

Developments in Petrology 6

TRONDHJEMITES, DACITES, AND RELATED ROCKS

Edited by

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PETROGENESIS OF HIGH PRESSURE TRONDHJEMITIC LAYERS IN ECLOGITES AND AMPHIBOLITES FROM SOUTHERN MASSIF CENTRAL, FRANCE

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ABSTRACT

Layers of trondhjemite occur in eclogites and high pressure amphibolites belonging to the leptyno-amphibolitic complex of Rouergue (Southern Massif Central). These trondhjemites are low in Al and depleted in K, Rb, Cs, but they have high content of other lithophile elements compared to oceanic plagiogranites and granites. Trace element data imply at least two stages in the genesis of these rocks. The textures and initial mineral assemblage (quartz, plagioclase, kyanite, zoisite, garnet) suggest that these rocks crystallized from a melt under high pressure granulite facies conditions ($P \simeq 12.5 - 20$ kb; $T \simeq 750-840^{\circ}\text{C}$). Solid-solid reactions, such as zoisite \rightarrow Al-epidote, indicate a subsequent retrogression under conditions of the amphibolite facies.

(Abbreviations for phases in text and figures: qz = quartz, pl = plagioclase, Ab = albite, ol = oligoclase, an = anorthite, ky = kyanite, sill = sillimanite, ga = garnet, stl = staurolite, zo = zoisite, al ep = Al epidote, cpx = clinopyroxene, amph = amphibole, hb = green hornblende, mus = muscovite, bi = biotite, co = corundum, sp = green spinel, rt = prismatic rutile, il = ilmenite, sph = sphene, V = H₂O vapor, L = liquid.)

INTRODUCTION

A distinctive association of rock types known as the leptyno-amphibolitic complex occurs in the highly deformed and metamorphosed part of the Variscan belt of Europe (e.g., in the Granulitgebirge, Munchberg, Bohemian Massif, Brittany Massif, NW Iberic peninsula, french Massif Central).

The distinctive characteristics of the association includes bimodal association of acidic and basic rocks, tholeiitic affinities of the basic rocks, presence of metagraywackes, pyroclastic rocks, carbonaceous rocks, quartzites and ultramafic rocks (Behr, 1961; Forestier, 1963; Scharbert, 1963; Lange, 1965; Matejowska, 1967; Vogel, 1967; Losert, 1971; Zoubek, 1971; Briand, 1973; Marchand, 1974; Lasnier, 1977; Piboule, 1977; Piboule and Pontier, 1977).

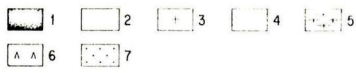
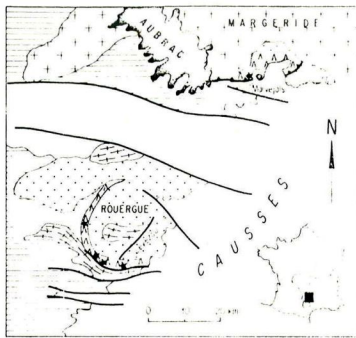


Figure 1a.--Sketch map of the studied zone (SW Massif Central). Stars: location of trondhjemites layers. (1) Plio-Quaternary basalts, (2) Post Variscan rocks, (3) Variscan granite, (4) quartz-pelitic series, (5) orthogneiss, (6) leptyno-amphibolic complex, (7) migmatites.

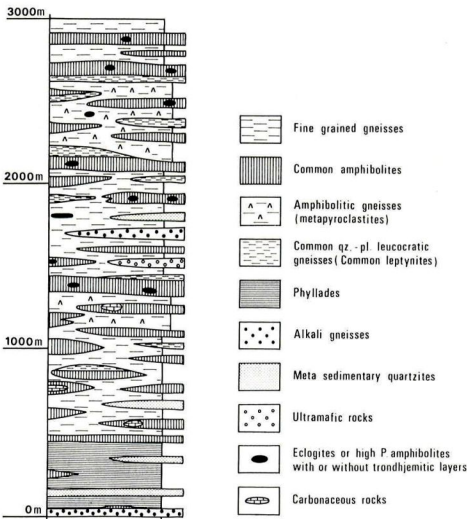


Figure 1b.--Stratigraphic sequence of the leptyno-amphibolic complex of Lézou.

In the studied area (Fig. 1), the leptyno-amphibolitic complex has been subjected to high and low pressure metamorphism (Briand, 1973; Nicollet, 1978). We are presently concerned with the leucocratic (acidic) layers with trondhjemitic composition in the high pressure rocks. The petrogenesis of these rocks imposes constraints on the formation and evolution of the leptyno-amphibolitic complex and provides information about the origin of trondhjemites in a metamorphic context.

