

Annual Report, 1982

THE GENESIS OF THE MINERALIZATION ASSOCIATED
WITH THE HEEMSKIRK GRANITE

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Work undertaken during 1982 has included field work, sulphur, oxygen and carbon isotope analysis, geochemical analysis of tourmaline and biotite, fluid inclusion thermometry and petrographic studies of greisen and the Globe mine mineralization. The results are summarised below.

Field Work:- Three weeks field work during the 1981-82 summer included mapping and sampling of all the mineralised areas associated with the Heemskirk granite, sampling of recent drill cores and bulk sampling of the Heemskirk granite for whole-rock geochemical analysis.

Sulphur Isotope Studies:- Sulphur isotope analysis of sulphide minerals in the Heemskirk granite mineralization have been used to:

- (1) determine the source of sulphur
- (2) deduce physicochemical conditions of the mineralization and their temporal and spatial variations.

The sulphur isotope compositions of forty-two representative samples including pyrite, sphalerite, galena, arsenopyrite, chalcopyrite, molybdenite, pyrrhotite have been determined (Table 1, Fig. 1 and 2). These include disseminated sulphides within the granite, local concentration of ore (e.g. Globe mine) and sulphides from the country rocks. Figure 3 shows the locations of the workings from which the samples were taken. The values (Table 1) show considerable variation between these three environments ranging from +1.8 to +17.1 per mil. Only small $\delta^{34}\text{S}$ variations are observed within each individual mineralised area, with each locality more or less characterised by its own sulphur isotope composition (Fig. 1). Although the mineralogy of the Sweeney's mine is complex there is no systematic variation in the $\delta^{34}\text{S}$ values of sulphides between the various generations. However, at Federation there is variation between different generations (e.g. the $\delta^{34}\text{S}$ values for disseminated pyrite in completely sericitised granite range from +5.5 to +6.5‰ but the values of pyrite in a later veinlet are around +12‰). $\delta^{34}\text{S}$ values for individual small prospects within the Heemskirk granite are similar to the Sweeney's mine. Figure 2 illustrates the frequency distribution of $\delta^{34}\text{S}$ values in the Heemskirk granite.

The determination of geologically unreasonable temperatures from coexisting sulphide pairs suggest disequilibrium sulphur isotope fractionation among coexisting minerals.

Discussion

Absence of sulphates and uniformity of values within deposits indicates derivation from reduced fluids. The abundance of sericite and alteration of feldspar indicates acid conditions so that the aqueous sulphur species is probably H_2S . The results thus indicate wide variations in the compositions of $\delta^{34}S_{H_2S}(aq.)$ between deposits. The high positive values are outside the likely magmatic range (Ohmoto and Rye, 1979) and may include sedimentary components; note the high $\delta^{34}S$ values in the sedimentary pyrite in the Precambrian country rocks.

Oxygen isotope studies: Almost five months of 1982 were spent on the redesign, calibration and trial runs on the silicate oxygen isotope line. The line is now producing consistent and accurate oxygen isotope analyses (precision $\pm 2\%$). Values are with respect to SMOW. To date twenty-one samples have been analysed for $\delta^{18}O$ contents, these include whole rock $\delta^{18}O$ analyses of both red and white granite, country rocks and altered granite. $\delta^{18}O$ values of the ^{fresh} red granite range from ~~+8.6~~ ^{+8.9} per mil SMOW (standard mean oceanic water). The $\delta^{18}O$ values of the ^{fresh} white granite are ^{similar} heavier, ranging from +9.6 to +10.8 per mil (Table 2). *now ~ 10-11*

but note depletion in $\delta^{18}O$ in altered rocks. - economic implications

The Heemskirk granite is unusual in that the initial ratio of $^{87}Sr/^{86}Sr$ is very high, ranging from 0.7197 for the red granite to .741 for the B-type white granite (Brooks, 1965). Fifteen samples from the granite and country rocks with known initial $^{87}Sr/^{86}Sr$ ratios were selected for the whole rock oxygen isotope analyses (samples from A.N.U.). *Brooks.*

A plot of whole rock $\delta^{18}O$ vs. initial $^{87}Sr/^{86}Sr$ (Fig. 4) suggest possible assimilation of country rocks by the Heemskirk granite. The positive correlation between initial $^{87}Sr/^{86}Sr$ and whole rock $\delta^{18}O$ values may indicate mixing of a magma derived from lower crustal rocks with upper crustal rocks of high oxygen isotope and high ^{87}Sr composition (i.e. Precambrian rocks). *now unlikely*

The $\delta^{18}O$ values in highly altered rocks (kaolinised) are lighter (around +6‰) than those of fresh granite. *- this is supported by 1983 J/H work.*

Carbon and oxygen isotope studies of siderite: Siderite occurs in altered and mineralised zones, generally as a late-stage mineral formed

after sulphides. Carbon and oxygen isotope analyses were performed on seven siderites from Sweeney's, Globe and Federation mine area (Table 3). The siderites have isotopic compositions in the range $\delta^{13}\text{C} = -8.9$ to -2.0 per mil PDB (Chicago Pee Dee Belemnite). The oxygen isotope values range from $+15.4$ to $+18.5$ per mil SMOW.

The significance of these isotopic values are not clear at this stage, but they are very similar to those of siderites at Renison (Patterson et al., 1981).

Geochemistry of biotites $(\text{K,Na,Ca,Ba})(\text{Mg,Fe}^{2+},\text{Fe}^{3+},\text{Mn,Ti}^{4+},\text{Al})_3(\text{Al,Si})_4\text{O}_{10}$
(OH,F,Cl)₂

Chemical analysis of biotite separates as well as probe analyses were used to study compositional and structural variations of biotites from the red and white granite and to provide some information about the chemical variations of the original magma (i.e. temperature, $f\text{O}_2$, $f\text{H}_2\text{O}$). Biotites comprise about 3-5% of the granite mineralogy and occurs as deep red-brown subhedral to euhedral flakes ranging from 0.1 to 3 mm in size. It is commonly interlocked with quartz and feldspar or as inclusions in K-feldspar, quartz and rarely plagioclase.

Biotites in the red granite are compositionally different from those in the red granite. Considering the different types of the red and white granite in terms of grain size (i.e. coarse, medium, fine) the biotite in each type of the red granite have higher Mg, Fe and lower Al than the biotite of the same grain size type in the white granites (Fig. 5). The Ti content of biotites in the red granite also appear to be higher than those of white granites. This may indicate a higher temperature of crystallization for the biotite in the red granite (Czmannske and Wones, 1973; Anderson, 1980; Forber and Flower, 1974). Biotites in each grain size type from the red and white granite are homogeneous possibly suggesting there was little variation in physicochemical conditions during crystallization of each granite type.

Chlorite: Most of the biotites in the rocks appear to have been chloritized to some extent and this is manifest in chemical analyses as higher H_2O and lower K contents compared with an ideal biotite composition. The F content of biotites also decreases as they become more chloritised. Figure 6 illustrates the fluorine content of biotites with respect to the degree of biotite alteration (i.e. K content). The fluorite which occurs in some of the altered granite may have formed from the fluorine released during biotite alteration. The biotites have a very high content of Rb

and Zr (up to 1300 and 1500 ppm respectively). The high content of Zr is possibly due to the zircon inclusions. The average content of tin is about 62 ppm. No correlation exists between the degree of alteration and the tin content of biotite.

It is hoped to use biotite geothermometry (i.e. K-feldspar-magnetite-biotite) to estimate temperature and fO_2 condition of crystallization.

Tourmaline geochemistry: Tourmaline separates and polished thin sections were used to study the colour-structure-composition relationships of tourmaline and the tourmaline-tin association. Generally tourmalines from the Heemskirk granite occurs in three settings, viz. quartz-tourmaline dykes, tourmaline associated with hydrothermally altered zones, and quartz-tourmaline nodules. Their colours in hand specimen vary from black to green or black-blue. In thin sections various shades of green-blue and yellow are observed. Pleochroism varies from pale to black green in green tourmaline, pale to dark blue in blue tourmaline and yellow to brown in yellow tourmaline.

