Mean	LOI % S.D.	LOI % Med.
1	Black Lake (S/stn)*	391	33.5	3.4	5.2	1.2	2800	207	322	112	770	47	74	22	96	3	7	1	218	53	40	40	92	41	22	43
1	Black Lake (Bsmt)†	278	26.0	2.6	3.8	1.3	7900	435	767	196	396	27	43	16	25	3	5	1	968	49	69	32	71	32	17	33
2	Hatchet L. (S/stn)	154	8.1	1.5	1.7	0.8	1172	160	204	90	444	44	50	28	48	5	7	3	144	47	23	45	86	38	20	40
2	Hatchet L. (Bsmt)	101	7.1	1.3	1.5	0.8	7375	336	734	199	94	29	17	25	51	6	6	4	129	51	19	48	79	38	18	40
3	Wollaston L. (S/stn)	305	20.0	2.5	2.9	1.4	8959	554	1242	187	663	54	67	35	50	6	6	4	130	61	28	60	89	37	18	38
3	Wollaston L. (Bsmt)**	115	12.7	2.3	2.4	1.4	25160	1878	3358	554	140	29	21	22	37	4	5	2	124	36	30	25	80	19	17	14
4	S.E. Edge (S/stn)	304	22.9	5.7	3.4	5.2	10177	1190	1615	626	180	45	29	40	19	2	3	2	75	22	11	21	73	32	13	31
4	S.E. Edge (Bsmt)	83	20.2	5.8	4.3	5.2	10633	1255	1649	593	109	37	20	34	16	3	3	3	65	24	10	23	70	28	13	25
5	Cree Lake (S/stn)	109	30.4	2.9	4.7	1.3	2430	434	398	326	52	18	12	15	9	2	1	1	28	12	6	12	58	24	13	24
5	Cree Lake (Bsmt)	79	16.0	4.1	5.1	1.8	10532	527	1284	123	120	18	18	14	7	2	1	1	162	51	31	43	89	39	18	41
6	Virgin River (S/stn)	313	21.0	2.6	5.0	0.5	1900	113	153	77	192	25	32	14	10	1	1	1	162	51	29	44	92	48	19	50
6	Virgin River (Bsmt)	218	24.0	5.1	6.1	1.3	54000	606	3665	134	392	34	45	16	38	1	3	1	184	48	32	38	85	44	16	43
7	Patterson L. (S/stn)	527	53.7	4.7	8.6	0.8	4985	225	572	55	435	20	28	13	14	1	2	<1	not determined							

*(S/stn): sediment samples from lakes situated on the Athabasca Sandstone
†(Bsmt.): sediment samples from lakes situated on the crystalline basement
** sediments from the Rabbit Lake area (high (U) omitted because of contamination from mine workings.

n = number of samples; Max. = maximum concentration;
S.D. = standard deviation; Med. = median

TABLE 2

FACTOR ANALYSIS (VARIMAX ROTATION) SUMMARY OF ELEMENTS ASSOCIATED WITH URANIUM, ARRANGED IN ORDER OF DECREASING FACTOR LOADINGS. ELEMENTS IN PARENTHESIS INDICATE LOWER ORDER ASSOCIATIONS. ELEMENTS WITH LOADINGS <0.3 OMITTED.

Area No. (see Fig. 2)	Lakes on Athabasca Sandstone	Lakes on crystalline basement
1	V, U, Mo, [Ni] also Pb, Cu, U	U, U (in water) also Cu, Ni, [Zn, U]
2	U, Ni, Cu	U, Pb, [Mo]
3	F^-, U, [V] also Mn, Fe, Zn, Pb [U] also V, Mo, Ni, Co [U]	Cu, LOI, U, Zn, [Ni, Fe, Mo] also V, Mo [Fe, U]
4	U, Cr	U, Ni, Zn, Co
5	U, V, Cr, Ni, Zn, Cu, Co [Pb]	U, Cu, Ni [Co]
6	U, V	Cu, U, Ni, V, Co
7	U, V, Ni, Cu [Co]	no samples

Data included in the analysis were for U, Cu, Ni, Pb, Co, Fe, Mn, V, Mo, Cr, LOI, plus U in water for areas 1 and 2, and F^- in water for areas 2 and 3

that between U and Co is confined mainly to the south. Of the four populations for which F^- values in water were obtained (Areas 2 and 3), only the lakes on the Sandstone in the Wollaston Lake area show a marked affinity of U in sediments for F^-. A few dozen waters collected in the Key Lake and Cree Lake regions show low F^- concentrations (<50 ppb) with no detectable increase near uranium deposits. Data for U in water are included only in the factor analysis for Areas 1 and 2.

