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Exploration Geophysics for Intrusion-Hosted Rare Earth Metals

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Minerals Containing REEs Occurring in Economic or Potentially Economic Deposits: Some Rock Properties

Table 3: from Castor and Hedrick, 2006

Rock properties mainly from Mineralogical Society of America website: www.handbookofmineralogy.org

Mineral	Formula	REO wt%	Density g/cm³	Radioactivity	Magnetic Properties
Aeschynite	$(Ln,Ca,Fe,Th)(Ti,Nb)_2(O,OH)_6$	36	5.19	radioactive	magnetic
Allanite	$(Ca,Ln)_2(Al,Fe)_3(SiO_4)_3(OH)$	30	3.50 - 4.20	may be radioactive	
Anatase	TiO_2	3	3.79 - 3.97		
Ancylite	$SrLn(CO_3)_2(OH)\bullet H_2O$	46			
Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$	19			
Bastnasite	$LnCO_3F$	76	4.90 - 5.20		
Brannerite	$(U,Ca,Ln)(Ti,Fe)_2O_6$	6	4.20 - 5.43	radioactive	
Britholite	$(Ln,Ca)_5(SiO_4,PO_4)_3(OH,F)$	62	4.20		
Cerianite	$(Ce,Th)O_2$	81	• 7.195 highest	radioactive	
Cheralite	$(Ln,Ca,Th)(P,Si)O_4$	5	5.28	radioactive	
Churchite	$YPO_4\bullet 2H_2O$	44	3.26		
Eudialyte	$Na_{15}Ca_6(Fe,Mn)_3Zr_3(Si,Nb)Si_{25}O_{73}(OH,Cl,H_2O)_5$	10	• 2.74 lowest		
Euxenite	$(Ln,Ca,U,Th)(Nb,Ta,Ti)_2O_6$	<40	5.30 - 5.90	radioactive	
Fergusonite	$Ln(Nb,Ti)O_4$	47	5.45 - 5.80		
Florencite	$LnAl_3(PO_4)_2(OH)_6$	32	3.52		
Gadolinite	$LnFeBe_2Si_2O_{10}$	52	4.20 - 4.77 (non-metamict)		
Huanghoite	$BaLn(CO_3)_2F$	38	4.51 - 4.67		
Hydroxylbastnasite	$LnCO_3(OH,F)$	75	4.745		
Kainosite	$Ca_2(Y,Ln)_2Si_4O_{12}CO_3\bullet H_2O$	38	3.52		
Loparite	$(Ln,Na,Ca)(Ti,Nb)O_3$	36	4.60 - 4.89		
Monazite	$(Ln,Th)PO_4$	71	4.98 - 5.43	radioactive if Th-rich	paramagnetic
Mosandrite	$(Ca,Na,Ln)_{12}(Ti,Zr)_2Si_7O_{31}H_6F_4$	<65			
Parisite	$CaLn_2(CO_3)_3F_2$	64	4.33		
Samarskite	$(Ln,U,Fe)_3(Nb,Ta,Ti)_5O_{16}$	12	5.00 - 5.69	radioactive	
Synchisite	$CaLn(CO_3)_2F$	51	3.90 - 4.14		
Thalenite	$Y_3Si_3O_{10}(OH)$	63	4.16		
Xenotime	YPO_4	61	4.40 - 5.10		paramagnetic
Yttrotantalite	$(Y,U,Fe)(Ta,Nb)O_4$	<24	5.70		weakly magnetic

General density range: 3.26 - 5.90 g/cm³

Density range of some common crustal rock types: 2.60 - 3.30 g/cm³

□ thorium present
□ uranium present

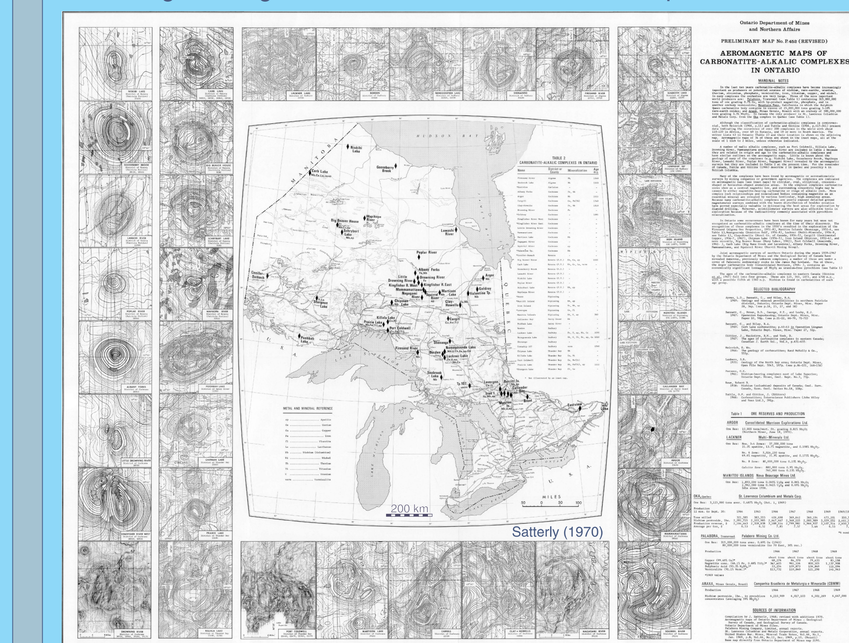
Introduction

Intrusion-related deposits of rare earth metals are characteristically associated with alkaline and carbonatitic intrusions, pegmatites and intrusive veins. Historically, intrusion-related rare earth metals have been discovered using a variety of exploration techniques and occasionally by chance. Geophysical methods have featured prominently. Here we present examples of geophysical signatures and case histories.