Colour-composition relationships: Tourmalines in the Heemskirk granite are very Fe-rich (schorlite) with FeO_t contents ranging from 16-20 wt.%. There is a distinct relationship between colour and composition of the tourmaline. Green and blue tourmaline have low Mg and Ti while yellow tourmaline contain up to four weight percent MgO and one weight percent TiO_2 and is correspondingly low in Al.

Ca appears to be more common in dark green or yellow tourmaline with values up to two weight percent as CaO.

Figures 7 and 8 illustrate the compositional variations within zoned (blue cores, green rims) tourmaline in terms of Al, Na, Fe contents. The green tourmaline is enriched in Fe and Na and depleted in Al compared with the blue cores.

Structure-composition relationships: According to Foit and Rosenberg (1977), two coupled substitutions, the dehydration type $OH^- + R^{2+} = R^{3+} + O^{2-}$ and the alkali-defect type $R^{1+} + R^{2+} = R^{3+} + \square$ account for most of the chemical variability in schorlite and dravite (Mg rich tourmaline). Since the tourmaline separates have not yet been analysed for F and Na no comment can be made on the importance of the dehydration substitution. Na and Fe show a strong positive correlation with the total number of cations. This is illustrated in figures 7 and 9. Considering figures 7,8 and 9,

then the deficiency in the total number of cations can be accounted by the following substitution - $\text{Na}^+ + \text{Fe}^{2+} = \text{Al}^{3+} + \square$

However a different type of coupled substitution is observed in the yellow tourmaline. The following coupled substitution has been suggested (Ford, pers. comm.) - $2\text{Al}^{3+} = \text{Mg}^{2+} + \text{Ti}^{4+}$.

Cassiterite-tourmaline relationships: Cassiterite appears to occur mostly as fine grained crystals in quartz tourmaline veins and possibly in the quartz-tourmaline nodules. Based on analyses of seventeen tourmaline separates (>99% purity) it appears that tin (possibly as cassiterite) occurs in all the tourmaline types. The values range from 64-1300 ppm with an average of 330 ppm. There is no correlation between colour, type of occurrence or the composition of tourmaline with tin concentration. The lack of correlation between tourmaline composition and tin concentration may indicate that the tin is not included in the structure of the tourmaline. It very likely occurs as tiny inclusions (possibly as cassiterite) in the different types of tourmalines.

Mineralogy of the Globe ore: The most common mineral assemblage in the altered zone is quartz, tourmaline, sericite, pyrite, sphalerite and galena. Fine grained dark green tourmaline is the most common mineral. Galena appears to be a later hydrothermal product replacing pyrite and/or sphalerite. In some cases minor chalcopyrite occurs with galena as inclusions or/and around the edge of the galena. Corroded arsenopyrite inclusions occur within some sphalerite crystals. Minor topaz, commonly containing tourmaline needles, is closely associated with quartz. Siderite occurs as late stage minerals, replacing pre-existing minerals (similar to Sweeney's mine). Accessory minerals are zircon, cassiterite and possibly monazite. More polished thin sections are required to obtain further information about the alteration and the associated mineralization in this area.

General mineralogy of the greisen veins: The greisen veins are composed of quartz-muscovite-topaz and tourmaline. The greisens may consist of two, three or all four of these minerals. Sericite commonly forms during later hydrothermal alteration of the greisens. Arsenopyrite is the common sulphide mineral in the greisen veins and is associated with pyrite. Wolframite is a rare mineral and is associated with tourmaline or euhedral quartz. Accessory minerals include zircon, monazite and cassiterite.

The arsenopyrite geothermometer of Kretschmar and Scott (1976) using arsenopyrite-pyrite assemblage gives an estimated formation temperature between 430 and 480°C. However experimental control on this geothermometer is relatively poor.

Fluid inclusion studies: During the last field trip an attempt was made to obtain more appropriate samples for fluid inclusion studies. Some twenty fluid inclusion wafers were subsequently prepared mainly of samples pegmatite, quartz-tourmaline and greisen veins. Most of the wafers have been studied using the petrographic microscope and some thermometric measurements have been made on the Chaixmeca heating/freezing stage.

The majority of the fluid inclusions consist of two phases (liquid and vapour) with low vapour-liquid ratios. These fluid inclusions have homogenization temperatures around 170°C and low salinities. Fluid inclusions containing daughter minerals (mainly halite) have homogenization temperatures around 150°C and daughter mineral(s) melt around 220°C

Although the fluid inclusions appear to be primary their low homogenization temperatures suggest they may be secondary.

A few isolated small fluid inclusions have been found in quartz which have high vapour-liquid ratios. The homogenization temperatures obtained from these fluid inclusions are in the range of 400 to >550°C. Freezing temperature measurements were not possible due to the small size of the inclusions.

High density CO₂-rich fluid inclusions are found in pegmatitic quartz. The homogenization temperature of the CO₂ phases occurs in the range of +10 to +26°C. Temperature of melting of the CO₂ is between -54 and -56.4°C and the clathrate melting temperatures range from +2 to +5°C.

Further fluid inclusion studies will be undertaken in the near future. Further work will include:

- (a) Completion of work performed in 1982, e.g. fluid inclusions.
- (b) Chemical compositions of fresh and altered granite.
- (c) Modelling of magmatic and hydrothermal processes.

Course work included:

1981 -	Points
Geochemistry of hydrothermal ore deposits	2
Advance techniques in mineralogy	2
1982 -	
Statistics	3

German scientific language	3
Advances in Geochemistry	1

References:

- Anderson, J.L. (1980): Mineral equilibria and crystallization conditions in the late Precambrian Wolf River Rarukivi Massif, Wisconsin. Am. J. Sci. 280, 289-332.
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- Kretschmar, U. and Scott, S.D., (1976): Phase relationship involving arsenopyrite in the system Fe-As-S and their application. Canadian Mineralogist, v.14, 364-386.
- Ohmoto, H. and Rye, R.O. (1979): Isotopes of sulphur and carbon. In: Barnes, H.L. (Ed.), Geochemistry of hydrothermal ore deposits, 2nd edition, 798pp.
- Patterson, D.J., Ohmoto, H. and Solomon, M. (1981): Geologic setting and genesis of cassiterite-sulphide mineralization at Renison Bell, Western Tasmania. Econ. Geol. 76, 393-438.

TABLE 1

SULPHUR ISOTOPE ANALYSES, HEEMSKIRK GRANITE AND COUNTRY ROCKS

HEEMSKIRK GRANITE

Sample	Locality	Mineral	$\delta^{34}\text{S}\%$
F9,96.8	Federation Mine	pyrite	+6.5
F6,20.8	"	"	+6.5
F5, 179.0	"	"	+5.1
F10,35.6	"	"	+6.7
F18,148.2	"	"	+5.5
F12,254.4	"	"	+5.5
F19,41.9	"	"	+8.7
F18,135	"	"	+10.6
F18,244.4	"	"	+8.4
F18,165	"	"	+9.3
F18,168.5	"	Molybdenite	+8.3
*F18.145	"	pyrite	+3.8
F12,184.0	"	"	+11.9
F13,63.4	"	"	+9.4
G1	Globe Mine	galena	+9.7
G2	"	pyrite	+11.3
G6	"	"	+12.8
G10	"	sphalerite	+12.7
G18	"	pyrite	+7.8
G14 }	"	galena	+11.6
G14 }	"	pyrite	+12.9
G9	"	sphalerite	+13.0
S4,25.9	Sweeney's Mine	sphalerite	+14.9
S4,16	"	pyrite	+13.1
S7,11.9	"	sphalerite	+13.6
*S6,34.5	"	pyrite	+1.8
S8,14.6	"	sphalerite	+13.9
S14,126.0	"	pyrite	+15.0
S14,112.7	"	pyrite	+14.5
S8,78.5	"	pyrrhotite	+13.5
SP1	Spencer workings	arsenopyrite	+14.5
Gr,1	S. of Phar Lap workings	py	+17.1
UN1	S. of White Facing Workings	ccp	+13.5
UN1	"	py	+16.9
PL1	Phar Lap workings	py	+12.8
EC1	East of Camberland lake	py	+8.9
PP1	Peripatetic Mine	py	+13.0
F20	N.E. of Sweeney's Mine	py	+12.1
F21	"	py	+13.5
F22	"	py	+7.2
G88,286.1	Country rocks Zeehan	py	+18.5
	"	py	+19.4

* = disseminated sulphide in fresh granite

10-33
22-108

Table 2: Oxygen isotope analyses. Heemskirk granite and country rocks.