Along the southern edge of the Sandstone (Areas 5 and 7) uranium shows sympathetic associations with a large number of elements, attesting to the generally low background values of all elements sought and the lack of element associations in the secondary environment which might indicate mineralization.

Except for Area 3, which shows more complex patterns than other areas, the associations between U and LOI, U and Fe, and U and Mn are notably absent. This indicates that organic matter and the ferromanganese component do not play a significant role in scavenging uranium in this environment, and is in accord with the findings of Cameron and Ballantyne (1977) in the Rabbit Lake area.

The data analysis reveals several dominant trace-metal associations with uranium, but also demonstrates that no single suite of elements around the Sandstone is solely diagnostic of uranium mineralization.

CONTROLS OF GEOCHEMICAL PATTERNS

CHEMISTRY OF THE ORE BODIES

Pitchblende is dominant among the minerals constituting uranium ores marginal to the Athabasca Sandstone. The others represent only a small percentage of the ores; however, information released on the four major deposits discloses much diversity in the chemistry of the ore bodies. In the north, near Uranium City, Fe and Cu characterize the deposits (Beck, 1969); at Cluff Lake, where mineralization is within the meteorite-impact Carswell circular structure, U is in association with Fe, Au and Se (plus many other trace metal enrichments: Harper, 1978); only minor enrichments of a few trace metals occur at the Rabbit Lake deposit (Knipping, 1974); and at Key Lake there are complex associations of U with abundant Ni sulphides and arsenides, Co, and some Zn (Watkinson *et al.*, 1975). These diverse mineralogies may be expected to produce different geochemical assemblages in the secondary environment.

CRYSTALLINE ROCKS ADJACENT TO AND INTRUDING THE SANDSTONE

Basement rocks comprise mainly felsic and pelitic gneisses, locally schistose and graphitic, and a small percentage of calc-silicates. Anatexis has produced local pegmatitic segregations relatively enriched in uranium. Diabase dykes intrude the Sandstone, particularly in the Cree Lake area; here fused pink Athabasca Sandstone (Ramaekers, 1977) and a radiometric date of 1230 m.y. from a dyke (Burwash *et al.*, 1962) provide conclusive evidence that igneous activity took place after deposition of the Sandstone. Aeromagnetic linear anomalies suggest that other dykes may exist beneath the Sandstone. These dykes could have acted as traps for U being transported through the Sandstone.

Quantitatively, the Aphebian and Archean basement is strongly dominated by rocks of granitic composition, so that trace elements of granitic affinities might be expected to comprise the main trace metal suites in lake sediments. However, the basic intrusive event may have introduced appreciable quantities of elements characteristically associated with basic rocks—Ni, Cu, Co and V. Munday (1978) observed that graphitic pelites at the base of the Wollaston Group carry uraninite in felsic segregations and biotitic pegmatites. U may have been leached from these rocks during the development of the pre-Athabasca regolith, and may have been concentrated in pockets and veins by normal weathering processes. Alternatively, or perhaps in addition to the above process, the igneous event of basic dyke intrusion may have had immiscible uraniferous volatiles associated with it; it may have generated sufficient heat to remobilize U from the uraninite segregations, driving it ahead of the hot intruding rock into the Sandstone; from whence the U has since been redistributed and concentrated as pitchblende deposits. Circular structures apparent from aerial photographs could be reflecting diatremes associated with this igneous event. It is noteworthy that dykes are frequently found in the general vicinity of U ore bodies, e.g. west of Key Lake, near Cluff Lake and near Midwest Lake. En route to suitable depositional sites U has become associated with other metals. The secondary environment is now reflecting these metal associations.

CARBONATES

Aphebian calc-silicates are present locally south of Key Lake (Baer, 1969); in the Virgin River area (Wallis, 1970); and on the western side of Wollaston Lake (Fahrig, 1958; Wallis, 1971). At Rabbit Lake the ore is associated with dolomite, and calc-silicates form part of the hanging-wall of the reverse fault-bounded U ore (Hoeve and Sibbald, 1977). Calc-silicates and carbonates are not commonly found elsewhere adjacent to the Athabasca Formation, hence their role in controlling geochemical assemblages is local, but of potential importance.

Helikian carbonates are only known in the western part of the Athabasca Basin, occurring as dolomites, locally stromatolitic, in the vicinity of the Carswell structure.

