12 Feb 87

ESS 236 Igneous Petrology

DePaolo

Problem Set 2

Using the approach used in my EPSL (53, 189) paper, derive the differential equation that describes the trace element concentration and isotope ratio changes for continuous assimilation, fractional crystallization and recharge in a magma chamber.

Note that in equation 1a of my paper, the time dependence is superfluous and the equation could be written:

$$d\mu = C_a\, dM_a - DC_m\, dM_c = C_m\, dM_m + M_m\, dC_m$$

The resulting equation for the isotope ratio in the magma (ε_m) is:

$$\frac{d\varepsilon_m}{d\ln F} = (a+r-1)^{-1}\left[a\,\frac{C_a}{C_m}(\varepsilon_a - \varepsilon_m) + r\,\frac{C_r}{C_m}(\varepsilon_r - \varepsilon_m)\right]$$

where:

$$a = \frac{\text{rate of assimilation}}{\text{rate of crystallization}} = \frac{\dot{M}_a}{\dot{M}_c} \equiv \frac{dM_a}{dM_c}$$

$$r = \frac{\text{rate of recharge}}{\text{rate of crystallization}} = \frac{\dot{M}_r}{\dot{M}_c} \equiv \frac{dM_r}{dM_c}$$

NOTE: I changed the definition of "r" from that given in the paper. That "r" is now "a" and "r" is used for the recharge ratio.

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ESS 236 - Igneous Petrology

Petrography - Isotopology Lab

Alteration phenomena in a shallow tonalite intrusion.

A brief description of the San Telmo pluton is given in the accompanying abstracts.

The key to the map should be:

- Qal - alluvium
- KTg - Late Cretaceous or Early Tertiary gravel
- grd - other granodiorite bodies
- gr - granophyre } San Telmo pluton
- t - leucotonalite } San Telmo pluton
- gb - gabbro } San Telmo pluton
- pbv - prebatholithic volcanic rocks

The thin sections provided are:

800, 852 - leucotonalite; minimal alteration
DG-2, DP-86, 802 - leucotonalite, substantial alteration
808, 809 - granophyre
DG-1,3 - wallrock volcanics

Note that sample 844 (map) is a dike in the wallrock, sample K27 is an apophyse of granophyre in a roof pendant, and sample 230 is tonalite.

Peruse these thin sections and note:

1) mineralogy of mafics
2) "plagioclase" composition and texture
3) overall texture

Then:

1) Write a paragraph summarizing any relationships between petrographic characteristics and the O and D isotopic data.

2) Calculate and graph the $\delta^{18}O$ of water that would be in equilibrium with the average feldspar for the granophyres and the average feldspar for the "unaltered" tonalites as a function of Temperature from 800°C-100°C. This graph need not be extremely precise, just use the graphed 1000 $\ell n\alpha$ values from the Taylor paper (xerox on reserve).

Do the same for δD of water in equilibrium with Hornblende (or chlorite) and epidote. For the former use the values of 1000 $\ell n\alpha$ for biotite and assume Fe/(Fe+Mg)=0.5. For epidote, use the muscovite values of 1000 $\ell n\alpha$.

Estimate the composition of the "alteration water" from the granophyres (you must assume Temperatures for these calculations).

How do you explain the constancy of $\delta^{18}O$ values in quartz for all of the samples for which data are graphed?

What are your conclusions about the temperature of alteration and the source of the water?

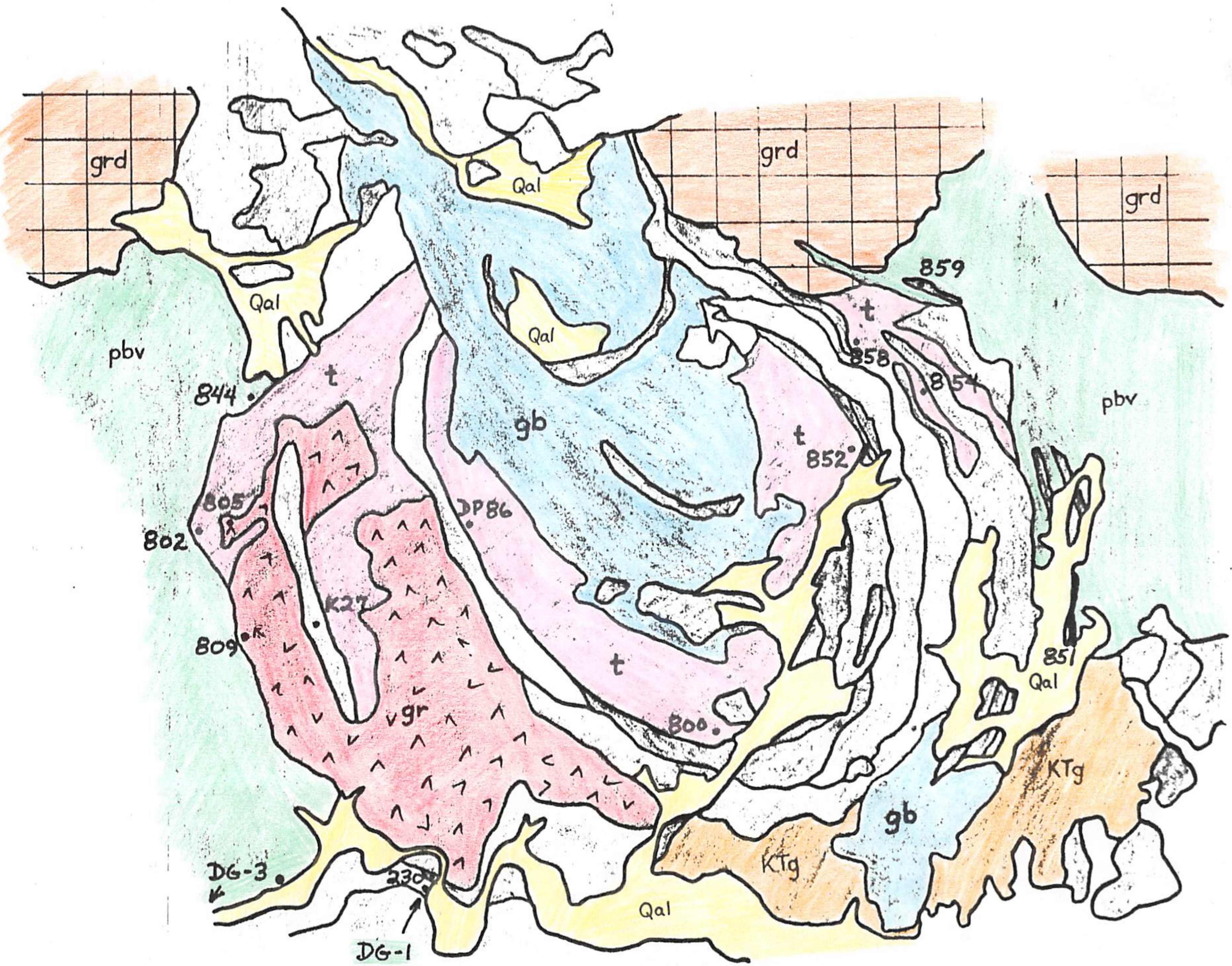
SAN TELMO RING COMPLEX, PENINSULAR RANGES BATHOLITH, NORTHWEST BAJA CALIFORNIA, MEXICO

DePaolo, D., Gromet, P., Powell, R., and Silver, L. T., Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125