Sample No.	Rock types	1982	1983
* **10	coarse red granite	+8.9	} → ~10
* **26	coarse red granite	+8.9	
* **80	medium red granite	+8.6	
* **28	coarse red granite	+9.3	
* 1451	coarse white granite (series A)	+10.1	} confirmed
* 1444	coarse white granite (series A)	+10.8	
* 827	white tourmaline granite (series A)	+9.7	
* 821-A	marginal grey granite	+11.1	
* 821-B	marginal grey granite	+10.6	
* **89	coarse white granite	+9.6	
* 1200	augite axinite pegmatite-aplite	+11.6	
S250-1	sericitised granite	+10.1	
* F18,145.0	kaolinized w/disseminated py	+5.6	
S15,136.8	sericitised granite	+10.6	
* F5,91.4	highly sericitised granite	+7.8	}
47	chloritised, sericitised granite	+8.9	
* G88,268.1	Oonah quartzite	+15.4	
* G89,2108	Oonah quartzite	+14.1	
* 1207	Cambrian hornfels	+13.2	
* 1194	Oonah quartzite	+13.1	

* sample from Brooks; collection, A.N.U.
** sample from Klominsky's collection, Univ. Tas.

checked
w/ JPH
mid 1983

Table 3: Carbon and oxygen isotope analyses of siderite.

Heemskirk Granite

Sample No.	Locality	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{SMOW}}$
S14,118.5	Sweeney's Mine	-2.05	+15.44
S15,232.8	Sweeney's Mine	-6.23	+15.9
S8,72.6	Sweeney's Mine	-5.2	+16.3
S14,114.5	Sweeney's Mine	-4.41	+17.9
F21,51.0	N.E. of Sweeney's Mine	-8.9	+16.6
F12,221.5	Federation Mine	-6.04	+18.5
G44	Globe Mine	-5.3	+16.0

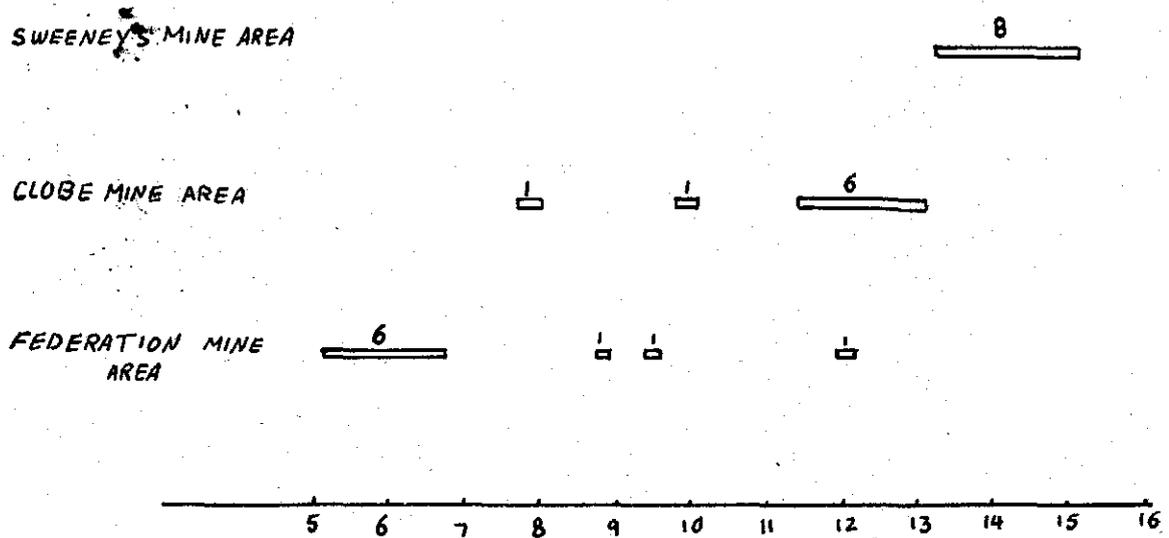


Fig. 1. Range of $\delta^{34}S$ of sulphides in Sweeney's, Globe and Federation mine areas; 8 = number of analysis

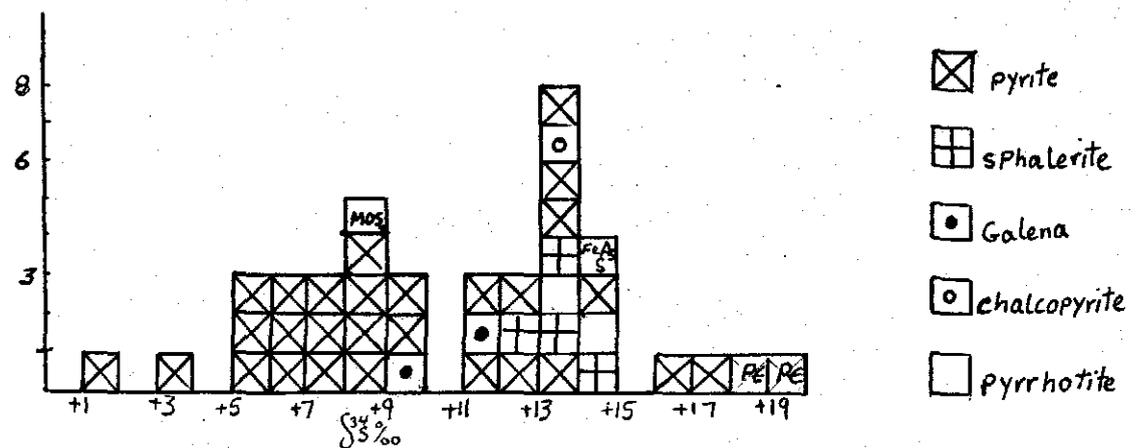
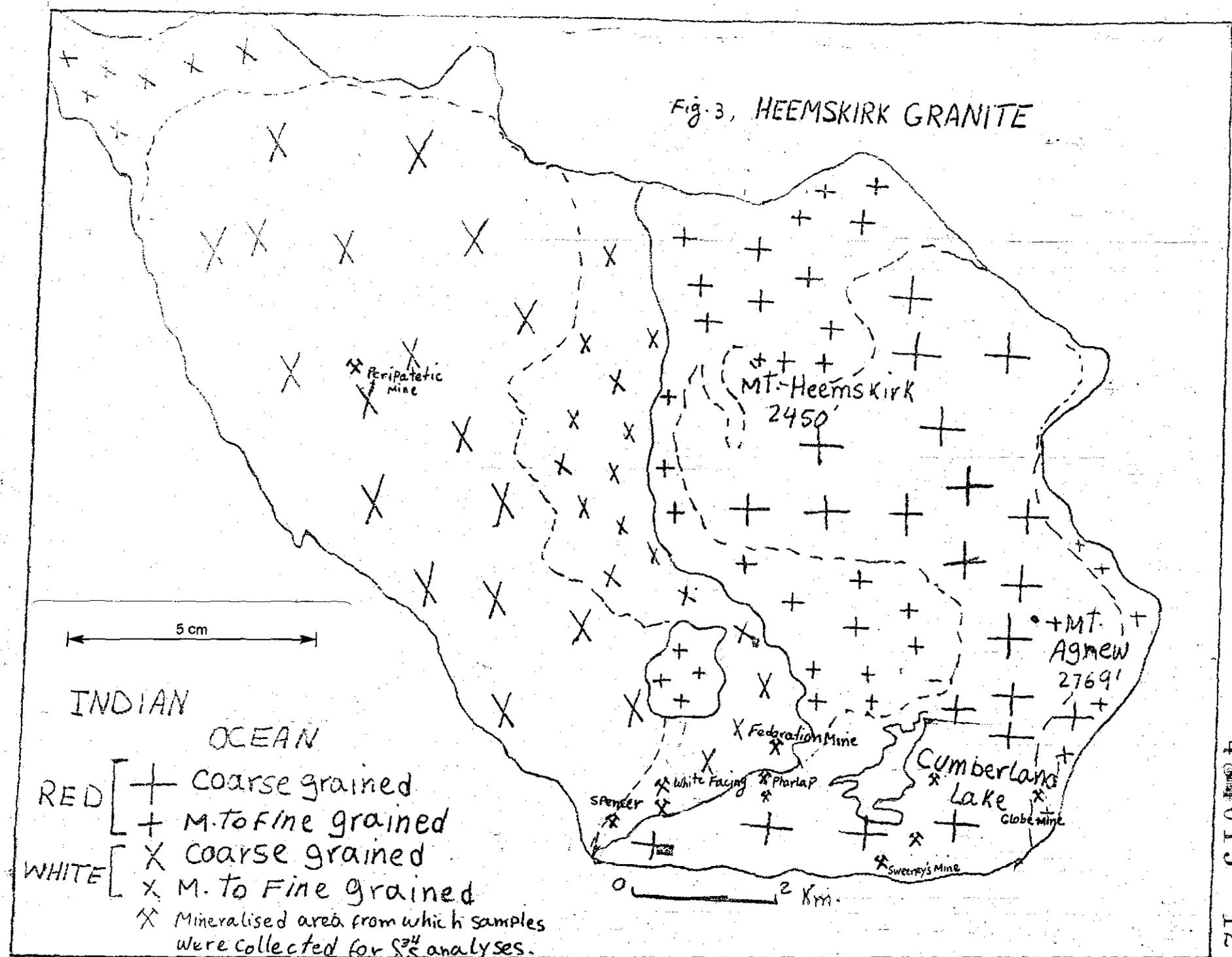