PALEOCURRENT SYSTEMS

Figure 3 depicts paleocurrent directions measured on outcrops of the Athabasca Sandstone. On the basis of several thousand measurements three major deposystems have been identified (Rameakers, 1976, 1977). Poor exposures may preclude the possibility of examining contacts between these systems to see whether or not unconformities of any great magnitude exist; if they do there could be implications for further exploration of the basin interior in that they could be sites for unconformity-type U deposits. The contact zone between the Moosonees and Ahenakew deposystems lies close to the course of the Waterfound River, and has a corresponding geochemical expression in the overlying lake sediments, in that U, V, Mo, and Pb concentrations are generally anomalous ($>\bar{x} + 2\sigma$) along this trend. Similarly, the junction between the Ahenakew and Karras deposystems coincides with the Cable Bay Shear Zone (Ramaekers, 1977; Gilboy, 1977). Lakes on the basement near the shear zone contain anomalous concentrations of U, Ni, V, and Cu, with above-background concentrations of several additional elements. Geochemistry does not reflect the sub-Athabasca presence of the shear zone, which is projected below the western margin of Cree Lake—a large body of water which would tend to disperse trace metals.

The Waterfound River lies directly on strike as projected with the Cable Bay Shear Zone beneath the Sandstone. This, and coincident aeromagnetic lineations, make possible the hypothesis that the shear zone continues to the Waterfound River, and represents a major lineament that exercised control on the morphology of the deposystems, and has provided an important channel for the migration and local deposition of metal-bearing solutions.

GRAIN SIZE DISTRIBUTION

Because the basal Athabasca conglomerates are locally radioactive, an examination of grain size distributions of the Athabasca Formation has a potential bearing upon the metal concentrations expressed in lake sediments. Figure 3 illustrates the regional distribution of grain sizes at outcrops near the margin of the formation. Cored sections show that locally, conglomerates or grits are periodically encountered for several hundred metres up the succession. However, above the basal conglomerates it is the fine-grained silt and clay bands which typically have the highest concentration of U, presumably because of the much greater surface area offered by the clays for adsorption of ions. An important consequence of this observation is that the fine-grained material can be analyzed to help focus upon areas of U enrichment.

SUBSURFACE WATERS

The ephemeral nature of formation water movements makes their past role in metal transport and precipitation difficult to interpret. The complexity of truncated sequences of hematized Liesegang rings within the Sandstone reflects past changes in the water table. Evidence for formation waters having transported uranium comes from the presence of U in clay seams.