GEOLOGICAL SETTING AND FIELD RELATION

Such leucocratic layers have been described in various metamorphic belts (Lange, 1965; Vogel, 1967; Mottana et al., 1968; Bryhni et al., 1970; Green and Mysen, 1972; Lasnier, 1977). They were first recognized in the leptyno-amphibolitic complex of the Rouergue by Collomb (1964), where the leucocratic layers (2-10 cm thick) are intercalated with eclogites or garnet-clinopyroxene amphibolites. In some cases the interlayering is on a millimeter scale with sharp contact between basic and leucocratic layers. Where the layers are thicker (centimeters), quartz appears along the margin of basic rocks.

The complex rock system (leucocratic layers + eclogites or garnet-clinopyroxene amphibolites) is always surrounded by the low P amphibolites which are themselves included in low P fine-grained pelitic or volcano-detrital gneisses. No direct contact between leucocratic layers and low P surrounding rocks is observed.

A systematic sampling of the acidic layers has been carried out for petrographical study in Lézéou and Marvejols regions (Fig. 1). The analyzed samples were taken from two outcrops 3.5 km (far apart from each other) in the Levezou area ($X = 633.4$; $y = 3197.2$; $X = 637$; $Y = 3196.6$).

PETROGRAPHY

The characteristic observed mineral association of these trondhjemitic rocks may be subdivided into quartz-rich and plagioclase-rich leucocratic layers. In the following list of mineral assemblages, the minerals in brackets form corona around the preceding mineral (e.g., $ky(ol)$: oligoclase corona on kyanite). Successive coronas are designated by two or more brackets. Apatite, magnetite, pyrite, and zircon are present in all rocks.

Quartz-rich leucocratic layers

- (a) $qz-ky(ol)-zo(ol)-ga-rt-il$
- (b) $qz-ky(co+qz^{\pm}sp(ol))-zo(ep(ol))-ga(hb+ol)-stl-rt(sph)-il(sph)$
- (c) $qz-ky(sill(ol))-zo(ep(ol))-ga-rt(sph)-il(sph)$
- (d) $qz-ky(ga(ol))-zo(ol)-ga-rt-il$

- (e) qz-ky(sp + pl(ga(ol)))-zo(ep(ol))-ga(hb + ol)-rt(sph)-il(sph)
 (f) qz-ky(musc(ol(fk)))-zo(ol)-ga-rt-il
 (g) qz-ky(musc(biot + pl(ol(fk)))-zo(ep(ol))-ga-rt(sph)-il(sph)
 (h) qz-zo(ol)-ga-rt-il
 (i) qz-zo(ep(ol))-ga(hb + ol)-rt(sph)-il(sph)-

Plagioclase rich leucocratic layers

- (j) qz-ol-ky(ol)-zo(ol)-ga-hb-rt-il-
 (k) qz-ol-ky(co+qz[±]sp(ol))-zo(ep(ol))-ga(hb + ol)-hb-rt(sph)-il(sph)
 (l) qz-ol-ky + stl(ol)-ga-hb-rt-il-ap-mg-pt,zr
 (m) qz-ol-ky + stl(ol)-ga(hb + ol)-hb-rt(sph)-il(sph)-ap-mg-pt-zr

The most frequent parageneses are (a), (b), (d), (j), and (k).

Figures 2-6 illustrate the complex textures of the rocks. The detailed mineralogy has been recently described (Nicollet and Leyreloup, 1978); only a few important points are included here: The unzoned oligoclase (An₁₀-An₂₅) (Table 1) appears as polycrystalline coronas of thin crystals arranged radially around kyanite (Fig. 2), zoisite (Fig. 3) and muscovite (where it has replaced kyanite) when in contact with quartz or matrix oligoclase. Such a corona is lacking when these minerals are in contact with or included in another mineral (e.g., kyanite in garnet). The kyanite may be partially (Fig. 4) or completely rimmed by garnet. A peculiar association: kyanite, staurolite, plagioclase is found forming polycrystalline dendriform aggregates (Fig. 5a). Crystals of the