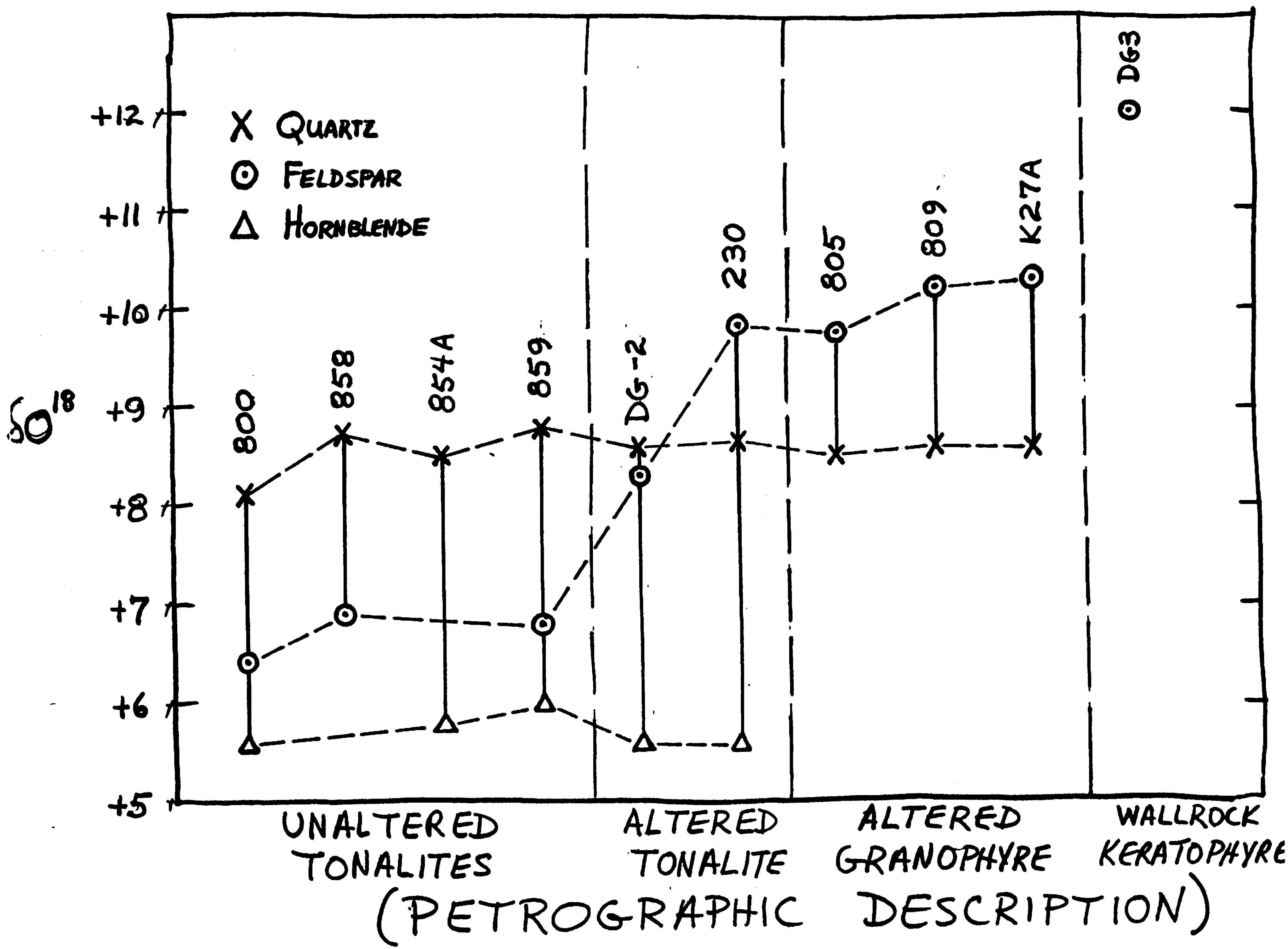
The San Telmo pluton is a ring complex of tonalite and granophyre, 13 km in diameter, emplaced in older gabbro and gently westward-dipping andesitic volcanics, 120 km SSE of Ensenada. Zircons yield U-Pb isotope ages of 120 ±3 m.y. for the gabbro and 110 ± 2 m.y. for the tonalite. Intrusive rings are elliptical and share a common focus and direction of major axis parallel to the regional tectonic grain (N35° W). The concentric distribution of country rock screens, tonalite, and textural units within the tonalite is believed to result from intrusion along inward-dipping to vertical ring fractures. Inward-dipping fracture structures in gabbro, successively penetrated by stockworks of tonalitic dikelets, grade into gabbro-fragment-rich (50-80%) tonalite intrusion breccias. Near-vertical ring fractures are observed as external arcuate valleys in country rock and steep internal contacts.

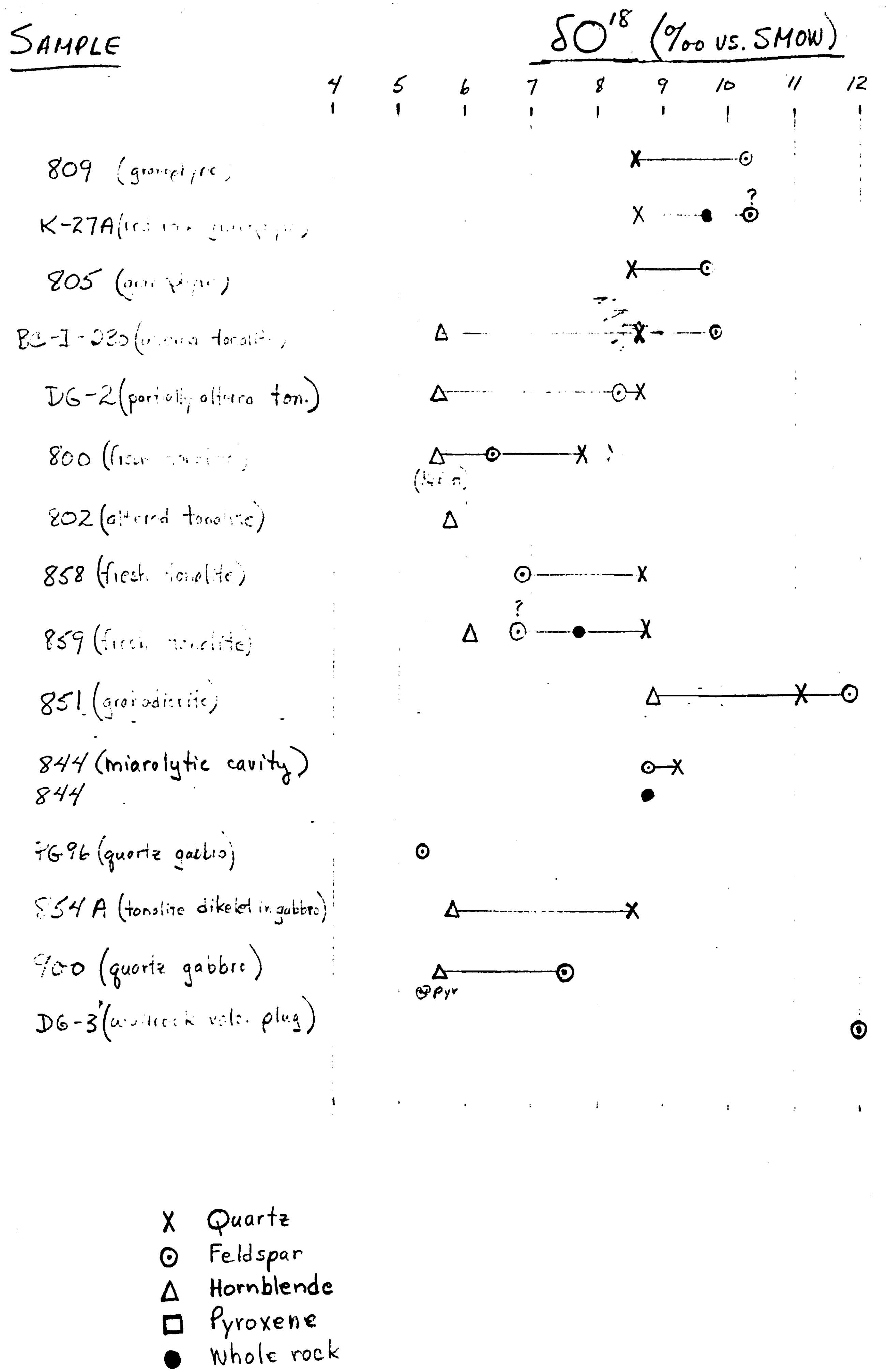
Individual tonalite intrusive units may be medium to coarse grained and either equigranular or seriate porphyritic. Tabular zoned plagioclase, An_{25-36}, (45-55%) and equant quartz anhedra (25-40%) dominate interstitial hornblende ± biotite (C.I. 8-14) and alkali feldspar. Granophyre contains quartz and turbid albitized plagioclase phenocrysts among finer-grained alkali feldspar-quartz micrographic intergrowths; microlitic cavities are common. Gabbroic rocks range from calcic hornblende norites to hornblende gabbros with > 10% quartz.

All felsic rocks are distinguished by high SiO_2 and low K_2O. They are poor in Rb (2-29 ppm) and Sr (71-171 ppm) and have high K/Rb ratios (>500). Initial $^{87}Sr/^{86}Sr$ ratios in the pluton vary from 0.7045 in the west to 0.7037 in the east independent of lithology. A quartz gabbro value of 0.7027 is distinctly lower. These values seem to preclude a derivation by melting older continental crust.