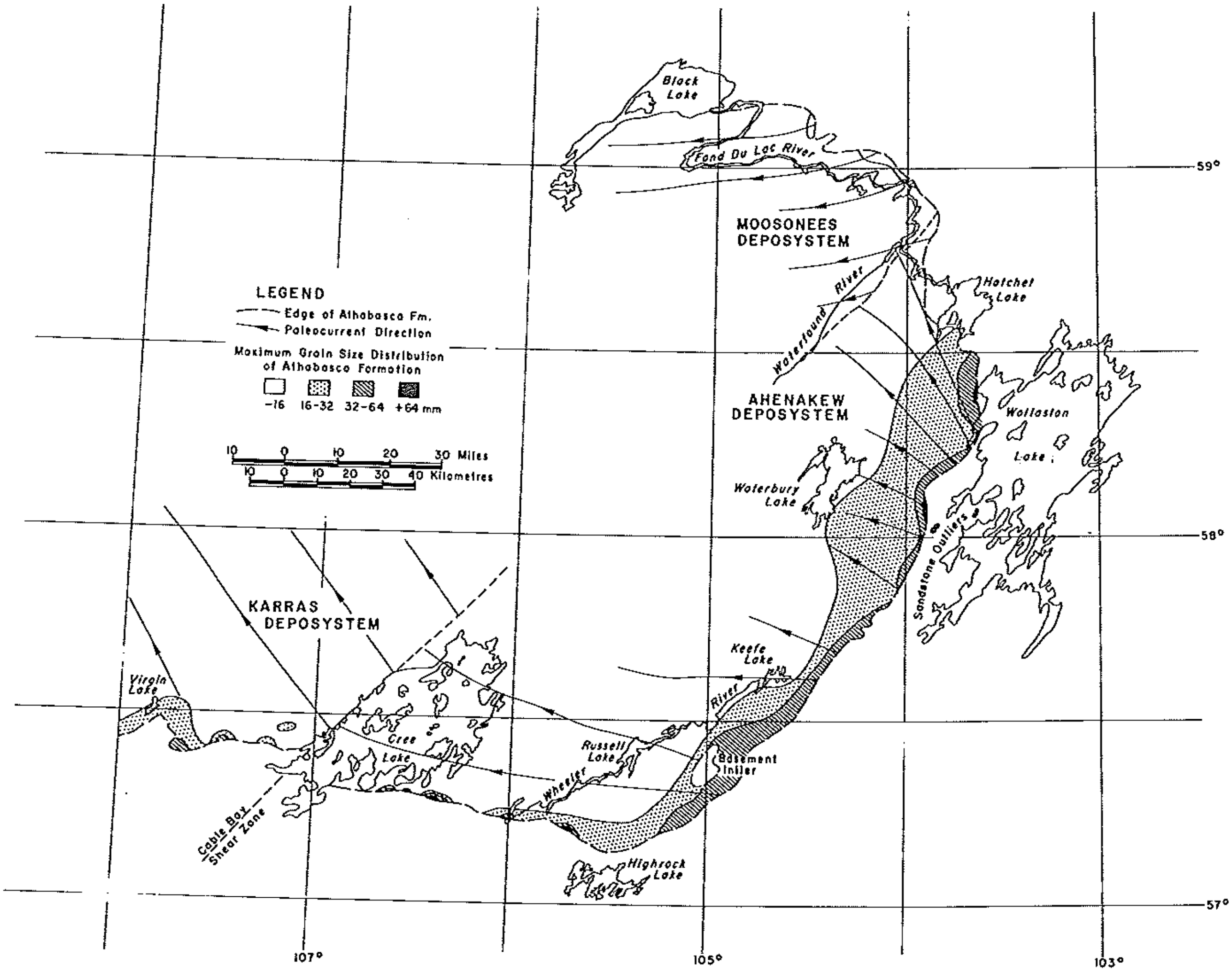

FIGURE 3. Athabasca Formation Grain Size Distribution and Paleocurrent Directions.

At present it seems that the pH of subsurface waters is playing an important role in the separation of ionic species. In the Key Lake area the Deilmann ore body, which lies at a maximum depth of 150 m (Dahlkamp and Tan, 1977), extends at least as far north as the shore of Key Lake, and groundwaters flow from the ore body into the lake. Key Lake does not, however, contain anomalous concentrations of U in waters or sediments, (all the U anomalies lie to the south), whereas Ni is present in the lake sediment in excess of 500 ppm (Ramaekers and Dunn, 1977). Parslow (1977) pointed to the relatively high pH of Key Lake as a possible cause of the fractionation.

The movement and physico-chemical condition of subsurface waters may prove relevant to the explanation of geochemical patterns in the surface environment and aid in locating metal deposits.

FAULTING

Faulting is increasingly evident as the area is studied more intensively. Aeromagnetic maps (Agarwal, 1962, 1965a, 1965b) indicate many linear features which are best explained as faults. In the field, faults are difficult to identify, particularly where they lie parallel to the strike. Major northeast-trending shear zones occur, the most prominent of which are near Virgin Lake, west of Cree Lake, and west of Black Lake. Uranium mineralization is associated with northeasterly faults at Key Lake and Rabbit Lake.

Another prominent direction of faults is northerly. Geochemical patterns in the Black Lake/Newnham Lake region (Area 1) suggest that U may be associated with north-trending faults. Figure 4 shows all U values greater than three times the medians for two