Critical to the success of any geophysical method is the presence of a sufficiently large contrast in the rock properties of the investigated geological units. Rock properties of 28 minerals that may contain rare earth elements (REEs) in economic or potentially economic deposits (Castor and Hedrick, 2006) are indicated in the figure to the left. Properties are mainly from the Mineralogical Society of America (2010).

Noticeable are the high densities of practically all of the minerals, with a general range of 3.26 - 5.90 g/cm³, significantly higher than that of common crustal rocks 2.60 - 3.30 g/cm³. Notable also are the facts that many minerals are radioactive, and practically all are non-magnetic. Based on these properties it seems that the gravity and radiometric techniques have the greatest potential for ***direct*** detection of REEs, but it must be recognized that such ***direct*** detection is very much dependant on the concentration of these minerals and the size of the deposit. It would appear, more commonly, that detection of rare earth metals, like detection of several other commodities, is achieved by first locating a prospective host for the mineralization. In this respect, as will be demonstrated following, the gravity, magnetic and radiometric techniques are all important exploration tools.

Aeromagnetic Signatures of Carbonatite-Alkalic Complexes in Ontario

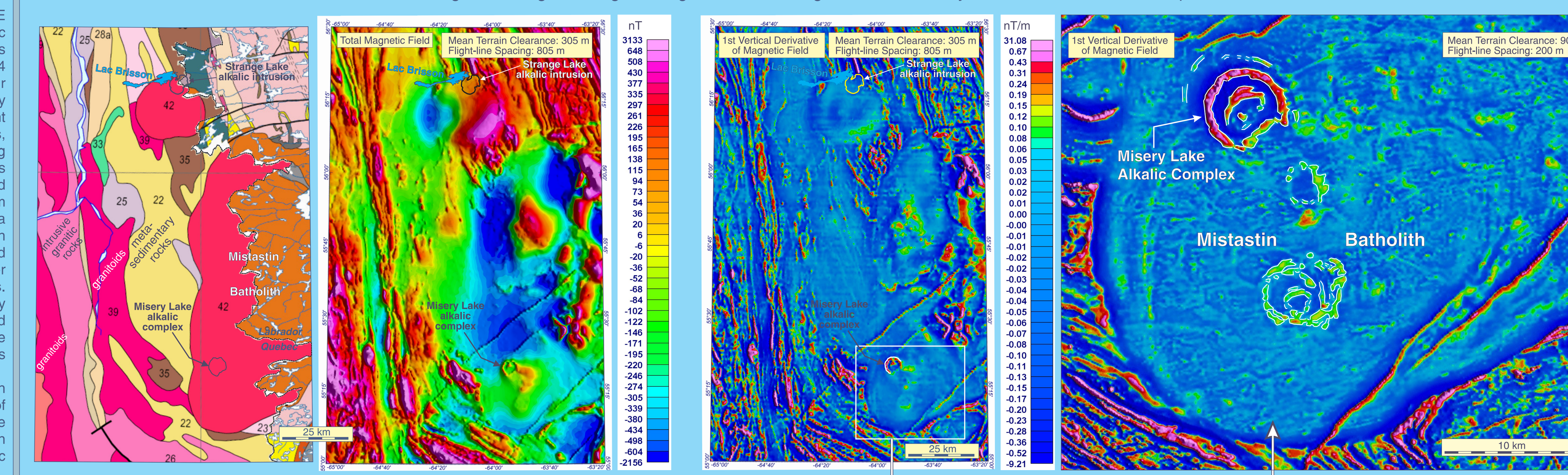


Magnetic Method in Exploration of Rare Earth Metals

In spite of the non-magnetic or weakly magnetic response of many of the REE minerals themselves, intrusive host rocks generally produce strong magnetic signatures. Satterly (1970) used mainly magnetic maps produced from Canada's national aeromagnetic program to compile the geophysical expression of 34 carbonatitic-alkalic complexes in Ontario (image to left), commenting on their potential for rare earths, and noting that many complexes had been found by "aeromagnetic or aeroradiometric" surveys by mining companies and government agencies. In the simplest complexes carbonatite cores coincide with magnetic lows, whereas surrounding annular highs might be associated with magnetite-bearing carbonatite or a ring of alkalic rocks. The most circular anomalies have diameters ranging from about 3 to 16 km, and amplitudes commonly attaining several thousand nT. A strong ring-like anomaly led to the discovery in 2007 of Quest Uranium Corporation's 6 km diameter Misery Lake rare earth alkali intrusive complex, a compositionally zoned ultramafic to granitic intrusion within the Proterozoic Mistastin batholith in northeastern Quebec (see geology map to right). The anomaly provided a target for grab sampling that yielded REE oxides and niobium oxide among other types of mineralization associated with magnetite-rich magmatic segregation layers. This magnetic intrusion is so strong and distinctive that it is obvious even on relatively low resolution national aeromagnetic data (see total magnetic field and corresponding 1st vertical derivative images to right), and is even more distinct on the image of 1st vertical derivative of high resolution data (far right). The latter indicates two other possible alkalic complexes south of the Misery Lake complex.

The Strange Lake alkalic intrusion is not associated with a prominent signature in images of the low resolution magnetic data, so perhaps is uncharacteristic in terms of magnetic expression. Higher resolution magnetic data are not available. The intrusion was in fact discovered by geochemical surveys (anomalous F and Pb in lake water and sediment), and is notable for associated prominent radiometric anomalies related to glacial dispersal trains, discussed in more detail below.