Fig. 2. Frequency distribution of $\delta^{34}S$ of sulphides in the Heemskirk granite and country rocks (PE).

Fig. 3, HEEMSKIRK GRANITE



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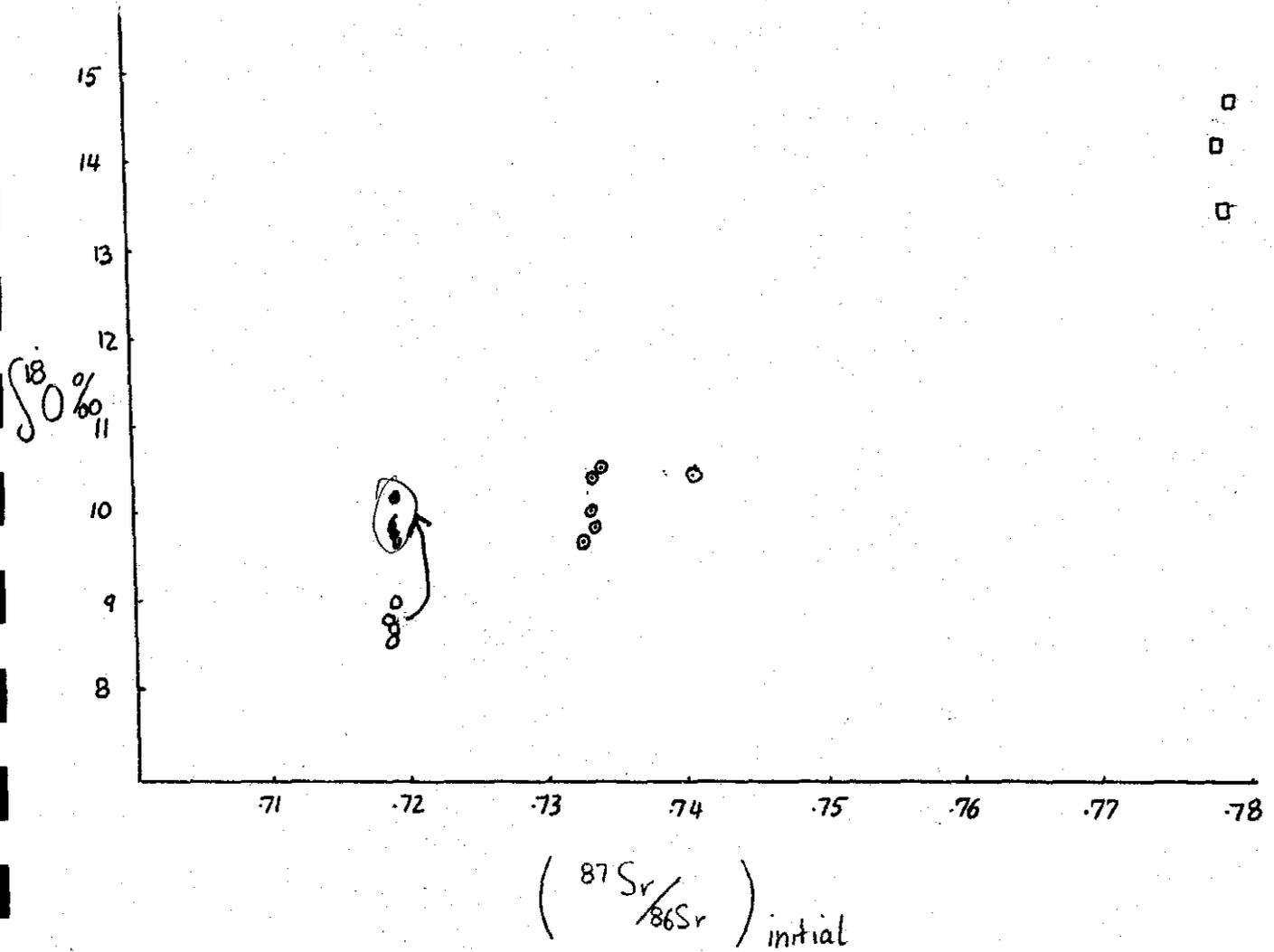


Figure 4. Plot of $\delta^{18}O$ vs. $(\frac{^{87}\text{Sr}}{^{86}\text{Sr}})_{\text{initial}}$ for Heemskirk granite and country rocks.