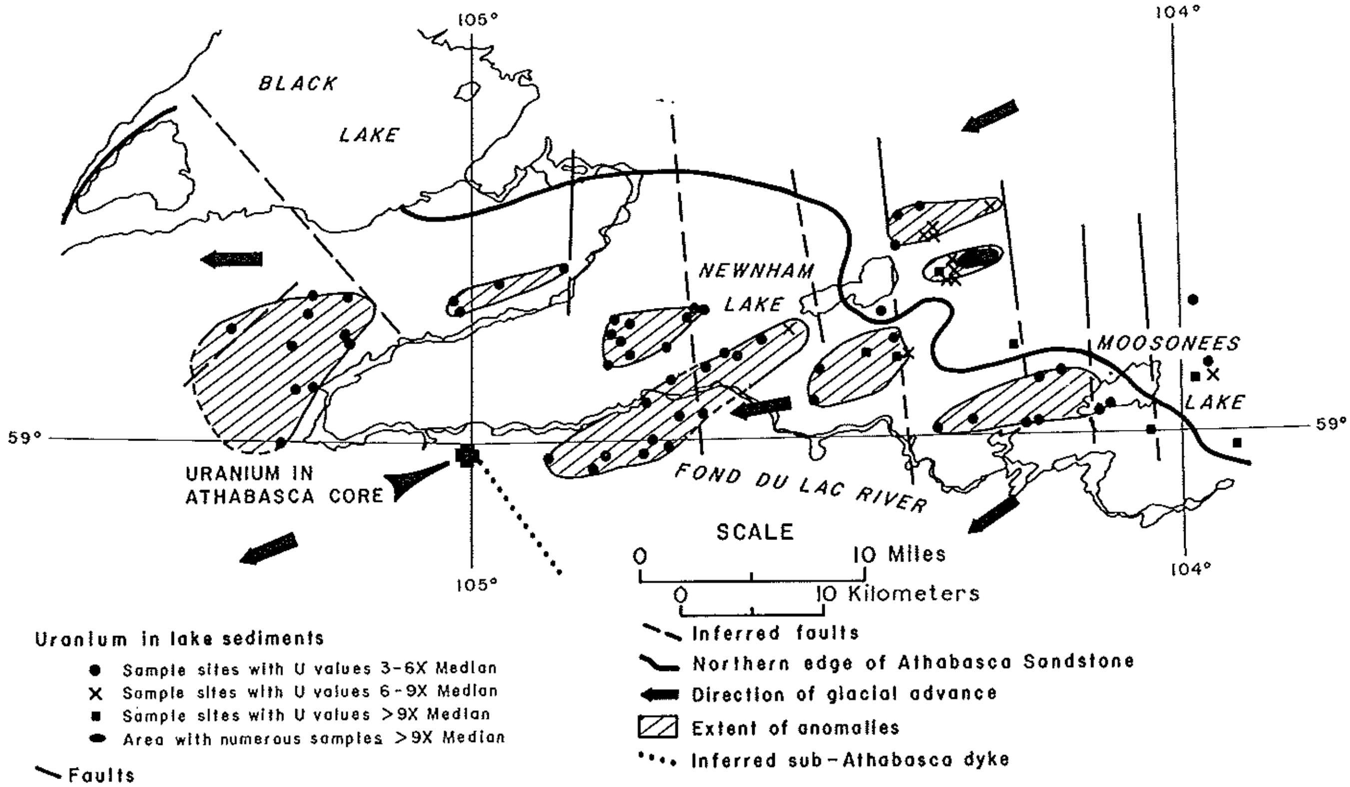

FIGURE 4. Uranium Distribution Patterns in Lake Sediments, and Their Relationship to Faulting and Glacial Smearing: Northeastern Edge of the Athabasca Formation

populations: sediments from lakes situated on the Sandstone, and lakes on the basement. Also plotted are known faults, inferred faults, and the direction of Pleistocene glacial movements. The picture which emerges indicates that U has migrated up fault zones and has been smeared down-ice. The few locations where anomalous U concentrations occur to the east of fracture zones can be explained by the direction of present-day drainage subsequent, in a geomorphological sense, to the main drainage pattern. More examples of the interplay between glacial smearing and modern drainage patterns are given in the section on glaciation.

Vanadium is the element most strongly associated with U in lakes situated on the Sandstone in this area. Figure 5 shows V concentrations greater than three times the median (lakes on the basement are omitted since the U:V association is weak). Comparison with the U distribution map emphasizes the strong association between the elements: V anomalies are of a similar intensity, but halos are slightly larger than those of U, and two areas of anomalous V occur in regions where U anomalies are not present. Worthy of note is the vanadiferous area at the northern end of the inferred dyke: it is coincident with a locality where U is found concentrated in a drill core from near the base of the Athabasca Sandstone at a depth of 250 m. The inference is that, similar to other well-documented sandstone-type U deposits, V may be a useful U-mineralization tracer. From our survey to date, areas with pronounced V anomalies are restricted to the Moosonees deposystem, although the U:V affinity is apparent elsewhere in the Sandstone basin where concentrations are lower.

GLACIATION

An example of U being smeared down-ice for 2 to 8 km from possible U sources has been presented. This deduction is based upon the premise that the source has been correctly identified. A more conclusive indication of the extent of glacial smearing is afforded by the example of the Gaertner and Deilmann U/Ni veins at Key Lake. Zimmer Lake lies 5 km southwest of the southernmost extension of the ore bodies, and itself extends for 6 km to the southwest. In Zimmer Lake, sediments are very highly enriched in U (up to 1787 ppm), Ni (638 ppm), Co (93 ppm), and Zn (239