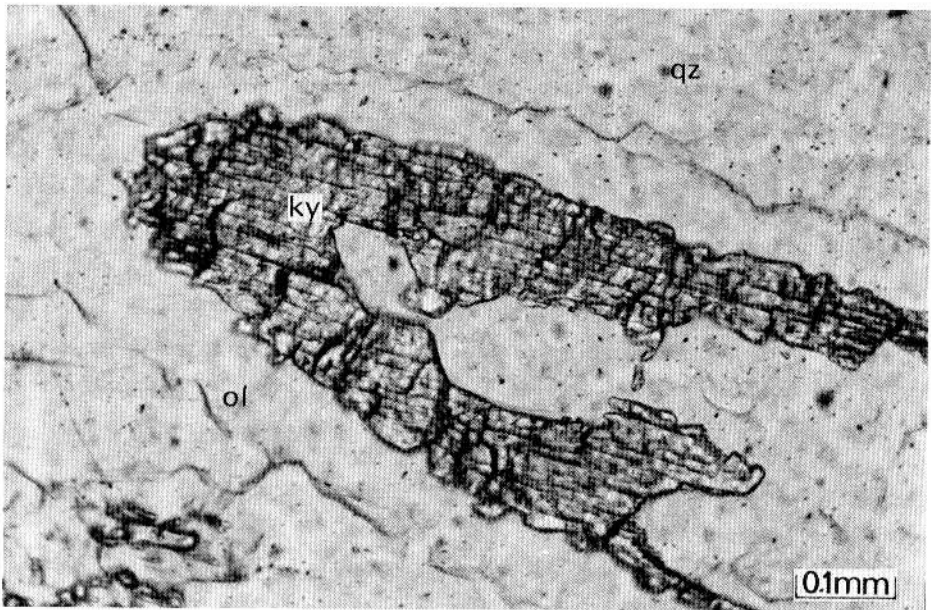


Figure 2.--Oligoclase corona surrounding kyanite.

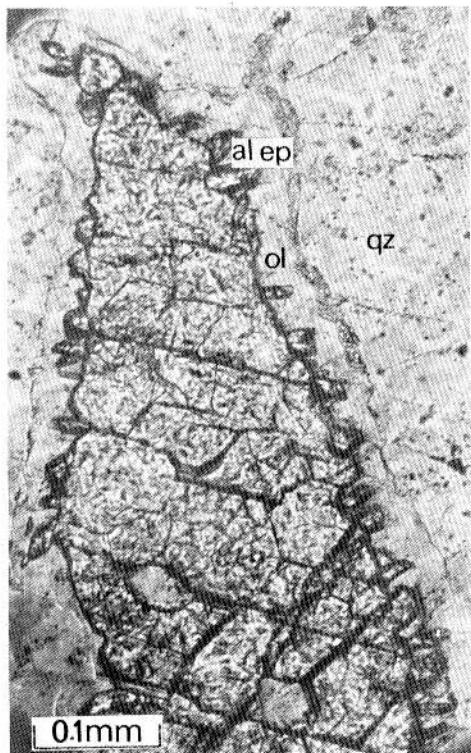


Figure 3.--Oligoclase corona surrounding zoisite. Secondary Al epidote radially arranged at the oligoclase boundary.

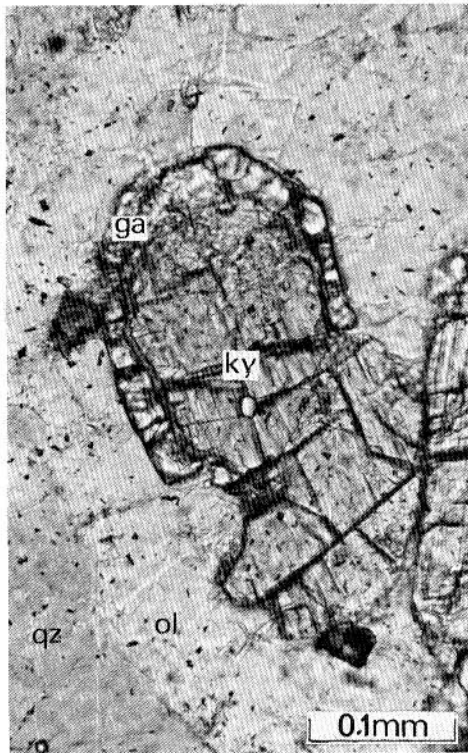


Figure 4.--Rim of garnet around kyanite within the oligoclase corona.

same nature display a unique optical orientation and are limited by curved boundary (Fig. 5b).

The mineralogical features suggest a complex petrogenetic history for these rocks which includes at least a high pressure granulite metamorphism followed by sub-solidus retrogression in the amphibolite facies.