o = red granite o = white granite □ = country rocks

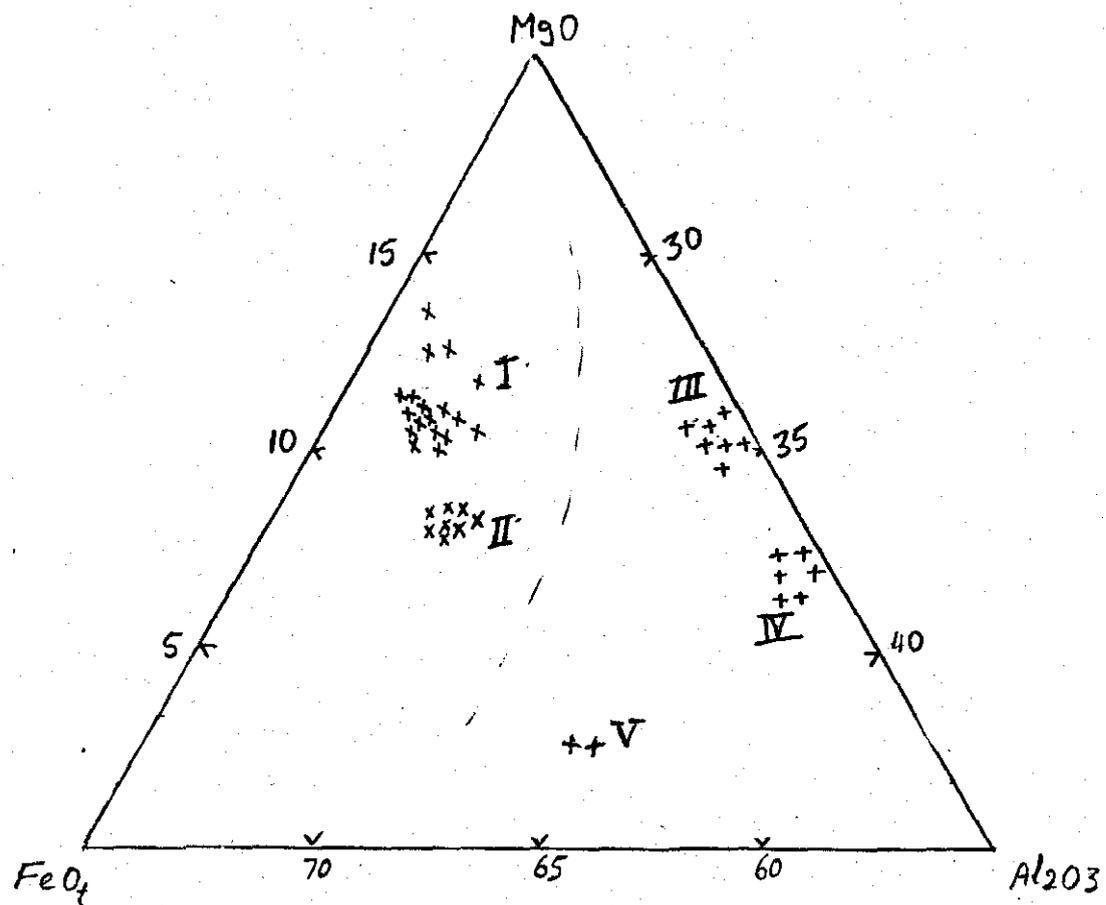


Figure 5. Diagram Al_2O_3 - FeO - MgO of the biotites from the white and red granite. I - Field of biotites from coarse and medium grained red granite. II - Field of biotites from fine grained red granite. III - Field of biotites from coarse grained white granite. IV - Field of biotites from medium grained white granite. V - Field of biotites from fine grained white granite.

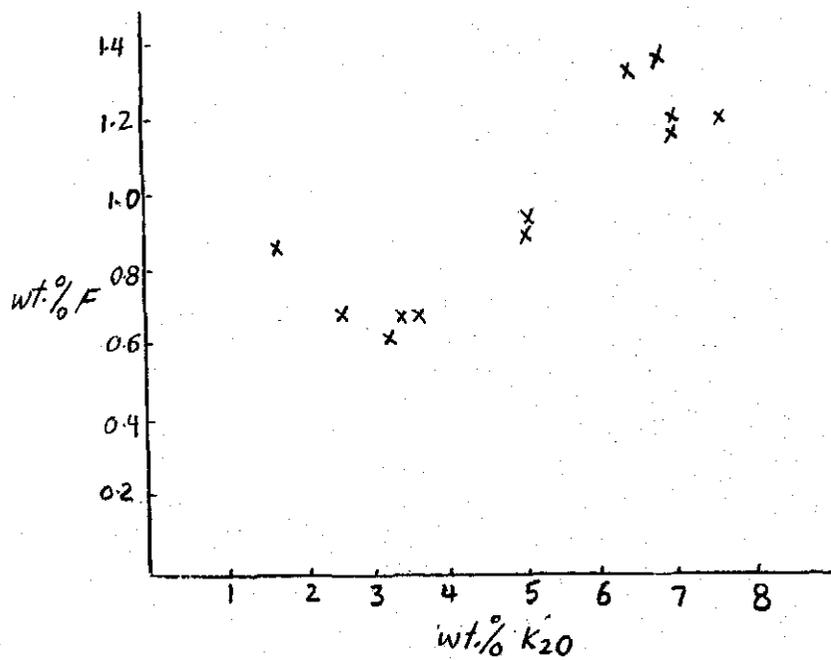


Figure 6. Variation of fluorine content with degree of biotite alteration (K₂O content) from the red and white granite, Heemskirk granite.

Figure 7. FeO-Na₂O relationship for zoned tourmaline, Heemskirk granite.

x = green tourmaline
+ = blue tourmaline

Figure 8. FeO-Al₂O₃ relationship for zoned tourmaline, Heemskirk granite.

x = green tourmaline
+ = blue tourmaline

Figure 9. Relationship between number of Na⁺ and total number of cations in zoned tourmaline, Heemskirk granite (oxygen number = 49).