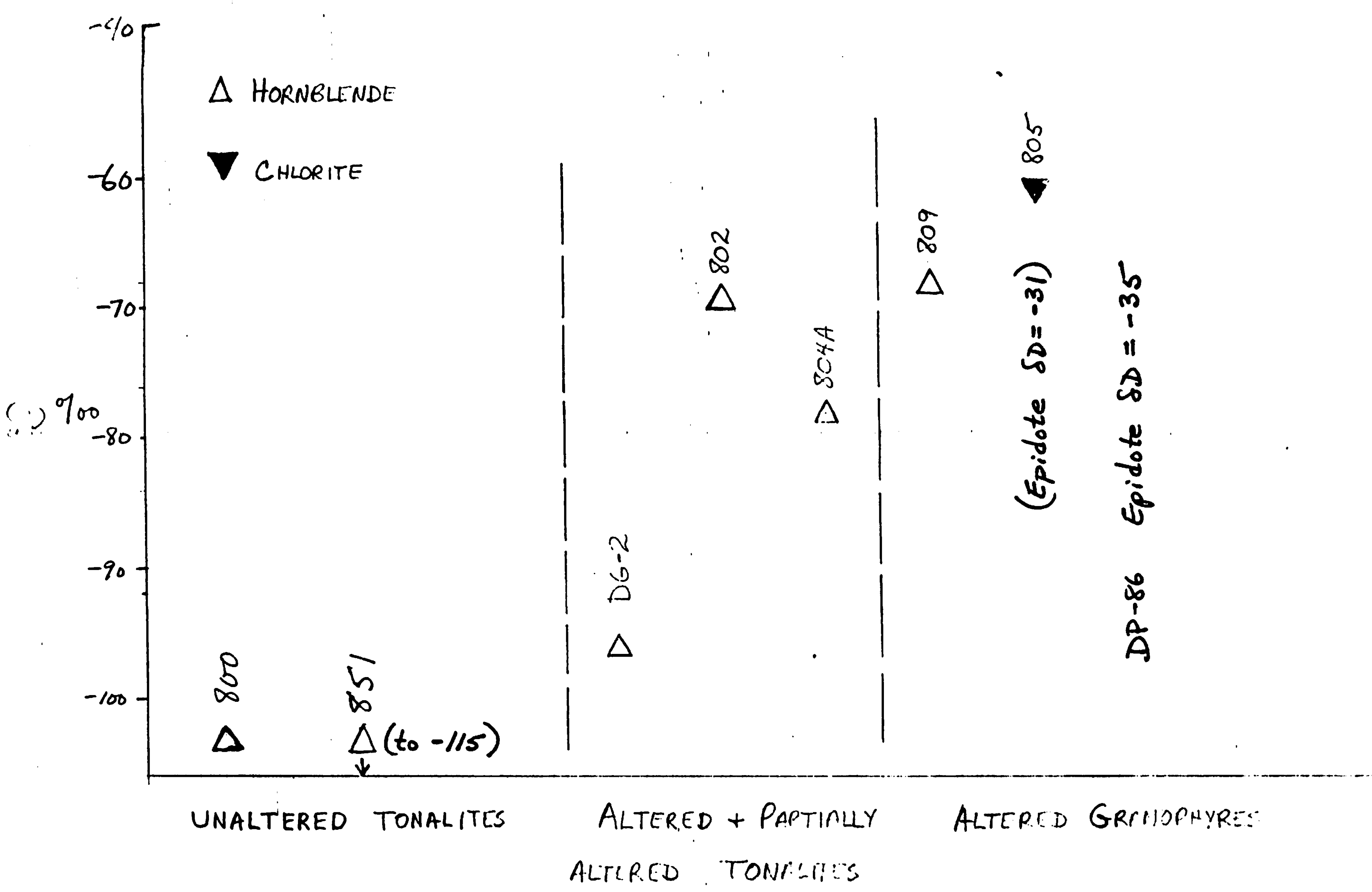

grd
grd
grd
pbv
pbv
Qal
Qal
Qal
Qal
Qal
t
t
t
t
gb
gb
vgr
KTg
KTg
844
805
802
809
K27
DP86
852
858
854
859
851
800
230
DG-3
DG-1

	Gabbro	— Seriate	porphyritic			—	Equi-granular	— Granophyre		—
	900	859	851	800	230	854A-2	858	805	808	809
Qtz	6.7	33.7	30.8	51.0	42.7	38.8	42.6	33.3	32.9	31.8
Alk-spar	—	0.6	9.1	4.0	41.4*	—	—	58.2	58.1	57.1
Plag	45.4	56.4	44.1	35.5	7.2*	38.8	49.1	↑	↑	↑
Pyrox	9.1	—	—	—	—	3.8	—	—	—	—
Hb + alt.	38.7	4.5	14.5	4.1	6.8	12.3	6.0	4.4	4.6	5.2
Biot	—	3.7	tr	2.0		3.3	0.5	—	—	—
Oxides	0.3	1.1	0.3	1.9	1.1	2.8	1.9	1.9	2.8	4.1
Sph	0.3	—	1.0	—	0.7	—	—	0.7	0.6	2.0
Epid.	—	—	—	—	—	—	—	1.5	1.0	—
Zircon	tr	tr	tr	0.1	tr	tr	tr	tr	tr	tr
Ap	tr	tr	.25	tr	tr	tr	tr	tr	tr	tr
Carb.	—	—	—	—	.06	—	—	—	—	—
An in core	93	35	35	36	—	43	35	—	—	—
rim	45	24	24	24		39	25			
rind		17	17	15			17			


δO18
+12
+11
+10
+9
+8
+7
+6
+5
X QUARTZ
⊙ FELDSPAR
Δ HORNBLENDE
800
858
854A
859
DG-2
230
805
809
K27A
⊙ DG3
UNALTERED TONALITES
ALTERED TONALITE
ALTERED GRANOPHYRE
WALLROCK KERATOPHYRE
(PETROGRAPHIC DESCRIPTION)



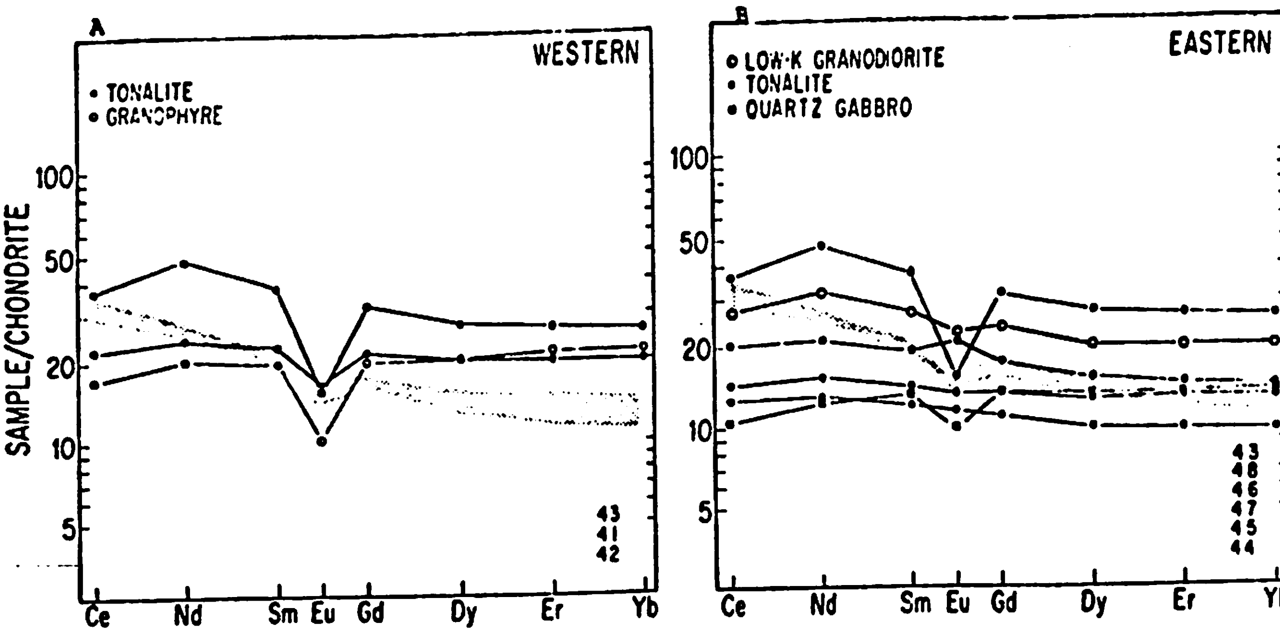
SAMPLE
δO18 (‰ vs. SMOW)
4
5
6
7
8
9
10
11
12
809
K-27A
805
DG-2 (partially altered ton.)
800
802 (altered tonalite)
858 (fresh tonalite)
859
851
844 (miarolytic cavity)
844
554 A (tonalite dikelet in gabbro)
900 (quartz gabbro)
Pyr
?
?
X Quartz
⊙ Feldspar
Δ Hornblende
□ Pyroxene
● Whole rock