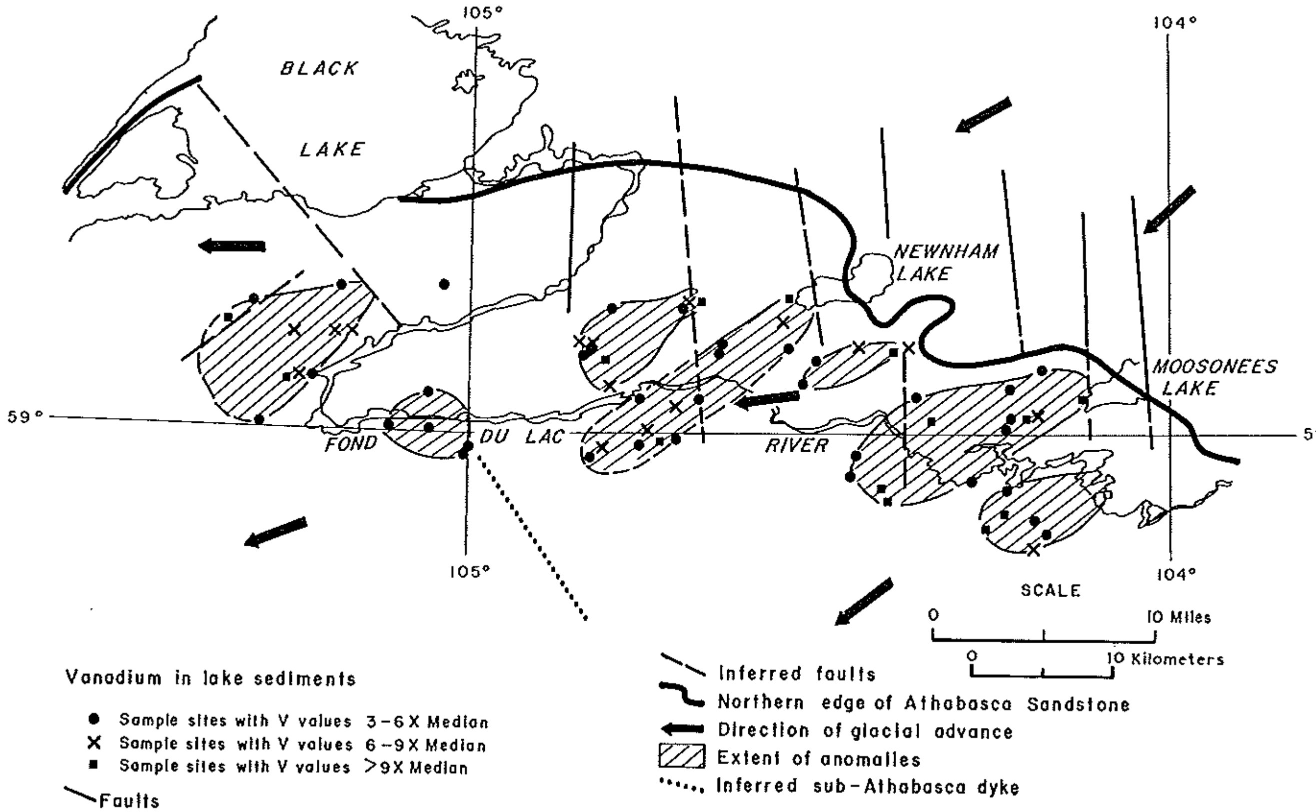

FIGURE 5. Vanadium Distribution Patterns in Sediments from Lakes Situated on the Athabasca Sandstone, and their Relationship to Faulting and Glacial Smearing: Northeastern Edge of the Athabasca Formation.

ppm). The limit of anomalous U values by glacial smearing cannot be defined because of the added contribution by U mineralization occuring 4 km southwest of Zimmer Lake (Ray, 1977). Thus, there is a minimum distance of 15 km of glacial dispersion. The dispersion pattern is complicated by the modern drainage system: Zimmer Lake drains southeastward into Highrock Lake which, relative to the general background of 4 ppm for basement rocks away from the ore zone, contains above background values throughout. Thus, the U dispersion extends at least 25 km southeastward from the ore body, giving a lake sediment halo of anomalous U on the order of 400 km^2.

Nickel, on the other hand, with a background value of 21 ppm, has a smaller halo of values greater than 3 times background extending 10 km down-ice, only a few isolated localities in the drainage system yielding anomalies of the same magnitude, yet above-background values extend across Highrock Lake. Cobalt closely follows Ni, but with lower magnitude anomalies. Zinc anomalies do not exceed three times background, but enhanced values exhibit the same distribution pattern as Ni and Co.

The situation at Rabbit Lake is different. Oozes of the drainage lake contain over 1000 ppm U (Dunn, 1976), but in the glacial dispersion halo to the southwest, values fall to 10 ppm in 10 km (Cameron and Ballantyne, 1977). Drainage is to the east through two small lakes into Wollaston Lake. Despite the sludge being disgorged by the mine workings, neither contamination nor natural dispersion of anomalous values of metals can be recognized where the waters enter Wollaston Lake, just 5 km away. Mine workings are, however, providing a clear secondary geochemical picture in the two lakes (which drain from Rabbit Lake into Wollaston Lake) of trace metal assemblages in the open pit. Mean and median concentrations of metals in sediments of Second Link Lake, situated 750 m from the open pit, are compared in Table 3 with values from sediments of the adjacent area (Area 3, Figure 2). Minor enrichments in Cu, Ni, Pb, Mo, and V occur, but U is the only metal to show appreciable concentration from the mine workings.