x = green tourmaline
+ = blue tourmaline

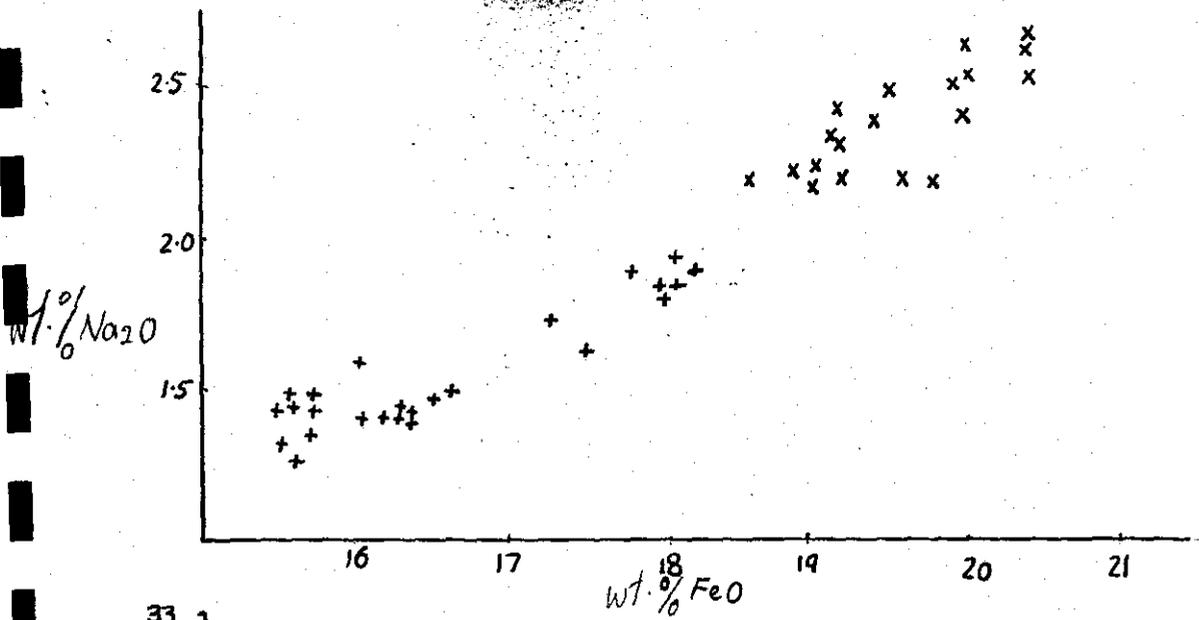


Figure 7

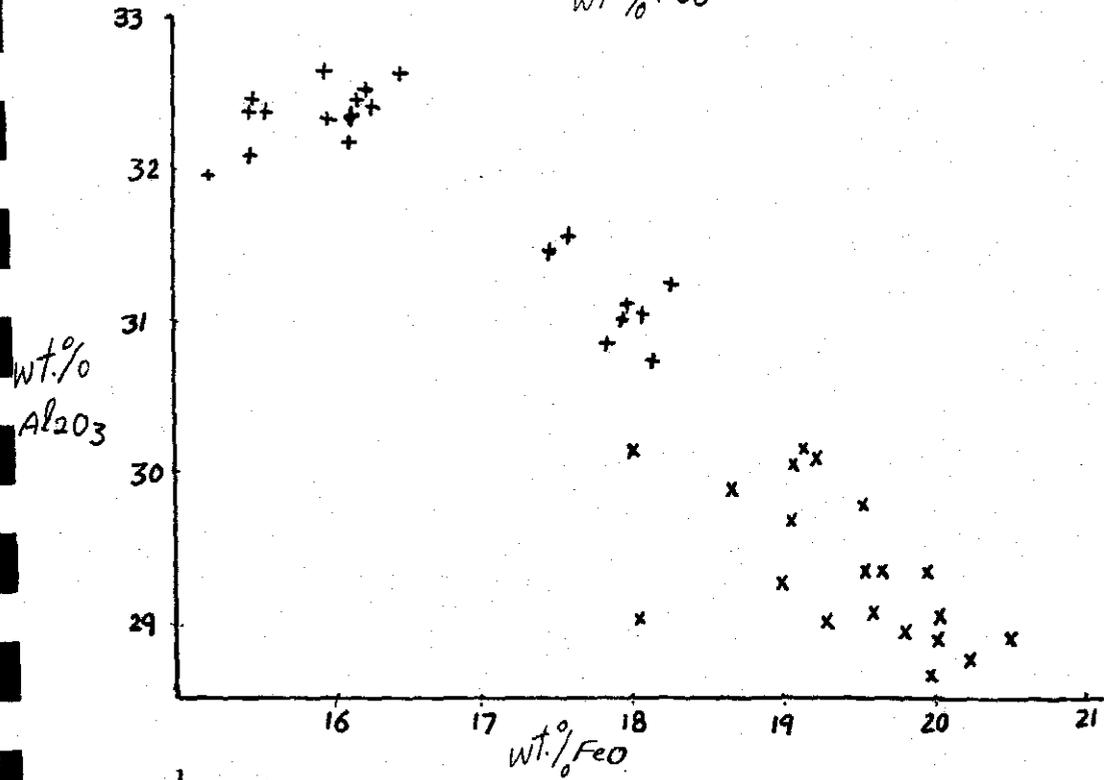


Figure 8

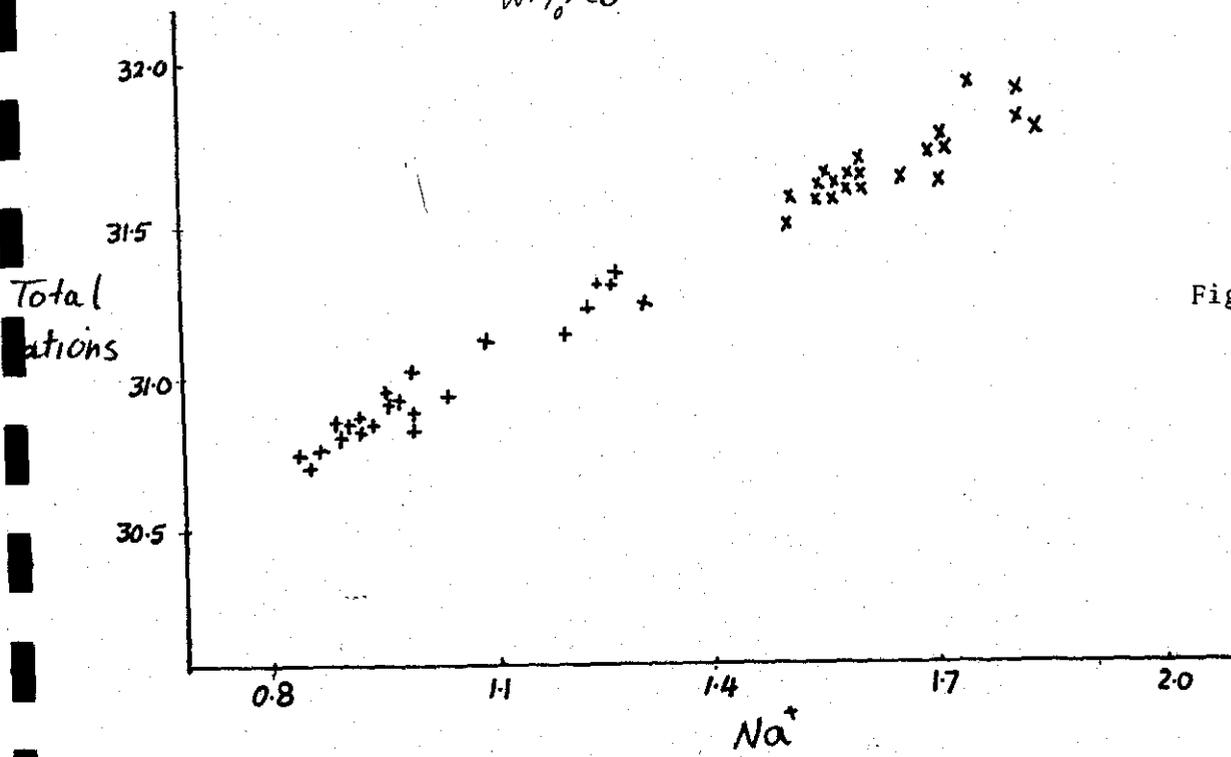


Figure 9

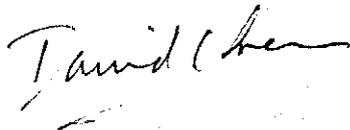
Note for FileRE E.L. 11/76 TCR 83-2070HEEMSKIRK GRANITE - THESIS J. HAZITAHERI

Enclosed is a copy of Jafar's 1982 report (to Renison) with some extra data obtained in 1983. Since most of the stable isotope work (partic. D/H and δO^{18}) was obtained with departmental assistance, it is reasonable to make this report available on a 'closed file' basis for those interested.

This is particularly the case since he has recognised low- δO^{18} zones and there is no doubt, in my mind, anyway, that we are dealing with an extensive hydrothermal system with a large input of isotopically light meteoric water at the time of 'epithermal?' mineralisation.

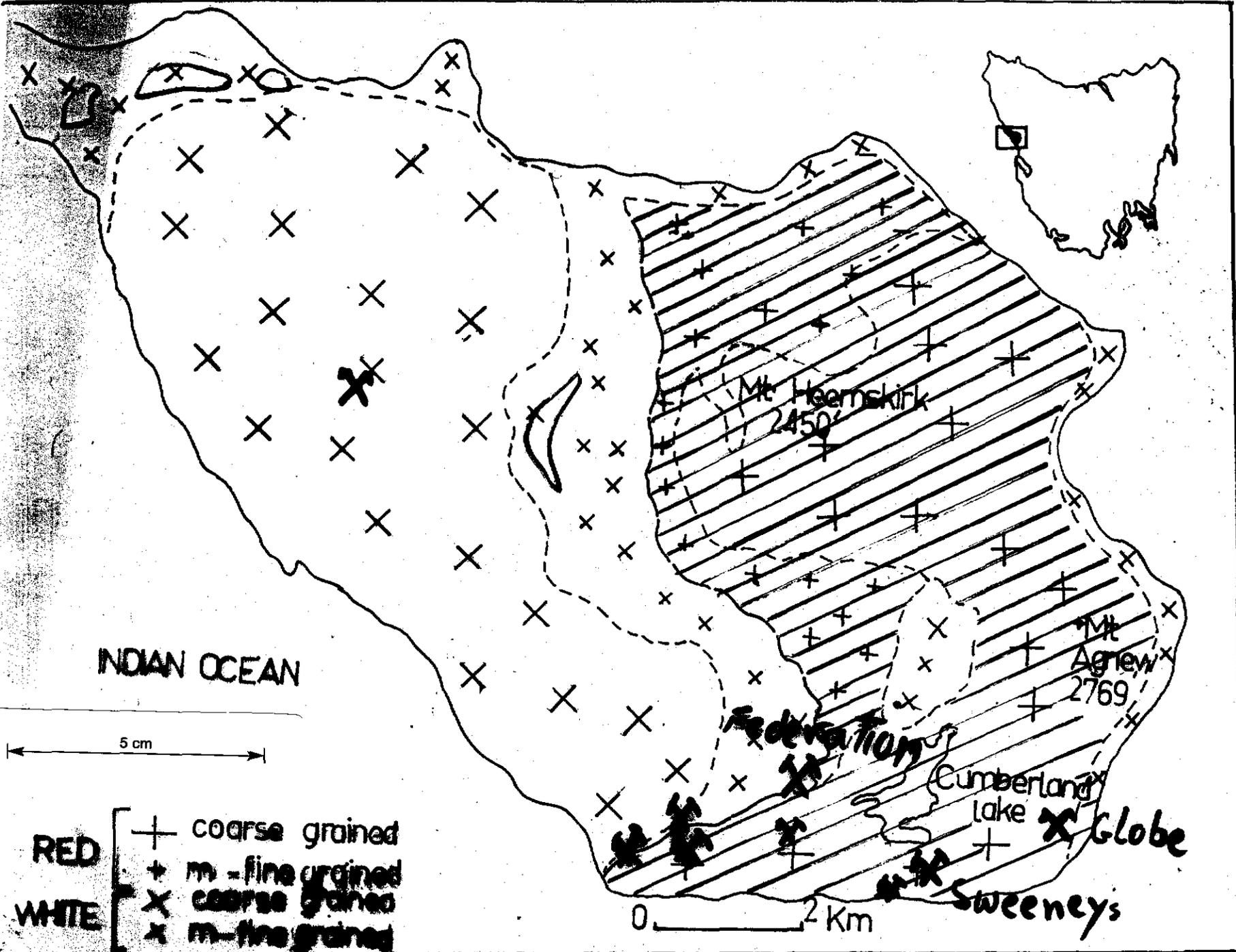
Workers in this area of geochemistry have suggested this as an ore control for some years but a recent paper (enclosed, p. 640) spells it out strongly on the basis of an extensive survey of the Idaho batholith. There the 'fossil' hydrothermal activity is Eocene and affects Mesozoic granites. At Heemskirk the time interval is much less but a very similar story - extensive isotopically light waters invading the cooling granite - hence: 1) the alteration; 2) good Rb/Sr isochrons (Brooks); 3) S isotope data - Sweeney's U/S Globe/Federation.