-50
-60
-70
-80
-90
-100
‰
Δ HORNBLENDE
▼ CHLORITE
800
851
(to -115)
DG-2
802
804A
809
805
(Epidote δD = -31)
DP-86
Epidote δD = -35
UNALTERED TONALITES
ALTERED + PARTIALLY ALTERED TONALITES
ALTERED GRANOPHYRES

San Telmo Pluton

Sample	Lithology	Age (T) (m.y.)	$^{143}Nd/^{144}Nd_{meas}$	$^{87}Sr/^{86}Sr_{meas}$	$\epsilon_{Nd}(T)$	$\epsilon_{Sr}(T)$
800	Tonalite	110	0.512237 ± 23	0.70334 ± 11	+7.8 ± 0.5	−15
805	Granophyre	110	0.512224 ± 24	0.70700 ± 4	+7.9 ± 0.5	+2
DG-1	Basalt (wallrock)	120+	0.512179 ± 22	0.70425 ± 10	+7.0 ± 0.4	−3
DG-3	"Keratophyre" (wallrock)	120+	0.512230 ± 26	0.70637 ± 6	+8.2 ± 0.5	−5

SAN TELMO RING COMPLEX



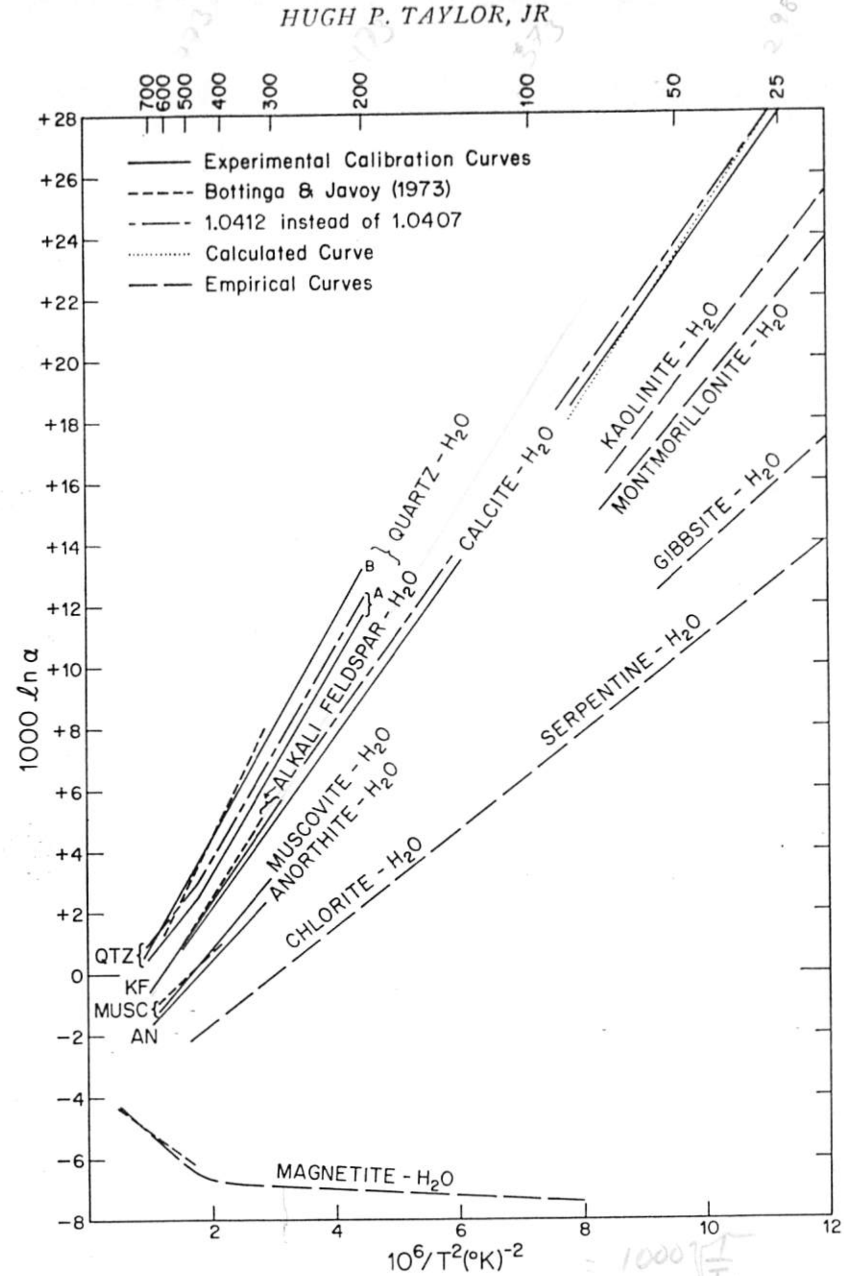


FIG. 2. Experimentally determined equilibrium oxygen isotope fractionation curves for various mineral-H_2O systems: calcite-H_2O (O'Neil et al., 1969); quartz-H_2O (B = "partial" exchange experiments, A = "complete" exchange experiments, Clayton et al., 1972); alkali feldspar (KF)-H_2O and anorthite (AN)-H_2O (O'Neil and Taylor, 1967); and muscovite-H_2O (O'Neil and Taylor, 1969). Also shown are some empirically derived curves: magnetite-H_2O (high-T portion = Anderson et al., 1971, low-T portion = Wenner and Taylor, 1971); serpentine-H_2O and chlorite-H_2O (Wenner and Taylor, 1971); kaolinite-H_2O (Savin and Epstein, 1970a); and gibbsite-H_2O (Lawrence and Taylor, 1971). In addition, some calculated curves of Bottinga and Javoy (1973) and Bottinga (1968, calcite-H_2O) are indicated, together with two readjusted experimental curves based on changing the CO_2-$H_2O(l)$ fractionation factor at 25°C from 1.0407 to 1.0412 (see text).

ward shift of the quartz-H_2O curve of Clayton et al., in Figure 2, bringing it into closer agreement with the other quartz-H_2O curves. Except for calcite-H_2O, the other curves on Figure 2 not affected, either because the H_2O was analy directly (O'Neil and Taylor, 1967; 1969), or could perhaps happen in a system containing abundant graphite (Eugster and Skippen, 1967), coal, or petroleum, but is unlikely in most hydrothermal environments.

Hydrogen isotope fractionation factors in silicate-H_2O systems have been investigated at high temperatures in only one laboratory study (Suzuoki and Epstein, 1970, 1974). Some of the results of Suzuoki and Epstein on biotite, muscovite, chlorite, serpentine, and kaolinite are incorporated into Figure 4, together with some empirical estimates of the low-temperature fractionation factors for some of these minerals based on data from natural mineral assemblages.

The most important results of the studies by Suzuoki and Epstein (1970, 1974) are that the D/H fractionations among silicates are mainly a function of the Mg, Al, and Fe contents in the minerals. Water concentrates deuterium relative to all OH-bearing silicates and Mg-rich and Al-rich minerals concentrate deuterium relative to Fe-rich minerals. This helps explain why muscovite in natural mineral assemblages is invariably richer in D than coexisting biotite, and why coexisting biotite and hornblende generally have similar δD values (they also generally have similar Mg/Fe ratios).

Above 400°C, the various silicate-H_2O D/H fractionation curves determined by Suzuoki and Epstein (1974) form subparallel lines on a plot of 1,000 ln α versus $10^6/T^2$ (Fig. 4). Below 400°C the positions of the curves are unknown, but if the low-temperature estimates of Savin and Epstein (1970a), Lawrence and Taylor (1971), and Wenner and Taylor (1973) are reasonably accurate, all the hydrogen isotope fractionation curves must flatten out, as shown on Figure 4.

If the curves shown in Figure 4 are approximately valid, it means that hydrogen isotope geothermometry on silicate minerals is virtually impossible. However, if one can independently estimate temperatures of formation (e.g., by $^{18}O/^{16}O$ geothermometry), the curves can be used to calculate accurately the δD values of coexisting H_2O. The major problem in applying these curves to natural mineral assemblages lies in whether or not the primary δD values in a mineral assemblage are preserved during later geological events. This is a more serious problem for D/H than for $^{18}O/^{16}O$, as discussed in more detail below.