High Pressure Parageneses

The assemblages (a) (d) (h) and (j) (l) represent the most common high pressure parageneses, in quartz and plagioclase-rich rocks, respectively. The association quartz, kyanite, zoisite suggests high pressure and temperature (Boettcher, 1970), consistent with that indicated by the surrounding eclogites (omphacite, almandin-pyropo, quartz, zoisite, kyanite and exceptionally corundum (Nicollet, 1977)) and garnet-clinopyroxene amphibolites (andesine,

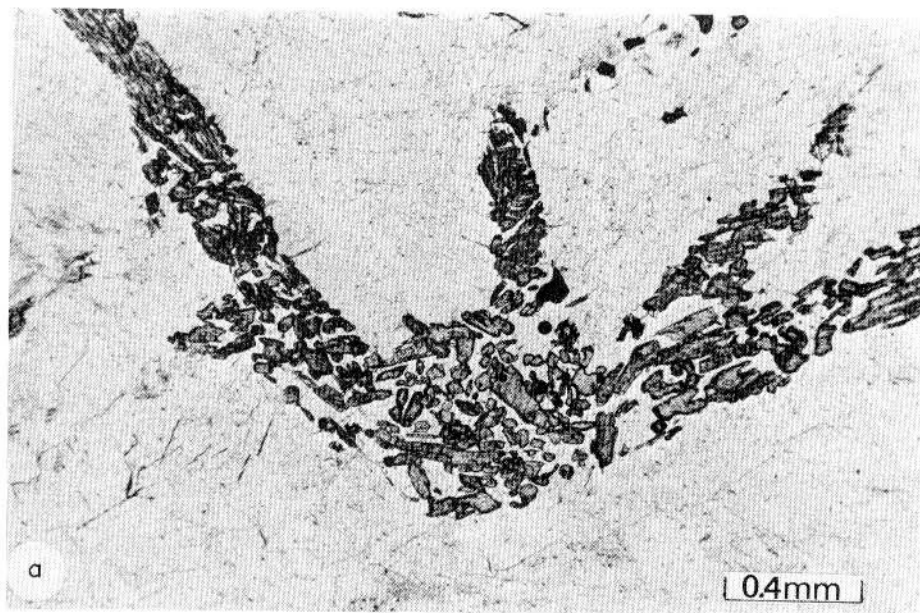


Figure 5.--Dendrites with kyanite, staurolite, oligoclase.
 (a) Trifold Texture. (b) Texture showing a curved
 boundary between aggregate of kyanite and staurolite.
 Oligoclase represents the interdendritic phase.

TABLE 1 : Microprobe analyses of some minerals of trondhjemites.

	Plagioclases ^(*)			Zoisite 1	Al		Muscovite
	(ky)	(zo)	(mus)		Epidote 2	Garnet	
SiO ₂				38.15	38.5	39.42	52.61
TiO ₂				0.11	-	0.16	0.48
Al ₂ O ₃				32.06	27.51	21.89	30.41
Fe ₂ O ₃				1.45	7.03		2.46
FeO						20.56	
MnO				-	-	0.67	-
MgO				-	0.8	6.58	2.17
CaO	3.27	3.03	3.38	25.75	24.68	11.51	-
Na ₂ O	9.39	8.48	8.22	0.05	0.08	0.01	.38
K ₂ O	0.03	0.05	0.9	0.04	0.05	-	9.78

* : Oligoclase corona surrounding kyanite, zoisite, muscovite.

TABLE 2 : Averaged compositions of the trondhjemites and surrounding metabasites.

	Quartz-rich Leucocratic layers	Plagioclase-rich Leucocratic layers	Eclogites	<i>ga-epx</i>	amfibolites
N	6	10	9	1	1
SiO ₂	76.77(4.52)	76.87(2.79)	48.86(2.02)	54.14	54.82
TiO ₂	0.33(0.13)	0.20(0.09)	1.01(0.57)	0.95	0.78
Al ₂ O ₃	12.10(1.79)	12.35(0.90)	17.32(2.51)	15.15	16.22
Fe ₂ O ₃	1.99(1.50)	0.72(0.44)	2.86(1.39)	4.37	4.19
FeO	2.10(1.34)	1.04(0.44)	6.68(2.00)	6.61	4.31
MnO	0.05(0.02)	0.03(0.01)	0.18(0.04)	0.21	0.11
MgO	1.06(0.58)	0.57(0.31)	7.91(1.50)	4.68	4.86
CaO	2.17(0.68)	1.64(1.07)	10.16(1.48)	3.90	7.26
Na ₂ O	1.86(0.81)	4.91(0.52)	2.50(0.95)	3.65	5.79
K ₂ O	0.48(0.51)	0.23(0.25)	0.39(0.39)	0.38	0.10
P ₂ O ₅	-	-	-	0.40	-
H ₂ O ⁺	0.07(0.02)	0.07(0.02)	0.12(0.10)	0.18	0.15
H ₂ O ⁻	0.53(0.23)	0.47(0.19)	1.32(0.56)	1.58	0.82

() : Standard deviation; N : Number of samples.