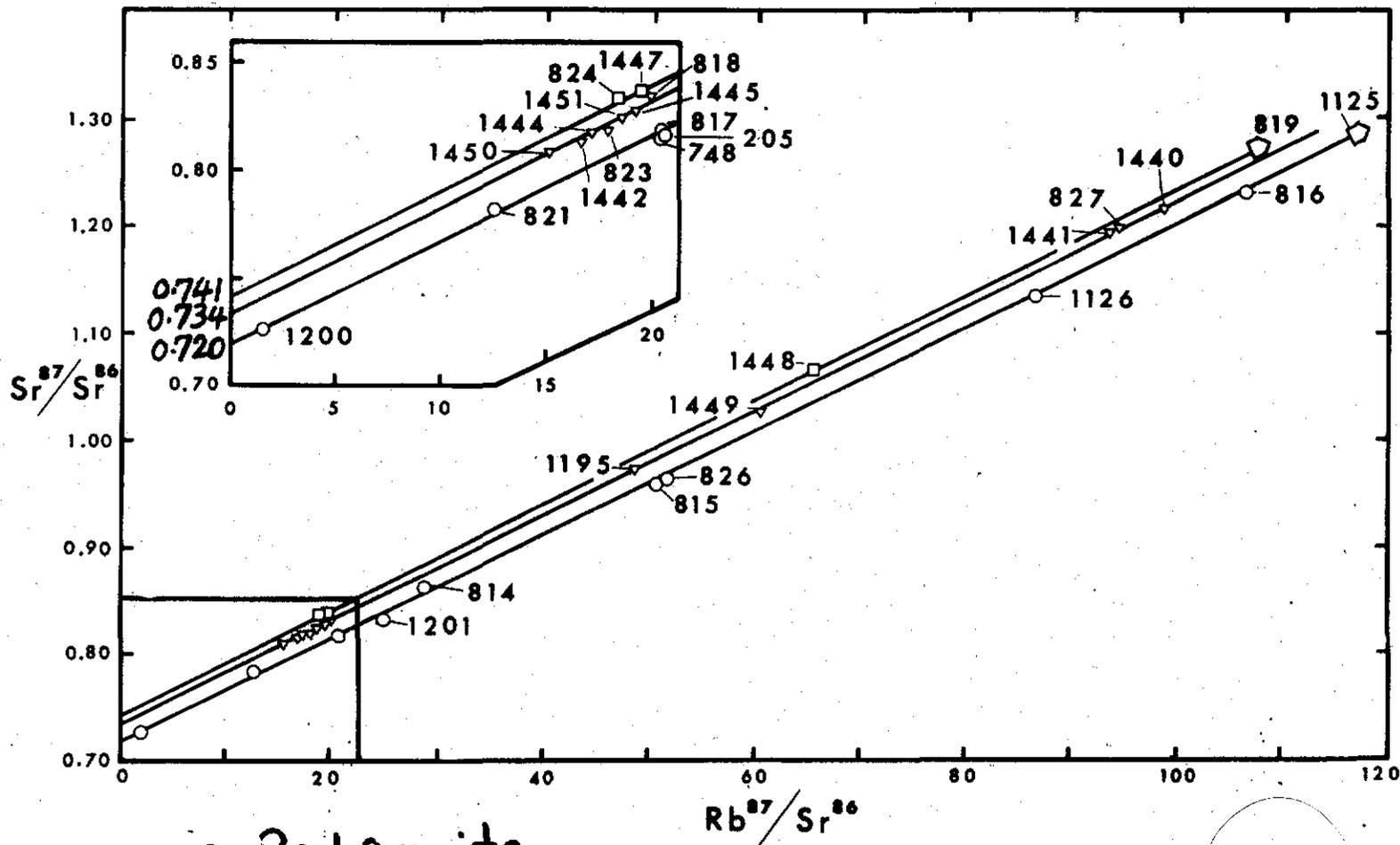
A similar story exists at Coles Bay - but there the W/R (water-rock) ratio appears to be less, and less sulphide mineralisation but similar reddening of feldspar and high initial Sr values.



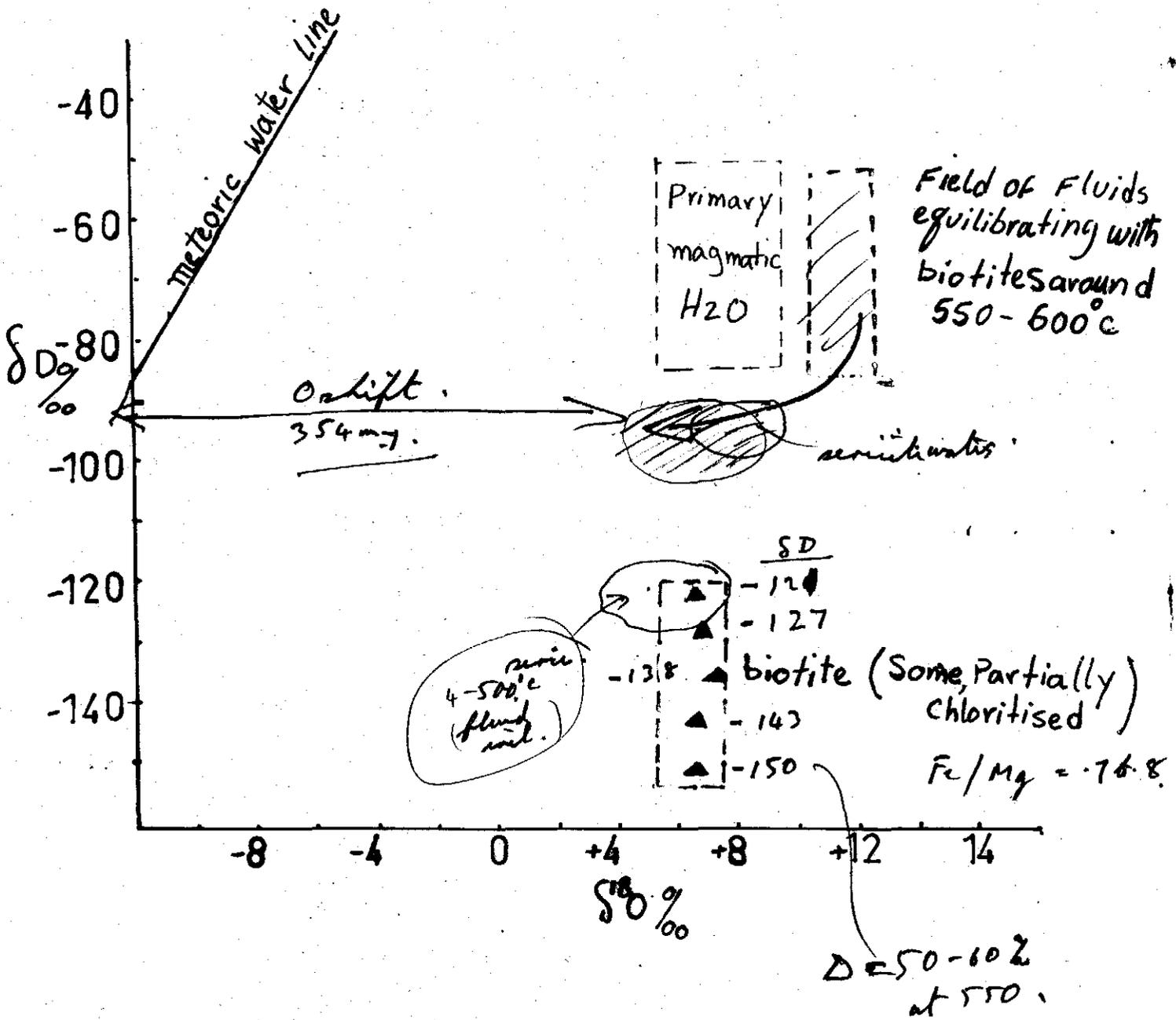
(D.C. Green)