Isotopic Variations in Natural Waters

Meteoric waters

The isotopic variations of H_2O in rain, snow, glacier ice, streams, lakes, rivers, and most low-temperature ground waters are extremely system-

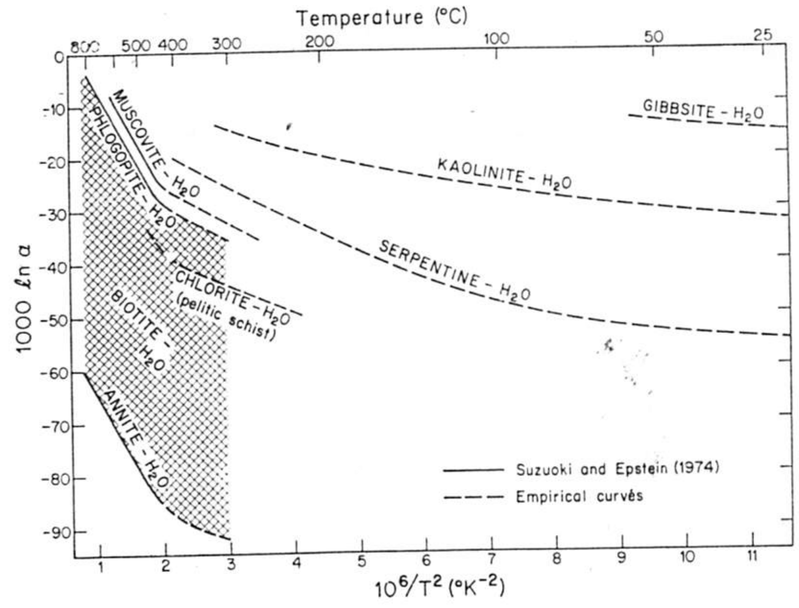


FIG. 4. Equilibrium hydrogen isotope fractionation curves for various mineral-H_2O systems. For temperatures above 400°C, the curves are based on laboratory experiments of Suzuoki and Epstein (1970, 1974). For temperatures below 400°C, the curves are based on empirical extrapolations to estimated values at earth-surface temperatures (Savin and Epstein, 1970a; Lawrence and Taylor, 1971; Wenner and Taylor, 1973) and on some preliminary laboratory experiments by Sheppard and Taylor (unpub. data, 1969) on kaolinite-H_2O at 300°C.

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DUE: 5 FEB 87

E&SS 236 - Adv. Igneous Petrology

Dr. DePaolo

LAB EXERCISE #1

The Muskox Layered Intrusion

This lab provides a look at rocks that are crystal accumulations from a body of basaltic magma. Many of the ideas that have governed petrological interpretations of igneous rocks have come from field, chemical, textural and mineralogical studies of layered mafic intrusions. The most intensively studied intrusion is the Skaergaard, which is located on the coast of Greenland opposite Iceland. The Skaergaard formed at the time of opening of the N. Atlantic (60 m.y. ago) and is associated with a large volume of basaltic lava. Other examples of layered intrusions are the Stillwater intrusion in southwest Montana (2.7 billion years), the Bushveldt intrusion in Zimbabwe (2.5 billion years), the Kiglapait intrusion in Labrador (1.3 b.y.), the Duluth complex in northern Minnesota (1.1 b.y.) and the Jurassic Dufek intrusion in Antarctica.

The Muskox intrusion is located in the Northwest Territories of Canada, straddling the Arctic Circle (Figure 1). The intrusion is shaped like the keel of a boat that is dipping gently to the north. In cross section (Figure 2) it looks like a shallow funnel. The rock layers, which are composed of varying proportions of the minerals olivine, clinopyroxene, orthopyroxene, and plagioclase, are nearly flat-lying. A "marginal zone" of unlayered rock separates the layered series from the wallrock (or "floorrock" if you prefer), and a feeder dike is well exposed below the layered series.

Mapping and studies of drill cores through the intrusion have resulted in the stratigraphic compilation shown in Figures 3 and 4. Some of the layers are laterally continuous for over 30 kilometers even though they are only a few feet thick! The lower part of the layered series (Cyclic units 1 through 16) are composed almost exclusively of ultramafic rocks (mostly olivine and pyroxene). The upper part of the intrusion (above cyclic unit #21) is gabbroic. The highest unit in the intrusion is granophyre, which is mainly melted roofrock. The gabbroic rocks also contain granophyre in increasing amounts as the roof is approached.

In this lab we will be concerned with crystallization sequences in this intrusion, and how these can be understood in terms of "simple" phase diagrams. The most difficult aspect of the petrography is distinguishing orthopyroxene from clinopyroxene. The first part of the lab will guide you through the necessary petrographic observations. The second part involves some problems.

Figure 7

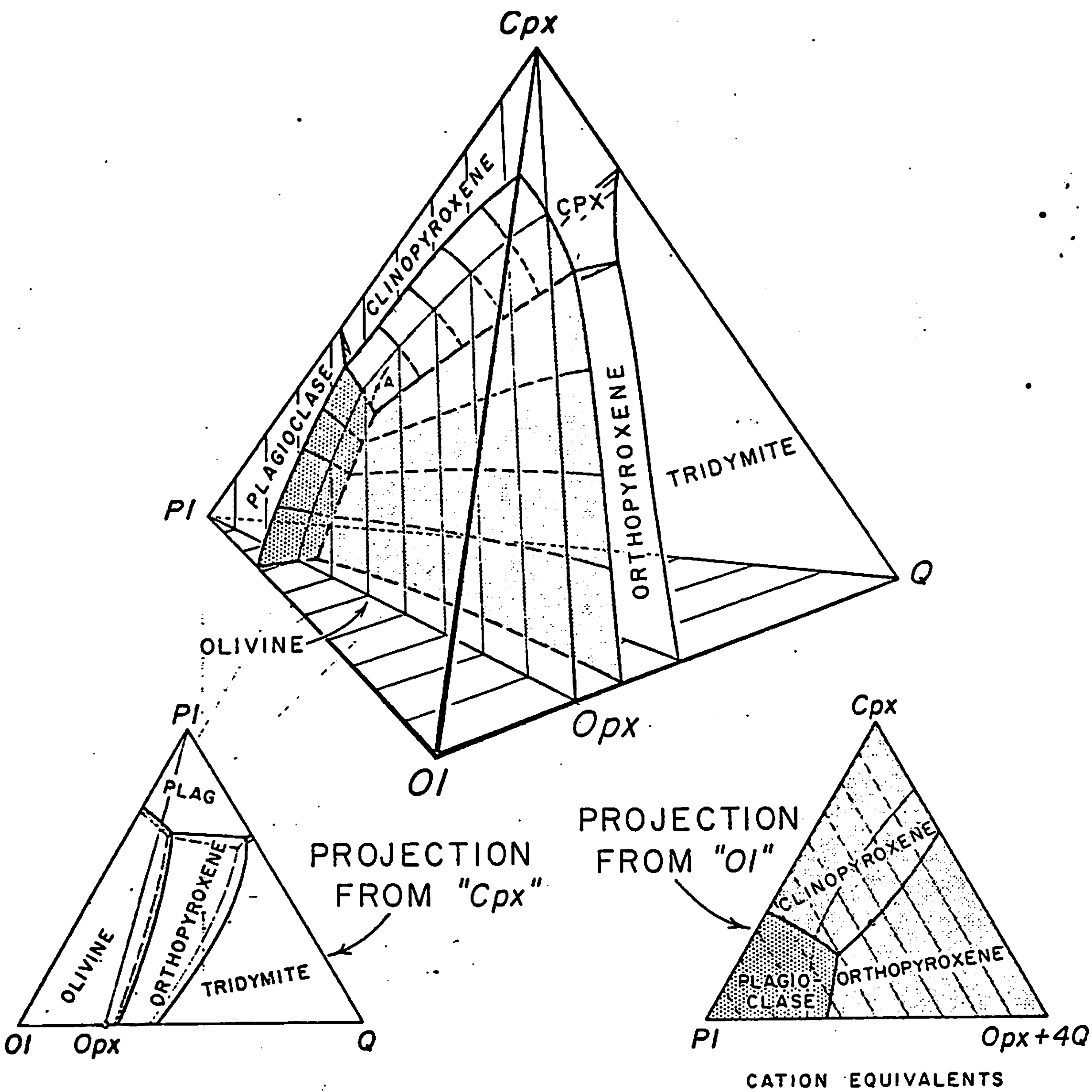

FIG. 11. Phase diagram model and projections of the "system" *Ol* (olivine)-*Cpx* (clinopyroxene)-*Pl* (plagioclase)-*Q* (silica), showing liquidus volumes for olivine, clinopyroxene, orthopyroxene (or pigeonite) and tridymite (or quartz). The olivine volume extends from the *Ol* apex to the three shaded surfaces. The dashed line A corresponds quantitatively to the curved olivine-clinopyroxene cotectic boundary projected in Fig. 10. Liquid immiscibility in the high-silica region is neglected.