Geological Setting and Magnetic Signatures of Strange Lake and Misery Lake Alkalic Intrusive Complexes

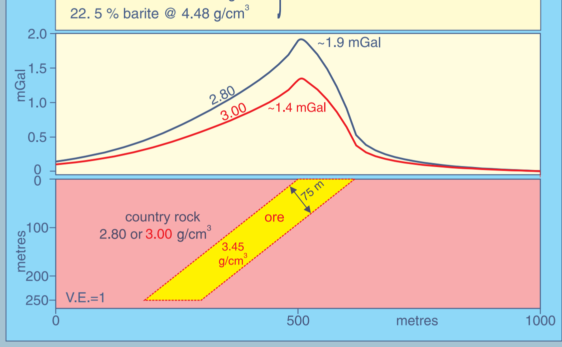


Theoretical Gravity Anomaly Mountain Pass, California, Bastnasite Ore Body

Castor and Hedrick (2006): The ore typically contains 10% to 15% bastnasite, 65% calcite or dolomite, and 20% to 25% barite.

Warhol (1980): Strike length of ore body is 750 m, thickness is 75 m and it dips 40° west.

12.5 % bastnasite @ 5.05 g/cm³
32.5 % calcite @ 2.71 g/cm³
32.5 % dolomite @ 2.86 g/cm³
22.5 % barite @ 4.48 g/cm³
= weighted mean density of 3.45 g/cm³



Gravity Method in Exploration of Rare Earth Metals

Physical rock properties of REE minerals indicate the gravity method to be a key technique in locating REE deposits, but public documentation of its implementation, apparently, is lacking. Until recently, also, gravity surveys capable of yielding data having sufficiently high resolution to effect detection have been carried out on the ground, a slow process not conducive to exploration of areas of any significant size. Seemingly, such surveys have been focussed on small areas after discovery of a prospective area by some other method.

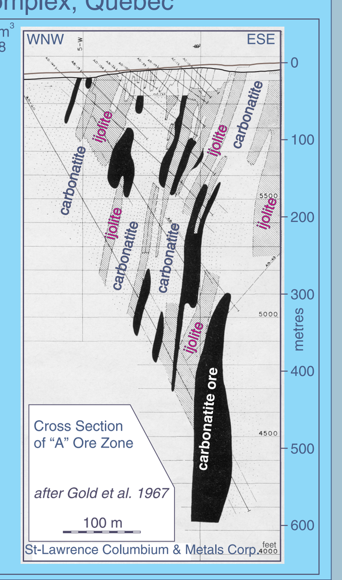
To the immediate left are shown theoretical gravity signatures for a bastnasite ore body hosted by the Mountain Pass carbonatite, California. The signatures are based on a description of the thickness and dip of a sheet-like ore body by Warhol (1980) and of its mineralogy by Hedrick and Castor (2006); the vertical depth extent of 250 m shown in the figure is assumed. Besides the high density of the bastnasite ore itself, the gravity signature is boosted by the presence of significant amounts of barite and to a lesser extent by the presence of dolomite. Compared to lower density country rock this ore body would produce a gravity anomaly of about 1.4 to 1.9 mGal amplitude (for assumed country rock density of 2.80 and 3.00 g/cm³, respectively). The gravity method, therefore, can be an important tool at the property scale.

The gravity method, given the high resolution data collected by modern airborne gravity meters, promises to be an important vehicle for detection of intrusions hosting rare earth metals. The figure below to the far left displays a cross section of an ore zone within the hosting Oka alkaline complex, Quebec, and density values for the alkaline and carbonatitic rocks, many of which fall in the range 2.84 - 3.09 g/cm³, compared to country rock values ranging from 2.70 - 2.75 g/cm³. This significant difference dictates that such host rocks could produce large gravity anomalies detectable by an airborne measuring platform.

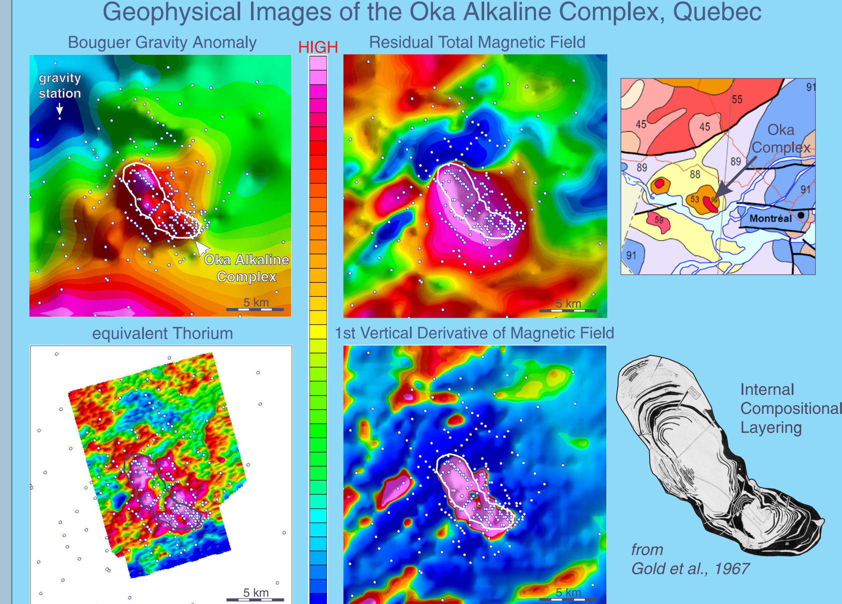
Below to the right a figure shows a Bouguer gravity anomaly closely associated with the Oka alkaline complex that attains an amplitude of about +15 mGal (Gold et al., 1967). Note also the strong residual total magnetic field anomaly and its 1st vertical derivative, and distinct equivalent thorium expression, that serve to demonstrate the viability of the magnetic and radiometric methods to discover such intrusions, further discussion of which is pursued in the right-hand two-thirds of the poster.