HEEMSKIRK GRANITE





○ Red granite
 △ White series "A"
 □ White series "B"



D

altend rocks

1983

%

S15, 193	-115
F15, 1428	-125
F18, 174	-128
F19, 165	-120
F17, 151-152	-123
S4 9.6	-119
S8 54-60	-120
F5 91-4	-123
F20, 49	-123

biotites (see diagram)

S D = -121 - -150%

+ Pter Lof "sericite" muscovite -112%

GA 1200 (Augit, Axinite, quartz, albite)	+11.67	0.03
K28	+11.99	0.01
GA 827	+11.69	0.03
KL 36		
GA 1194 oonah quartzite	+16.012	

228,83

GA 819	c.w.g. (A)	+9.90	+9.82	0.01	utatz -12.55 22.55 -22.96
GA 818	p. microjante (B)	+10.85	+10.76	0.02	
GA 824	c.w.y (B)	+10.252	+10.171	0.03	
1203	C. biotite hornfels	+13.711	+13.62	?(high yield) 0.04	
1447	P. granite (B)	+10.912	+10.8	0.01	

2318,83

F17,7-8	c.g.g.	+9.979	+10.07	0.02	-11.81 22.14
G 89/210-8	oonah atz.	+17.174	+17.17	0.02	
GA 1207	C. kint hornfels	+14.994	+14.98	0.02	
GA 1444	c.w.y. (A)	+9.5	+9.53	?(high yield) 0.02	
GA 1451	c.w.y. (A)	10.382	10.37	0.01	

2518,83

S1-75-100	c.r.y.	+10.834	+10.51	0.03	-11.488 21.82
GA 821B	marginal gray granite	+10.831	+10.51	0.03	
GA 823	c.w.y (A)	+10.777	+10.45	0.02	
KL 11	c.r.y.	+10.892	+10.22	0.02	

2618,83

GA 1144		+14.448	+14.58	0.025	-11.904 11.82 10.38 22.15
G 170-8		+14.215	+14.33	0.01	
GA 1444		+10.818	+10.90	0.02	
S175-100		+10.87	+10.95	0.02	

558

GA 827	c.r.y.	+10.11			-12.139 10.33 22.42
GA 1200	w. ton granite	+10.35			
# 36	Augite, Axinite	+10.87			
1447	Porph. granite (Mag.)	+9.8			
	porph. w. granite (B)	+11.53			

79.

An $^{18}\text{O}/^{16}\text{O}$ and D/H study of Tertiary hydrothermal systems in the southern half of the Idaho batholith

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ABSTRACT

During Eocene time, 37 to 49 m.y. ago, a series of large hydrothermal systems was developed around a group of epizonal granite plutons in the Idaho batholith. These systems involved ~~deep and extensive circulation of fluids derived from the~~ ~~and low δD (~ -120) meteoric waters.~~ Water-rock interactions occurred at temperatures of 150 to 400 °C, lowering the $^{18}\text{O}/^{16}\text{O}$ and D/H ratios in the surrounding Mesozoic rocks (tonalite, granodiorite, and granite), such that the feldspar $\delta^{18}\text{O}$ and biotite δD values became as low as -8.2 and -176 , respectively. These values contrast markedly with the primary isotopic compositions of $+9.3 \pm 1.5$ and -70 ± 5 , respectively. Widespread propylitization of the Mesozoic plutonic rocks accompanied these isotopic exchange effects. Systematic mapping shows that anomalous δD and $\delta^{18}\text{O}$ values occur over more than 15,000 km², indicating the extensive lateral dimensions of the ancient circulating systems. The former zones of intense hydrothermal activity are marked by low- ^{18}O zones, which were mapped in the vicinity of the margins of several Eocene plutons (for example, at Rocky Bar) and also within a giant (5- to 20-km wide, 60- to 40-km diam) ring zone that surrounds the Sawtooth Mountains. The latter anomaly is coincident with the high-permeability ring fracture zone of an Eocene caldera system. Most of the ore deposits in the southern half of the Idaho batholith are epithermal and mesothermal Au-Ag veins that are located near the periphery of the low- ^{18}O zones (that is, near the outermost $\delta^{18}\text{O} = 8$ isopleth). This association links these deposits with the Tertiary hydrothermal activity and has great potential as an exploration tool in the heavily forested region. Evidence is presented that the Eocene ground-water circulation pattern was affected over large lateral distances (25 to 50 km) and great depths (5 to 7 km). These conclusions, together with the indications that large amounts of water ($>7,000$ km³) were involved in some systems and that the circulation patterns probably are related to caldera ring structures, may be of particular importance in geothermal exploration and exploitation of analogous modern systems. For example, the "fossil" hydrothermal activity mapped in the Idaho batholith may be char-

acteristic of deep-level fluid circulation in geothermal systems such as Yellowstone National Park, Wyoming. In such regions, the major zones of hydrothermal activity seem to be principally associated with either (1) the caldera ring zones or (2) the central plutons (resurgent domes).

INTRODUCTION

A variety of geological evidence (Craig, 1963; Taylor, 1968, 1971, 1977; Taylor and Forester, 1971, 1979) and theoretical models (Norton and Knight, 1977; Norton and Taylor, 1979) proves that large-scale circulation of ground waters commonly occurs around shallow intrusive bodies in the Earth's crust. Stable isotopic studies have shown that the circulating fluid is dominantly meteoric water in subaerial regions (Craig and others, 1956) and ocean water in submarine environments (Craig, 1966; Wenner and Taylor, 1973; Gregory and Taylor, 1981), although fluids of other derivations are important in some environments (Clayton and others, 1966; White and others, 1973). Similar hot fluids are known to be responsible for the formation of many ore deposits (O'Neil and Silberman, 1974; Taylor, 1973, 1974a; Sheppard and Taylor, 1974; Ohmoto and Rye, 1970, 1974; White, 1974; Bethke and others, 1976).

Magaritz and Taylor (1976a, 1976b) discovered that, far from being limited only to the shallow plutonic environments mentioned above, widespread ^{18}O depletions produced by meteoric-hydrothermal activity were common in a number of deeper-seated plutonic environments within several of the great Mesozoic granitic batholiths of the North American Cordillera. Taylor and Magaritz (1976, 1978) extended these $\delta^{18}\text{O}$ and δD studies to the Idaho batholith and discovered wide zones of strong D and ^{18}O depletion produced by hydrothermal circulation systems associated with a group of crosscutting Eocene plutons. Their principal conclusions, other than demonstrating the existence and large scale ($\sim 10^4$ km²) of the ancient geothermal systems, were that the aqueous solutions were derived from ordinary meteoric waters and that the Eocene magmatic activity provided the requisite heat. They also noted that the areas of ancient hydrothermal activity coincided with large

Contribution No. 3575, Publications of the Division of Geological and Planetary Sciences, California Institute of Technology. The Appendix of this paper, which includes all of the isotopic data together with sample descriptions and localities, is available from the authors on request. It may also be obtained by ordering GSA supplementary material 83-4 from Documents Secretary, Geological Society of America, 3300 Penrose Place, P.O. Box 9140, Boulder, Colorado 80301.

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