Muskox Intrusion, Canada

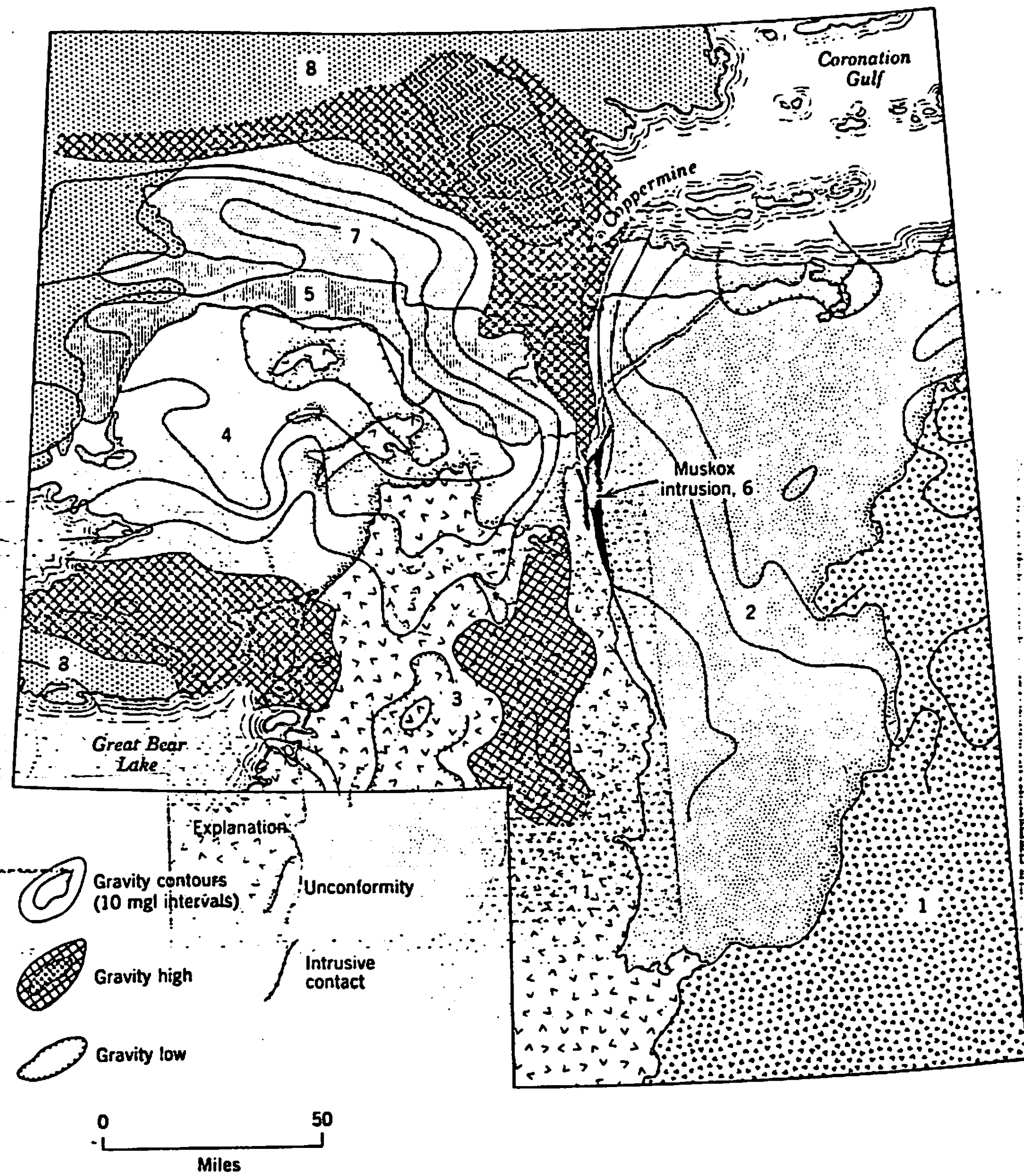

Fig. 2.1 Regional geology and Bouguer gravity map of the Coppermine region. Geology compiled from maps published by the Geological Survey of Canada. Gravity data from Hornal (1966). Legend, with K-Ar ages, as follows: 1. Archean granitic rocks, paragneiss, and volcanic rocks, 2300–2600 m.y. 2. Early Proterozoic sedimentary rocks. 3. Proterozoic granitic, rhyolitic and metamorphic rocks, 1700–1900 m.y. 4. Middle Proterozoic sediments. 5. Coppermine basalt. 6. Muskox intrusion, 1150–1250 m.y. 7. Late Proterozoic sediments. 8. Paleozoic sediments.

Figure 1

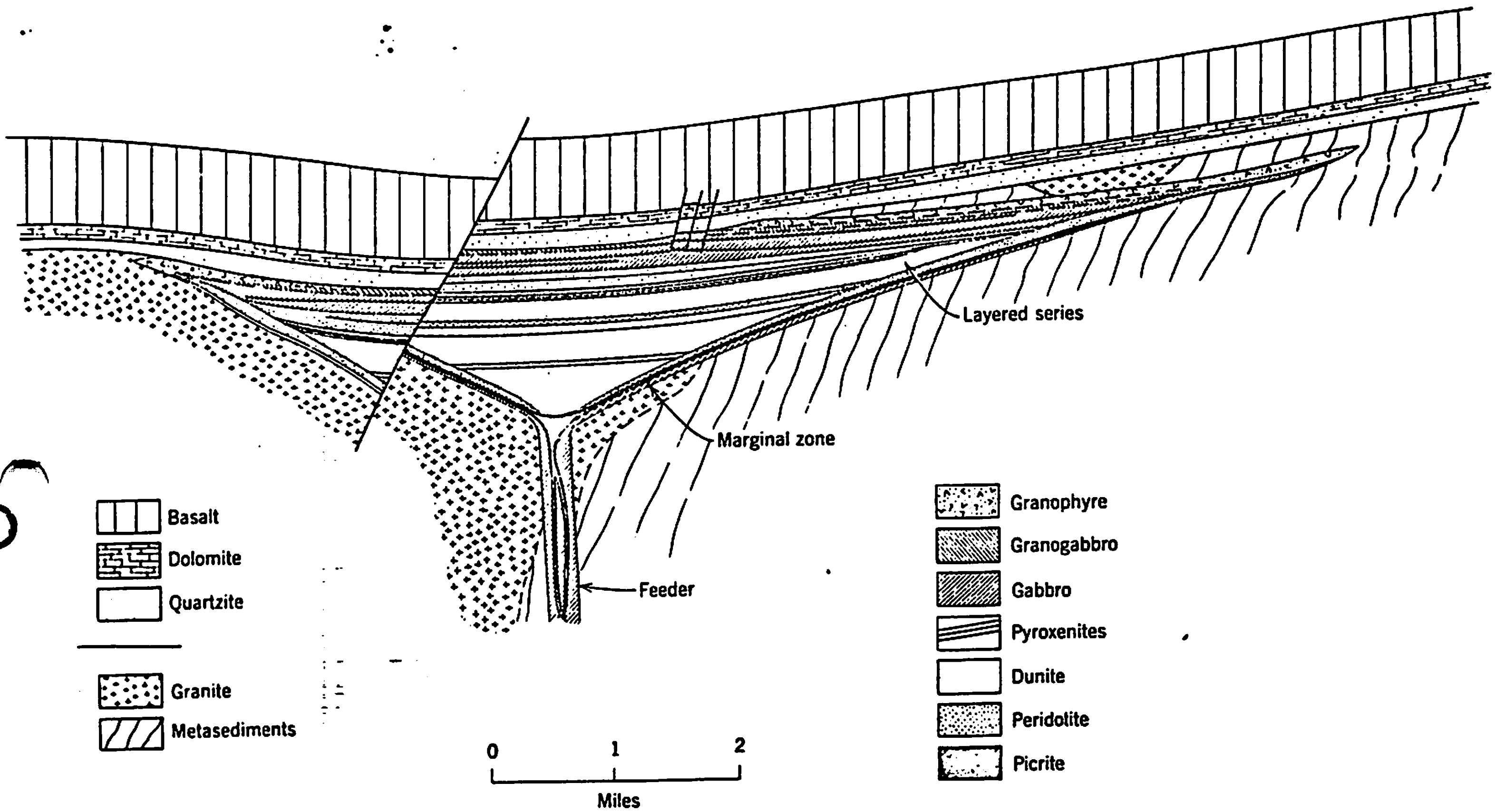

Fig. 2.2 Restored cross section of the exposed part of the Muskox intrusion. Granogabbro = granophyre-rich gabbroic rocks.