The example of Rabbit Lake serves to emphasize that near-surface U bodies may be expressed as only subtle anomalies in lakes down-drainage a few km

TABLE 3

MEAN AND MEDIAN VALUES FOR TRACE ELEMENTS IN SECOND LINK LAKE (DOWN DRAINAGE FROM RABBIT LAKE) AND AREA 3 (LAKES SITUATED ON THE BASEMENT IN THE WOLLASTON LAKE AREA). ALL VALUES IN PPM EXCEPT Fe AND LOI.

Element	Second Link Lake (n = 52) (data supplied by T. Sibbald, Sask. Geol. Survey)		Area 3 (n = 115), excluding immediate vicinity of Rabbit Lake	
	Mean	Median	Mean	Median
U	568	438	4.3	3.7
Cu	18	9	5	3
Ni	33	27	7	9
Pb	24	16	13	12
Zn	44	42	69	39
Co	13	13	9	6
Mo	15	13	4	2
V	52	39	29	22
Mn	200	216	1878	554
Fe	1.6%	1.5%	2.3%	1.4%
LOI	21.0%	18.0%	19.0%	14.0%

distant, and that suites of elements need to be considered. Thus although U is anomalous in lake sediments to the southwest of Rabbit Lake (i.e. down-ice), and U, Pb, and Ni values are only slightly above background to the south, Mo shows a six-fold concentration.

Another aspect of the effect of glaciation on geochemical patterns is the nature of the glacial material. A Pleistocene-mapping project currently under way (Schreiner, 1977) has included the southern periphery of the Athabasca Formation. Based upon Schreiner's interpretation of glacial deposits, three populations of lake sediments collected along the southeast edge of the Sandstone (Area 4, Figure 2) were taken to examine the effect the different types of glacial overburden might have on trace element patterns. Table 4 demonstrates that in this environment the tills and glaciofluvial sediments show no appreciable differences, but lacustrine sands tend to show slight enrichment in Zn, Co, Mo, V, Cr, Mn, and Fe. Parsons (1970) found glaciolacustrine clays in the Clay Belt of Ontario and Quebec to be impermeable to groundwater movement, thereby acting as an effective mask to mineralization. Around the edge of the Athabasca Sandstone, glacial material is generally sandy and porous, but locally glaciolacustrine clays are present (e.g. west of Wollaston Lake).

URANIUM IN THE ATHABASCA SANDSTONE AND ITS GEOCHEMICAL EXPRESSION AT THE SURFACE

A major aeromagnetic lineament, which is probably a sub-Athabasca dyke, extends southeastward from the Fond-du-Lac River (due south of Black Lake) for about 40 km. At the northern extremity of this feature cored section of Sandstone (mentioned in the section on faulting) has U concentrations up to 271 ppm in grits a little above its base, at a depth of 250 m. Two clay bands at 115 m and 150 m above the basement contain 40 ppm and 20 ppm U, respectively, thus providing support for the postulate that U-bearing solutions have passed through the Sandstone and precipitated U within it, not just as its base.

The latter observation raises the question as to what the geochemical expression of such mineralization might be in overlying lakes. At Midwest Lake (Figure 1) there was an announcement in March 1978 by

TABLE 4

COMPARISON BETWEEN TRACE METAL STATISTICS FOR SEDIMENTS FROM LAKES (AREA 4, ON THE ATHABASCA SANDSTONE) SITUATED WITHIN AREAS COVERED BY DIFFERENT GLACIAL SEDIMENTS. ALL VALUES IN PPM EXCEPT FOR Fe AND LOI.

Element	Fluvioglacial Sediments (n = 91)			Tills (n = 137)			Lacustrine Sands (n = 69)		
	Mean	Median	Std. Dev.	Mean	Median	Std.Dev.	Mean	Median	Std.Dev.
U	2.1	1.6	3.2	1.5	1.3	0.8	1.9	1.6	1.3
Cu	7	6	6	7	6	6	6	6	4
Ni	13	11	13	12	10	12	12	10	7
Pb	6	5	5	7	6	5	10	9	6
Zn	50	48	24	57	57	32	73	70	30
Co	12	9	10	13	13	8	18	18	10
Mo	2	1	1	3	2	2	4	3	3
V	33	32	19	46	42	31	62	54	33
Cr	19	18	8	22	20	12	27	24	13
Mn	1126	594	1453	846	481	1308	1814	1087	1903
Fe	5.8%	5.9	3.4	5.0	4.4	3.1	7.3	6.3	3.8
LOI	30%	29	12	33	31	15	32	32	10