Rock Densities & Cross Section of Ore Zone at Oka Alkaline Complex, Quebec

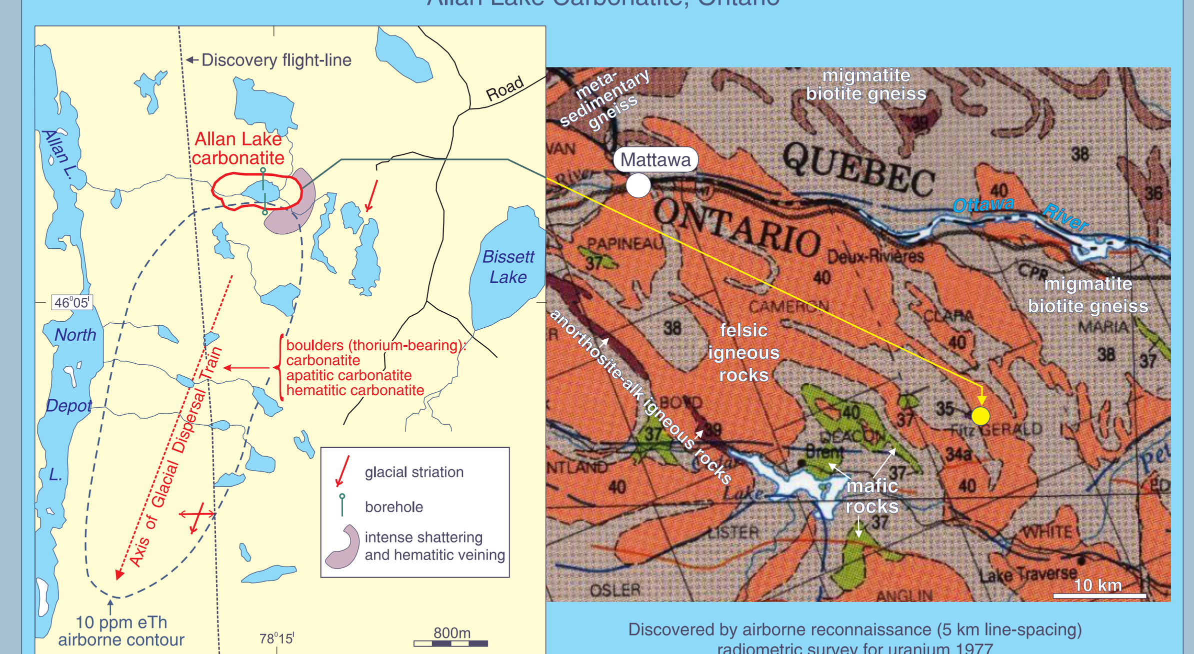
	Density - g/cm³
various tills and clay	1.90 - 2.38
late lamprophyre dykes	2.84
Alkaline Rocks	
alnoite	3.09
alnoite breccia	2.75
jacuparangite	3.14
melanite urtite, melteigite, & wollastonite-melanite ijolite	2.88
biotitized ijolite & biotite replacement rock	3.06
microijolite and ijolite	2.89
micourtite and juvite	2.70
okaite group	2.97
Carbonatites	
monticellite carbonatite	2.95
dolomite carbonatite	2.96
soda pyroxene carbonatite	3.09
coarse-grained carbonatite	2.88
very coarse-grained carbonatite	2.84
melilite carbonatite	3.02
niocalite carbonatite	2.90
magnetite-apatite carbonatite	3.41
Country Rocks	
anorthosite	2.74
fenite	2.70
gneiss	2.75
Carbonatite Ore	
carbonatite ore mined (using 11.5 cu.ft/ton, volume mined, & continuous weighings from conveyor belt)	2.79
carbonatite ore and waste from pit area	2.80



Geophysical Images of the Oka Alkaline Complex, Quebec



Allan Lake Carbonatite, Ontario



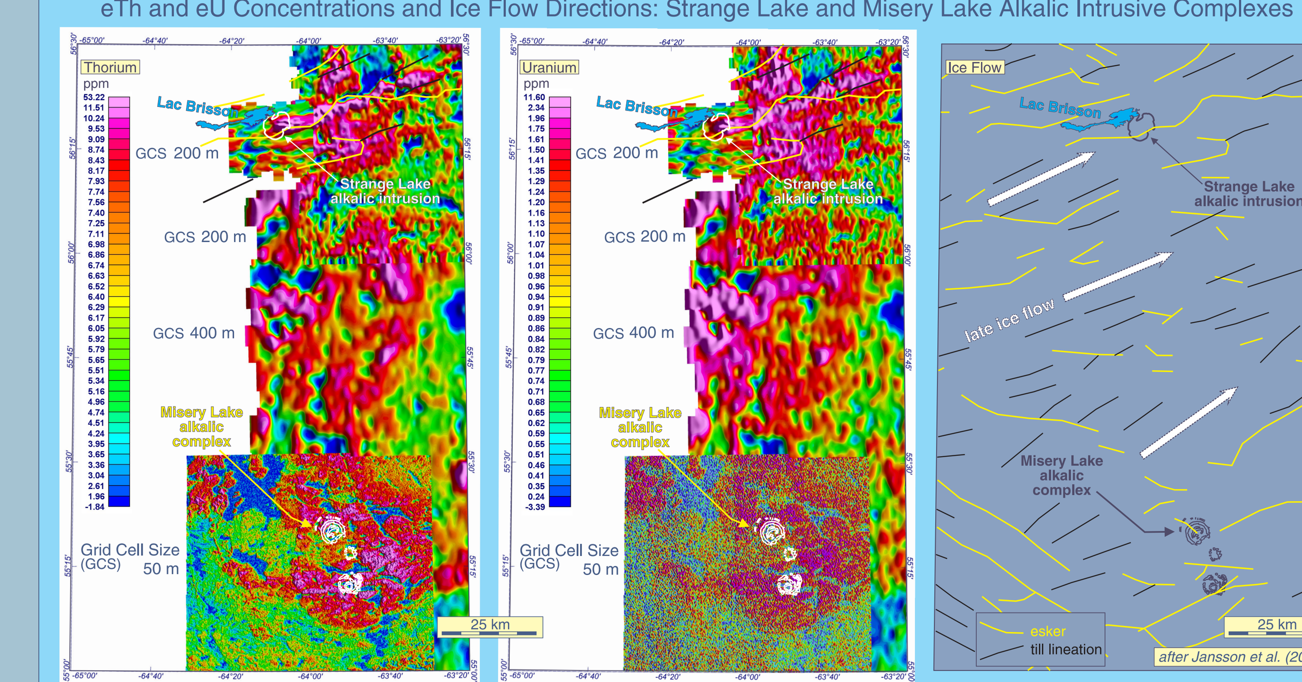
Discovered by airborne reconnaissance (5 km line-spacing) radiometric survey for uranium 1977