Figure 2

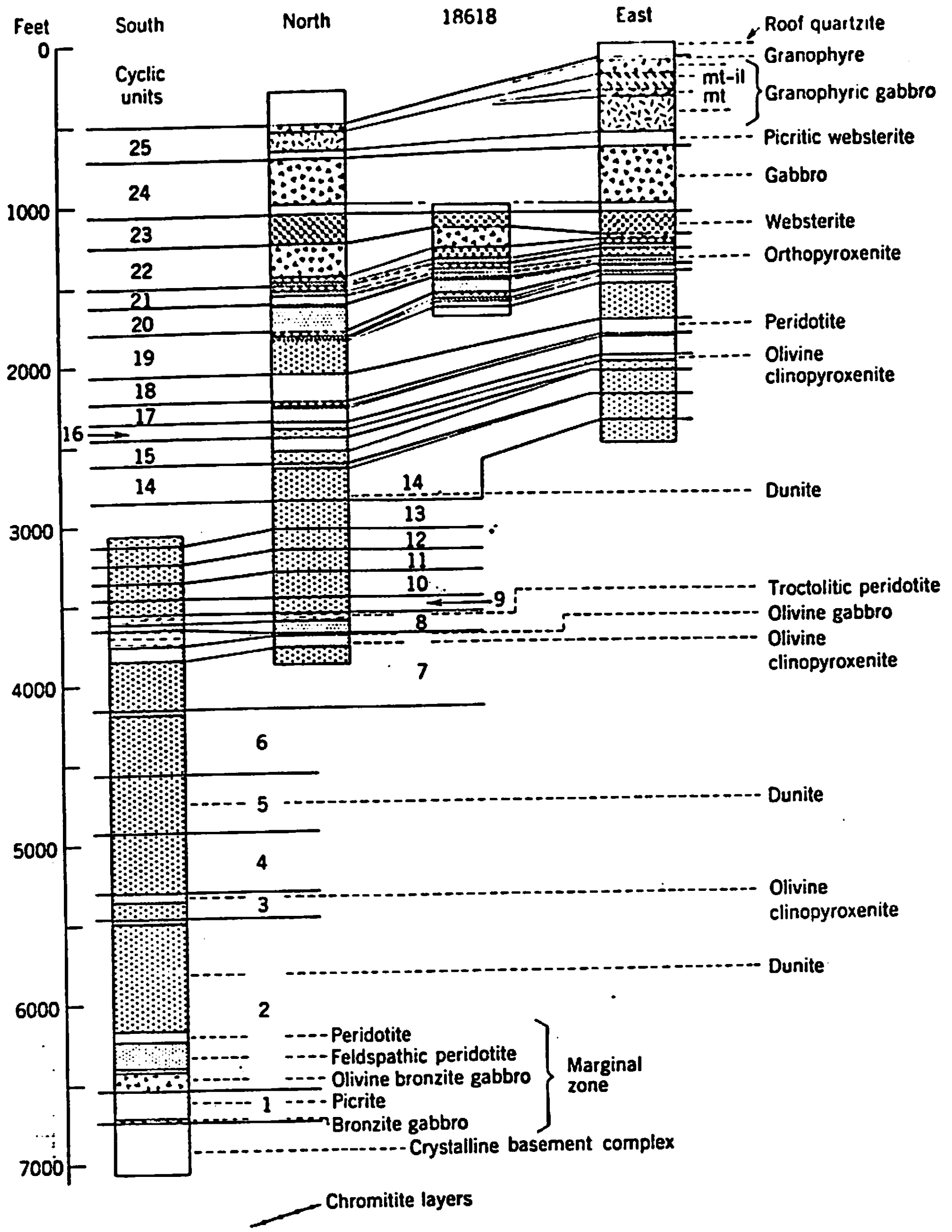

Figure 3

Fig. 2.3 Summary logs of diamond drill core sections from the Muskox intrusion showing the main cyclic units. Diabase dikes have been neglected.

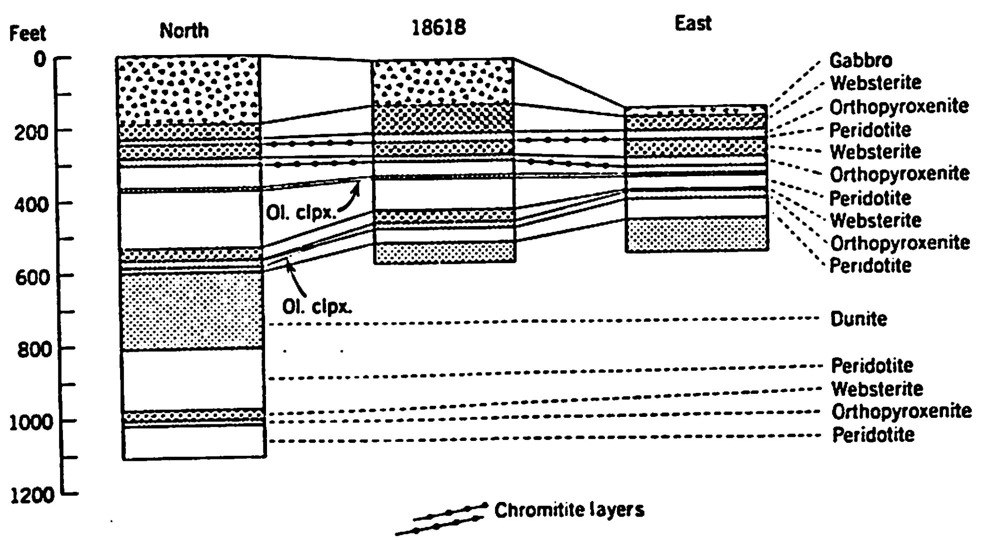

Figure 4

Fig. 2.4 Diamond drill core sections of part of the Muskox layered series showing repetition of the cyclic unit peridotite-orthopyroxenite-websterite. The upper peridotite layers are ... and more feldspathic than the lower ones.

nd diopsidic augite could sink
e process, provides evidence of
spended in it, there being little
ystal mush.
s composed of sheets of various
ere appears to be a dunite plug
ges of formation of the sheet
roic mass into which the ultra-
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s diposidic augite, olivine and,
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neral form of a shallow basin,

ck and Noble to have formed
to 80% diopside ($Di_{75}Hed_{25}$),
They consider that successive
heet structures, but admit that
tion of crystals. One argument
g due to crystal accumulation,
monomineralic rocks exist, i.e.
an intercumulus liquid. Since
n Rhum, Bushveld, Stillwater
ed as having formed from an
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arity, it may be that much of
of crystals as at Duke Island.
e or not, it again seems likely
enites, peridotites, and dunites
y are, for instance, in Rhum,
re several cases of very thick
y of Islands, Ch. XV) overlain
, genetically related. Whether
or, more probably, ultrabasic,
nesian olivines and pyroxenes
the Great Dyke) gradation into

rcle in the Coppermine River
in 1956. The intrusion was

MUSKOX, NORTHWEST TERRITORIES, CANADA

The Muskox intrusion, which crosses the Arctic Circle in the Coppermine River area, was discovered by the Canadian Nickel Company in 1956. The intrusion was

mapped for the Geological Survey of Canada by C. H. Smith in 1959 and 1960, and brief accounts have been published (Smith, 1962; Smith & Kapp, 1963). Attention was focussed on this intrusion as part of Canadian studies related to the International Upper Mantle Project, and in 1963 the Geological Survey of Canada drilled three separate, vertical holes of 4000 ft, 3500 ft, and 2500 ft depth (Findlay & Smith, 1965). At present, the intrusion and the rocks collected from the surface and the drill-cores are being investigated systematically and in great detail by Smith and his collaborators (e.g. Bhattacharji & Smith, 1964; Jambor & Smith, 1964; Agterberg, 1964). For this reason we have confined our discussion to this brief, preliminary mention, although it is already apparent that when the present studies have been completed the Muskox intrusion will be of great interest amongst layered intrusions. The intrusion is Pre-cambrian in age, the country-rocks having been dated as 1765 to 1720 million years old.

The intrusion is dyke-like in plan and funnel-shaped in cross-section, and as now exposed it appears as a narrow dyke, 35 miles long, which widens towards the north into an intrusion about 40 miles long and, at a maximum, about 7 miles wide (Smith & Kapp, 1963, fig. 2). The latter part has a synclinal form, the eastern and western edges dipping inwards at 5 to 20°, with a slight northward plunge of about 4°.

Smith (1962) has divided the intrusion into four main units:

1. A nearly vertical feeder-dyke, 500–2000 ft wide, consisting of bands of bronzite gabbro and picrite parallel to its walls.
2. A marginal zone, 200–1200 ft thick, parallel to the walls of the intrusion which dip inward at 23–57°. This zone grades inwards from fine-grained bronzite gabbro, through picrite and peridotite, to dunite in places.
3. A central layered series, 6500 ft thick, consisting of about 35 main layers which vary in individual thickness from 10 to 1100 ft. The lower layers are cumulates with orthopyroxene, olivine, and rare chromite as the cumulus minerals, while cumulus augite and plagioclase enter at higher levels.
4. An upper border zone, less than 200 ft thick, consisting of gabbro with interstitial micropegmatite, grading upwards into granophyre.