Imperial Oil that medium to high intensity radioactivity readings have been encountered in 14 of 17 holes drilled pursuant to the discovery of radioactive boulders in 1968. Midwest Lake is situated 20 km in from the edge of the Sandstone where its thickness is 200 to 300 m. Lakes sampled in the area in 1976 showed U to be concentrated in sediments up to four times the background of 2 ppm, with anomalous values for V, Mo, Ni, Pb and Zn occurring with Midwest Lake and its vicinity. Possible explanations are (1) that the lakes are reflecting mineralized boulders in the glacial drift; (2) mineralization is present in the Sandstone close to the surface; or (3) ions are being drawn through the Sandstone from a considerable depth. The first two possibilities may constitute the complete answer: the third is, however, worthy of consideration and needs some amplification. In regions of discontinuous permafrost, such as that of northern Saskatchewan, thawed (talik) zones lie beneath the larger bodies of water during the winter months, and ions tend to flow by capillary action toward the unfrozen waters at the bottom of lakes. Levinson (1974) reports that, whereas many factors come into play, on average, for every 1°C. that bottom lake waters remain above freezing, ions can migrate from a depth of 60 m. Thus, for bottom lake waters at 4°C (the temperature at which water is at its densest) ions could migrate from a depth of 240 m. Shvartsev (1972) indicated that a porous sediment is necessary for development of the capillary process: in the Athabasca environment both the glacial material (for the most part) and the Sandstone are porous and permeable and fracture zones would be particularly suitable for ionic migration. Since this process takes place during the winter, it follows that metal concentrations would be greatest during the spring, and tend to dissipate in the drainage system during the summer months.

Thus elsewhere in the basin it could be expected that subtle geochemical anomalies would be present in lakes on the Sandstone situated up to 200 to 300 m above an ore body. The hypothesis fits the conditions at Midwest Lake, and may explain other anomalous regions, such as the junction between the Moosonees and Ahenakew deposystems.

CONCLUSIONS

Lake sediments are enriched in U near the ore deposits, but contain differing associated suites of elements: at Key Lake Ni, Co, and Zn are strongly associated with U in the secondary environment, whereas near the Rabbit Lake mine, Cu, V, and Mo have a weak association with U. Dispersion halos vary in size, from tens of km^2 at Rabbit Lake to about 400 km^2 in the Key Lake area.

R-mode factor analysis of lake sediment analytical data reveals the following regional variations in the suites of elements associated with U:

1. U and V association is the most dominant within sediments from lakes situated upon the Athabasca Sandstone;
2. U, Ni, and Cu associations predominate in sediments from lakes situated upon the crystalline basement;
3. Mo and U associations are apparent only in the northern region;
4. Co and U associations appear only in the south, particularly in the vicinity of the Key Lake U/Ni ore bodies;
5. fluoride in lake waters showed a marked sympathetic relationship with U in sediments in lakes on the Athabasca Sandstone to the west of Wollaston Lake. The relationship is not apparent elsewhere;
6. organic matter, Fe and Mn do not play an important role in concentrating U.

Of the many factors which control geochemical patterns the more important are:

1. the varied chemistry of the ore bodies;
2. the composition of adjacent and subjacent basement rocks, and the local presence of basic igneous intrusions;
3. Athabasca deposystems: junctions between three major deposystems are indicated by changes in paleocurrent directions, with coincident anomalous trace metal concentrations in overlying lake sediments;
4. grain size of the Athabasca Sandstone: basal conglomerates are locally radioactive, and clay bands locally concentrate U;
5. glaciation, which has masked deposits and redistributed metals; sediments from lakes situated upon three different types of glacial material (all underlain by Athabasca Sandstone) show tills and glaciofluvial sediments to have no appreciable differences in average concentrations of trace metals, whereas there is a slight enrichment of several metals where the glacial medium is lacustrine sands;
6. faulting is considered of major importance; U and V dispersion patterns in the northern area can be related to glacial smearing from possible fault sources.

Uranium occurs within the Sandstone and may manifest itself in lakes by capillary transfer of ions during winter months.

ACKNOWLEDGEMENTS

About half of the samples upon which this study is based were given to us by exploration companies. We are extremely grateful to the Saskatchewan Mining and Development Corporation, Eldorado Nuclear, Uranerz, and Urangesellschaft for their generosity in this respect, and permission to release some of the data.

We thank Dr. J. E. Christopher and Dr. G. R. Parslow for kindly reviewing the manuscript, and the Saskatchewan Department of Mineral Resources for permission to publish this paper.

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