Radiometric Method in Exploration of Rare Earth Metals

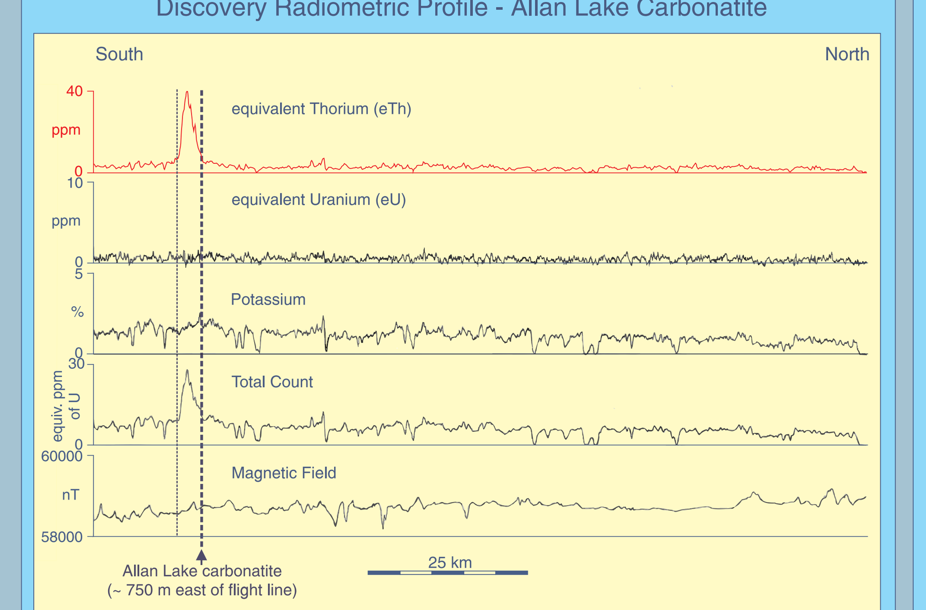
A classic example demonstrating the power of the radiometric method for targeting favourable intrusive hosts for rare earth metals is that of the discovery of the Allan Lake carbonatite, Ontario (figure to left). In spite of its small size (approximately 1000 m by 400 m), and being largely hidden beneath a lake and glacial overburden, it was discovered by a reconnaissance airborne gamma-ray spectrometric survey in 1977 under the Geological Survey of Canada's Uranium Reconnaissance Program (Ford et al., 1988). Line-spacing for this survey was 5 km, a much greater distance than either of the dimensions of the carbonatite, testifying to the search capabilities of the radiometric method. Attention was drawn to the carbonatite by a prominent equivalent thorium peak (see profiles to left and below) along one of the survey lines passing ~250 m to the west of the carbonatite. Note the absence of a corresponding peak in the equivalent uranium profile, and absence of a magnetic signature. Ground follow-up investigations detected a glacial dispersal train composed of Th-rich till containing Th-bearing carbonatite boulders. A refined radiometric-magnetic survey flown at 1 km and 0.5 km line-spacing along with various ground geophysical, geochemical and geological studies led to eventual drilling of a small unexposed carbonatite under a small lake. The equivalent thorium signature outlining the glacial dispersal train from the Allan Lake carbonatite is displayed in the image below. The example of the Allan Lake carbonatite demonstrates the utility of the radiometric method in Canada's glaciated environment, where glaciation offers a larger fingerprint of potential mineralization than would be observed in a non-glaciated environment. The Thor Lake REE deposit within the intrusive Blatchford Lake complex in the Northwest Territories was discovered by follow-up studies prompted by the presence of a strong equivalent uranium peak defined along a flight-line in a 1976 Geological Survey of Canada reconnaissance radiometric survey (Charbonneau and Legault, 1994).

In the case of the Strange Lake alkalic intrusion, already discussed from the magnetic perspective above, a post-discovery Geological Survey of Canada airborne survey flown at 805 m flight-line spacing outlined linear radiometric signatures extending at least 50 km down ice from the intrusion. These are prominently expressed in both equivalent thorium and equivalent uranium images shown to the right. The linear features extend ENE away from the intrusion, running parallel to eskers and glacial till lineations (Jansson et al., 2002). The direction of late ice flow associated with many of these glacial features was towards the ENE (Klassen and Thompson, 1993; Veillette et al., 1999). Glacial lineations and eskers near the intrusion are superposed on the radiometric images. The Strange Lake example again demonstrates the potential of the radiometric method for vectoring towards and targetting intrusive rare earth metal mineralization. Curiously enough a higher resolution radiometric survey in the area of the Misery Lake REE-bearing intrusion apparently does not define obvious down-ice radiometric signatures (images to right).