The feeder-dyke, at its southern end, consists of bronzite gabbro. Traced north-wards, pods of picrite are found which gradually coalesce to become a single, central band of picrite. Bhattacharji and Smith (1964) have proposed a mechanism to explain this, discussed below.

The marginal zone shows a decrease in plagioclase and orthopyroxene, and an increase in olivine, from the margins inward. Simultaneously, the olivine becomes more forsteritic and the plagioclase more anorthitic. The central layered series apparently exhibits the result of sedimentation of crystals, the layering dying out near the margins. The rock types are reported as dunite, peridotite, felspathic peridotite, picrite, olivinite, clinopyroxenite, websterite, orthopyroxenite, troctolite, olivine gabbro, norite, and anorthositic norite. More critically expressed, the rocks are igneous cumulates with orthopyroxene, olivine and, less commonly, chromite as cumulus phases in the lower layered rocks, joined by cumulus augite and, finally, by cumulus plagioclase higher in the layered sequence. The approximate proportions of the different rock types in the whole intrusion indicate an overall ultramafic character, the average amount of olivine being about 58%.

The compositions of the olivine in different parts of the intrusion have been described by Smith and Kapp (1963, fig. 4). The 'central core' of the intrusion has olivine which is Fo_{85-80} and this is said to become less magnesian towards the margins, to Fo_{70-60}. This is taken to mean a grouping together of marginal and layered rocks, rather than a lateral variation within individual layers. Apparently the top 2000 ft of the central layered series shows cryptic variation in the olivine from Fo_{80} to Fo_{60}, and with the beginning of the cryptic variation in the olivine, plagioclase enters as a cumulus phase. In the lower 4000 ft or so, the olivine only varies within the limits Fo_{85} to Fo_{80}.

Until more information is available on the compositions of each cumulus phase in the Muskox layered series, on the relationship between the marginal and layered rocks, and on the inward sequences in the marginal zones, it would be premature for us to give more than this brief summary. The layered series shows evidence for cryptic variation of the type found in other ultrabasic–basic layered intrusions, such as the iron-enrichment of the olivines and the late entry of cumulus augite and plagioclase (c.f. the Bushveld, Stillwater, and Great Dyke). The presence of cumulus orthopyroxene indicates, further, that the intrusion has tholeiitic, rather than alkali-basalt affinities. In regard to the feeder-dyke, marginal zone, and upper zone rocks, however, the situation is much more complicated. The character of the chilled rock, and the tendency for a change from orthopyroxene-bearing to olivine-bearing rocks inward from the margins, are suggestive of supercooling of a hypersthene-normative magma near the margins; in that case, slower cooling to give the olivine-rich rocks should give rise to abundant quartz-bearing differentiates in the upper part of the layered series. In fact, layered rocks containing magnesian olivine (Fo_{60-70}) are overlain directly by a 200 ft-thick zone of quartz-bearing gabbros and granophyres, called the 'Upper Border Zone'. If this is, indeed, a border zone (presumably crystallized against country-rocks), then the gabbro must represent the initial magma cooled against, and contaminated with, overlying siliceous country rocks, seeing that the amount of granophyre increases upwards rather than downwards. To postulate that the quartz-bearing rocks are late differentiates of the layered series would present greater problems, since one would then need to consider a sudden change from abundant ultrabasic rocks to rare, quartz-bearing gabbros and granophyres, and the absence of an upper border zone would also need to be explained. Whatever the ultimate explanation, it would seem to us that the importance of Muskox is chiefly as an ultrabasic layered intrusion with a well-preserved feeder, showing more than the usual amount of cryptic variation (in comparison with, say, the Great Dyke and Southeastern Alaska ultrabasic intrusions),

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rather than as one showing the extreme variations found in basic layered intrusions of the Bushveld, Skaergaard, Stillwater, and Kiglapait type.

A particular feature of special significance in the Muskox intrusion has been considered by Bhattacharji and Smith (1964) where they suggest, from model experiments, that magma flowage has resulted in the differentiated nature of the feeder-dyke. Flow of magma up the feeder is thought to have resulted in the concentration of the earlier, magnesian olivines at the centre of the dyke, successive surges precipitating less magnesian olivines outwards. This relationship is also related to the pattern in the funnel intrusion above the dyke, where the olivines are more magnesian in the 'core' (i.e. the inner marginal zone and the lower layered series). Although this is an interesting hypothesis, we find it difficult to accept as an important generalization. The range of olivine compositions involved is high, i.e. from Fo_{85} to Fo_{60}, and this must represent a large range in temperature of crystallization. This, in turn, means that the feeding fissure and the marginal zone need to be open continuously at temperatures down to those when Fo_{60} is in equilibrium with the magma, i.e. well after the deposition of about 5000 ft of layered rocks directly above the fissure (Smith & Kapp, 1963, fig. 4). It is difficult to accept these conditions, especially in the narrow feeder-dyke where extremely tall, thin, vertical sheets of successively-crystallized material would need to stand while magma poured past on each side without congealing at the walls, and while it found its way always between the thick cumulates of the overlying funnel-intrusion and its walls. At present we feel that further consideration might be given to the possibility that in the dyke and marginal zone, the inward increase in the Fo-contents of the olivines and the increase in olivine relative to orthopyroxene are due to a gradual decrease, inwards, in the degree of supercooling of the magma (i.e. in relation to the systems Fo–Fa and Fo–SiO_2, respectively).

h) *Caribou Lake, Ontario, Canada*

This basic intrusive body, situated in the Grenville Province of the Canadian Shield, covers an area of about 7 square miles (Friedman, 1957). Rhythmic layering helps to define two synclinal areas in the western part, but the cryptic variation suggests a differentiation path originating in the extreme southeast of the complex, where the only ultrabasic rocks are found. The olivine (Fo_{80}) is restricted in occurrence, whereas plagioclase, orthopyroxene and augite show systematic changes in composition which are suggestive of cryptic variation. The orthopyroxene range is from En_{88} (picrites) to En_{60} (norites) and the plagioclase range from An_{68} (picrites) to An_{50} (norites), the relatively sodic felspars in the picrites probably indicating that the measured plagioclase is of intercumulus rather than cumulus status. The compositions of 'coexisting' mineral phases are plotted against one another, and compared with similar data from other layered basic intrusions. We feel that certain anomalies observed by Friedman may well be due to the distinction not being drawn between cumulus and intercumulus phases.

E&SS 236 - Adv. Igneous Petrology Dr. DePaolo

LAB EXERCISE #1 - Muskox

PART 2
(Give your answers to the following directly on the pages containing Figures 5, 6 and 8)

1. In the lower part of the layered sequence in the Muskox intrusion, the crystallization sequence was OL followed by OL+CPX followed by OL+CPX+PLAG. The resultant cumulate rock types are dunite, olivine clinopyroxenite and olivine gabbro.

   a. On Figure 5 plot the modal compositions of samples M529 and DM-39 (and label them).

   b. Graphically determine the approximate composition of the liquid with which M529 was in equilibrium when it formed; indicate its composition with a small circle, labelled "M529-liq", on Figure 5.

   c. What would you estimate to be the percentage of intercumulus liquid in sample M529?

   d. Briefly explain how the above-mentioned crystallization sequence is produced by fractional crystallization (show the liquid path on Fig. 5, the starting point is somewhat arbitrary).

   e. Is the mode of sample DM-39 consistent with the phase diagram? In what way?

2. In the upper part of the layered sequence, the crystallization order was OL followed by OPX (alone), followed by OPX+CPX, followed by OPX+CPX+PLAG. The resultant cumulate rock types are dunite, orthopyroxenite, websterite and two-pyroxene gabbro (also known as gabbronorite).

   a. On Figure 6, plot the modal composition of samples DM-2 and DM-1 and label them.

   b. Explain using Figure 6 how the crystallization sequence OL→OPX→OPX+CPX arises.

   c. Explain how sample DM-2 came to have interstitial quartz.

   d. The phase diagram, Figure 8, is actually a projection in the 4-phase system shown in Figure 7. Is the mode of sample DM-3 consistent with Figure 8? Explain.

3. Sample DM-4 contains three cumulus minerals. Using Figure 6, explain how a liquid that originally crystallizes OL alone can evolve by fractional crystallization to a point where it can crystallize OL+2 pyroxenes simultaneously.