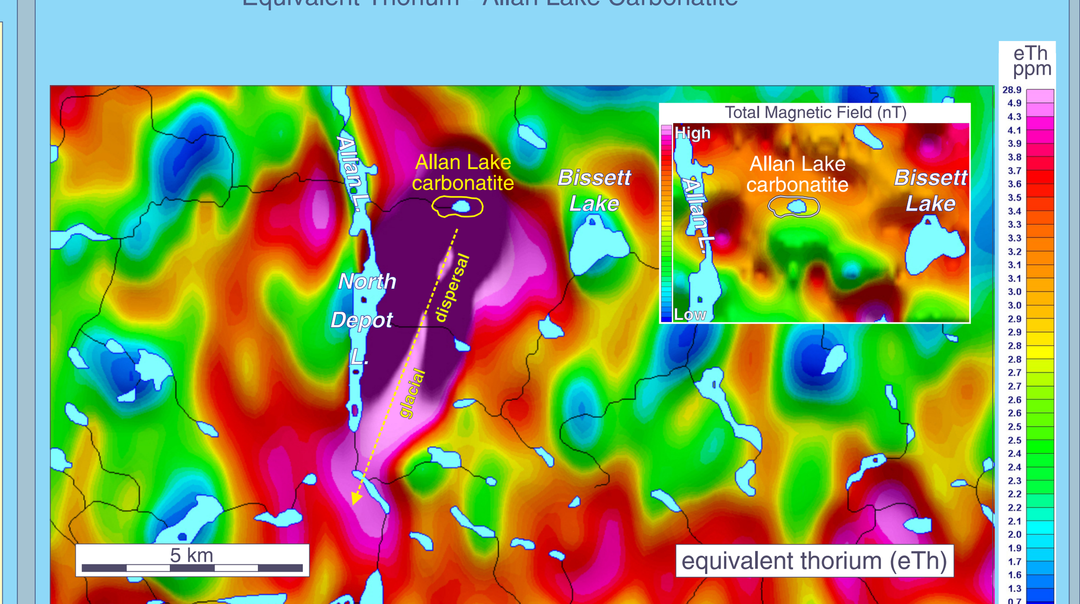
eTh and eU Concentrations and Ice Flow Directions: Strange Lake and Misery Lake Alkalic Intrusive Complexes



Discovery Radiometric Profile - Allan Lake Carbonatite



Equivalent Thorium - Allan Lake Carbonatite



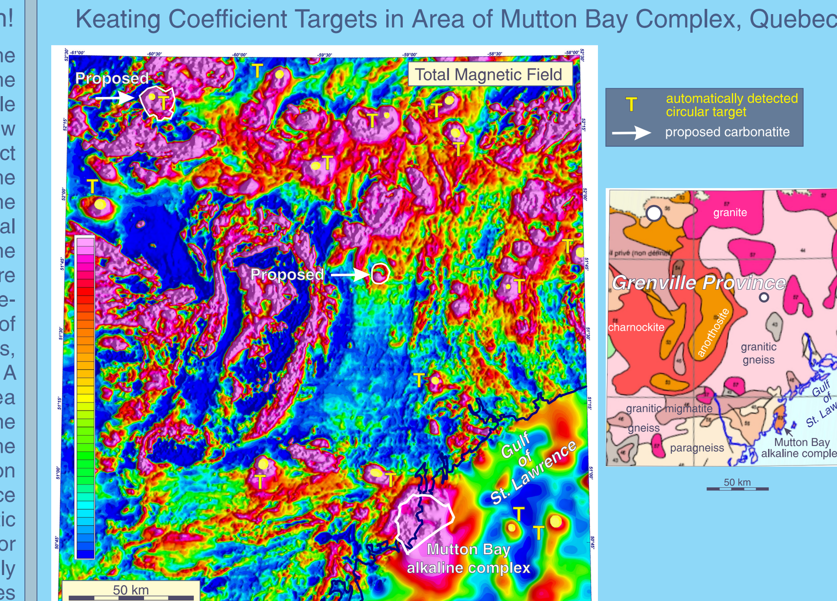
Now for Some Geophysical Exploration!

Examples have been presented to promote the effectiveness of geophysical techniques in the exploration for rare earth metals. A possible prospective area for such deposits is now examined using the magnetic technique to predict potential carbonatitic-alkalic host targets. The area lies within the Grenville Province along the north shore of the St. Lawrence River, a total magnetic field image for which is shown to the immediate right. The magnetic data were acquired by an airborne survey having a line-spacing of 805 m and mean terrain clearance of 305 m. The Mutton Bay alkaline complex (Davis, 1968) is located along the shoreline of the river. A regional gravity interpretation of the area conducted in the early 1970s delineated some major faults, support for which was sought in the aeromagnetic data. The occurrence of the Mutton Bay complex raised the possibility of the presence of other such complexes and possibly carbonatitic intrusions, which are commonly found near major faults. Two carbonatite intrusions were tentatively identified, and named the Circumference Lakes and Minipi Lake carbonatites (see both images to the right). Their signatures are strikingly similar to those of known carbonatite intrusions in Ontario (e.g. Nemogosenda) and Quebec (e.g. St. Honore) hosting rare earth metal mineralization.

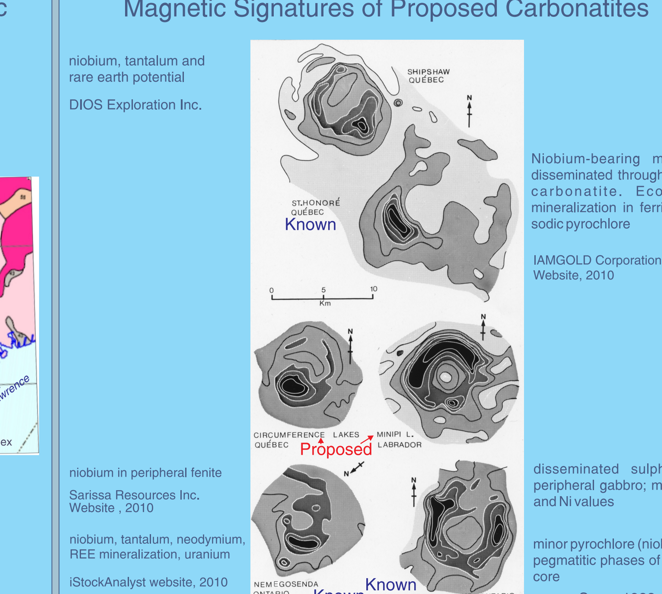
Recently an automatic method to identify circular anomalies in magnetic images (Keating coefficient of Keating, 1995) was applied to the magnetic image to the right above with the objective of identifying other circular magnetic anomalies possibly linked to carbonatite-alkalic intrusions. Twelve such anomalies were identified on land (labelled with a **T**), including the Minipi Lake example in the northwest corner of the area. The potential Cirumference Lakes carbonatite was not identified in this procedure, possibly because the morphology of the anomaly is not perfectly circular, having a somewhat hook-like shape with a central low. The predicted carbonatites are well expressed in a corresponding map of the 1st vertical derivative of the magnetic field, which also draws attention to some ring-like magnetic features.

Although originally designed to locate circular anomalies associated with kimberlite bodies, the Keating coefficient affords a rapid means of evaluating large areas for the presence of circular anomalies that may be prospective for rare earth metal mineralization. And the area near Mutton Bay would appear to hold considerable promise in this regard. Ground follow-up investigations in this part of the Grenville Province may lead to some exciting discoveries!

Keating Coefficient Targets in Area of Mutton Bay Complex, Quebec



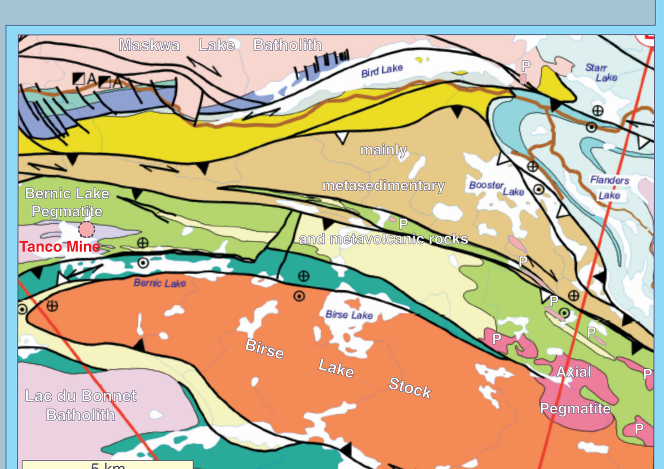
Magnetic Signatures of Proposed Carbonatites

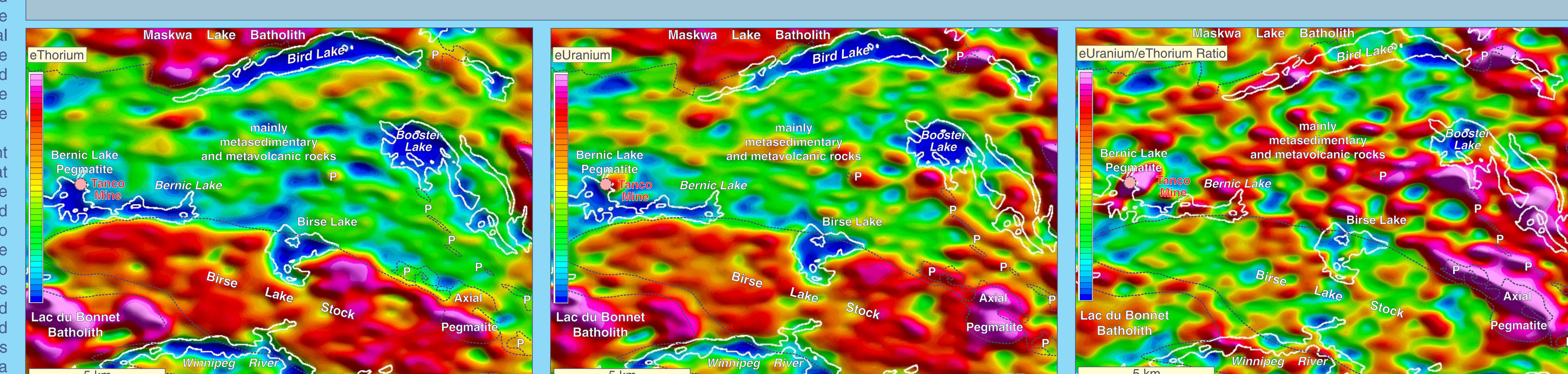


Radiometric Exploration for Pegmatite-Hosted Rare Earth Metals

Trueman (2010) notes that granitic pegmatites are significant hosts for many lithophile elements, citing the Tanco deposit in the Bird River Subprovince of the Archean Superior Province in Manitoba as an example. Its location is shown on the geological map (Gilbert et al., 2008) shown to the left, and on images of equivalent thorium and equivalent uranium concentration, and eUranium/eThorium ratio to the right. It is hosted by the Bernic Lake pegmatite. Several other pegmatite bodies are also shown on the various images, such as the large Axial pegmatite and smaller examples labelled **P**. Minerals that contain the lithophile elements and host pegmatites are considered by Trueman (2010), in general, not to be "good geophysical responders", although the magnetic and electromagnetic methods were considered to have some potential for outlining host rocks and favourable structures. Radioactivity was noted to be minimal in Li-Cs-Ta (LCT) pegmatites, the type of pegmatite hosting the Tanco deposit, in which uranium and thorium are very rare.

In spite of the reservations with respect to the radioactive technique, it is proposed that it could play an important role in exploration, if not for direct targeting then by helping to develop a more rigid exploration framework that includes mapping phases within possible parent granitic intrusions. The latter aspect is well displayed in the patterns of varying concentrations of thorium and uranium in the large intrusions such as the Birse Lake Stock and Lac du Bonnet Batholith (images to right). The thorium and uranium concentrations also draw attention to differences in the signatures of these two parameters within the portion of the Axial pegmatite lying within the Birse Lake Stock and that within adjacent country rocks, in this case mafic volcanic rocks. The eUranium/eThorium ratio image demonstrates the potential of the radiometric method for direct targeting. Note the strong signatures associated with the Axial and Bernic Lake pegmatites. By analogy, prominent anomalies near the east end of Bird Lake and southwest and southeast of Booster Lake, where small pegmatites have been mapped, may hold promise for rare earth metals. Reconnaissance airborne data in the Geological Survey of Canada's archives indicate that similar framework and possible direct targeting radiometric signatures extend east of this survey area towards the pegmatite-rich ground of the Separation Rapids area.





Conclusions

Geophysical techniques must be considered essential components of any exploration strategy for rare earth metals. The magnetic and radiometric methods, besides targeting hosts of rare earth metals, along with the gravity technique, can play a role in more focused exploration investigations once a target has been located. Modelling of anomalies provides structural and geometric information and a view into the third dimension. Modern airborne surveys now offer concurrent acquisition of magnetic, radiometric, electromagnetic and gravity data. Possession of such a suite of data significantly enhances the success for discovery of rare earth metal deposits.

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References

Castor, S.B. and Hedrick, L.B. 2006. Rare earth elements. *In* Industrial Minerals Volume, 7th edition, Kogel, J.E., Trivedi, N.C., Barker, J.M. and Krukowski, S.T., **eds.**, Society for Mining, Metallurgy, and Exploration, Littleton, Colorado, 769-792.
Charbonneau, B.W. and Legault, M.I. 1994. Interpretation of airborne geophysical data for the Thor Lake area, Northwest Territories. *In* Studies of Rare-Metal Deposits in the Northwest Territories, Sinclair, W.D. and Richardson, D.G., **eds.**, Geol. Surv. Can., Bulletin 475, 17-31.
Davis, R. 1968. Geology of the Mutton Bay Intrusion and Surrounding Area, North Shore, Gulf of St. Lawrence, Quebec. Ph.D. Thesis, McGill Univ., Montreal, Quebec, 321 p.
Ford, K.L., Delabio, R.N.W. and Rencz, A.N. 1988. Geological, geophysical and geochemical studies around the Allan Lake carbonatite, Algonquin Park, Ontario. Journ. of Geochem. Expl. 30, 99-121.
Gilbert, H.P., Davis, D.W., Duguet, M., Kremer, P.D., Mealin, C.A. and MacDonald, J. 2008. Geology of the Bird River belt, southeastern Manitoba (Parts of NTS 52L5,6). Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Geoscientific Map MAP2008-1, scale 1: 50 000 (plus notes and appendix).
Gold, D.P., Vallée, M. and Charette, J-P. 1967. Economic geology and geophysics of the Oka alkaline complex, Quebec. Transactions of the Canadian Institute of Mining, Volume LXX, 245-258.
Jansson, K.N., Kleman, J. and Marchand, D. 2002. The succession of ice-flow patterns in north-central Quebec-Labrador, Canada. Quaternary Science Reviews, 21, 503-523.
Keating, P. 1995. A simple technique to identify magnetic anomalies due to kimberlite pipes. Exploration and Mining Geology, 4, 121-125.
Klassen, R.A. and Thompson, F.J. 1993. Glacial history, drift composition, and mineral exploration, central Labrador. Geological Survey of Canada, Bulletin 435, 76 p.
Mineralogical Society of America. 2010. www.handbookofmineralogy.org.
Sage, R.P. 1988. Geology of carbonatite-alkalic rock complexes in Ontario: Killala Lake alkalic rock complex, District of Thunder Bay. Ontario Geological Survey, Study 45, 120 p.
Satterly, J. 1970. Aeromagnetic maps of carbonatite-alkalic complexes in Ontario. Ontario Department of Mines and Northern Affairs, Preliminary Map No. P452 (revised).
Trueman, D.L. 2010. Exploring for a Tanco type pegmatite. *In* International Workshop on the Geology of Rare Metals, Extended Abstracts Volume, November 9-10, 2010 Victoria, Canada. Simandl, G.J. and Lefebure, D.V. **eds.**, British Columbia Geological Survey, Open File 2010-10, p. 31.
Veillette, J.J., Dyke, A.S. and Roy, M. 1999. Ice-flow evolution of the Labrador Sector of the Laurentide Ice Sheet: a review, with new evidence from northern Quebec. Quaternary Science Reviews, 18, 993-1019.
Warhol, Warren N. 1980. Molycorp's Mountain Pass Operations, *In* Geology and Mineral Wealth of the California Desert, Fife, D.L. and Brown A.R., **eds.**, South Coast Geological Society, 359-366.