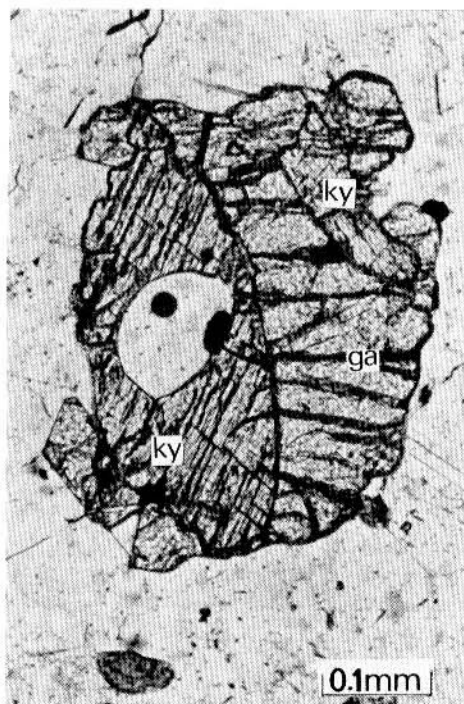


Figure 6.--Early composite garnet kyanite megacryst.

hornblende, almandine, clinopyroxene, quartz, zoisite, rutile, ilmenite). After the work of Storre and Karotke (1972), the occasional presence of muscovite may indicate a lower temperature for some samples. The occurrence of plagioclase associated with kyanite and zoisite (Boettcher, 1970) approximately established the minimum pressure these rocks were subjected to.

Sub-solidus Retrogressive Evolution.

The initial parageneses of trondhjemitic rocks and those of eclogites suffered the same static retrogressive evolution. It is noteworthy that the garnet-clinopyroxene amphibolites are not significantly affected by this secondary process, since their primary paragenesis may remain stable at intermediate pressure. The eclogites are generally retrorhormorphosed according to the scheme described by Lasnier (1977).

The observed sub-solidus reactions involved in the static retrogression of the trondhjemitic primary assemblages (a, d, g, h, f, h and j, l) may be summarized as follows:

- (1) $ky \rightarrow co + qz \pm sp$
- (2) $ky \rightarrow sill$
- (3) $ky + ga \rightarrow sp + pl \pm qz$
- (4) $ky + ga + H_2O \rightarrow stl + qz \pm sp$
- (5) $zo + pl \rightarrow Al \quad ep$
- (6) $ga + qz \rightarrow hb + ol$
- (7) $mus + Fe, Mg \rightarrow bi + pl$
- (8) $rt \rightarrow ilm \rightarrow sph$
 $rt \rightarrow sph$
- (9) $ilm \rightarrow sph$

Kyanite is surrounded either by very fine symplectitic intergrowths of corundum + quartz or green spinel + quartz (1); the plagioclase in contact with spinel and quartz symplectite is zoned and may be involved in the reaction. Such reactions, already known in eclogites (Lappin, 1966; Lasnier, 1977; Nicollet, 1977) are similar to that observed in alloys during a eutectoid decomposition (Nicholson and Davies, 1971; Fridberg and Hillert, 1977). As a garnet rim sometimes exists around the green spinel-quartz symplectite it is possible to explain the formation of the symplectite by a reaction involving kyanite and garnet: garnet + kyanite \rightarrow spinel + quartz \pm plagioclase (3). This reaction has been described in khondalito-kinzigitic metapelites (Kornprobst, 1971; Leyreloup, 1973; Marchand, 1974; Loomis, 1976) and in metabasic rocks (Lasnier, 1977; Nicollet, 1977). A second reaction similar to one studied by Ganguly (1972) can be inferred from some textural relations between kyanite and garnet: kyanite + garnet + $H_2O \rightarrow$ staurolite + quartz \pm biotite (4). Locally, kyanite is replaced by prismatic needles of sillimanite (2) and it alters in a later stage to a white mica mosaic.

Within the plagioclastic corona, small secondary Al-rich epidotes arranged radially around the primary zoisite (Fig. 3) can be explained by reaction (5). The Al-epidote becomes enriched in Fe^{3+} and may completely replace the zoisite in more retro-morphosed rocks with pistacite as ultimate product. At the end of the retrogression process, Na-plagioclase and sometimes allanite formed at the expense of the epidote solid solution minerals. After Holdaway (1972), the position of the destabilization curve for the zoisite-Al-epidote transition in the P-T grid depends on the respective iron (Fe^{3+}) contents of these two mineral species. Such a reaction is not pressure dependent and, for the composition given in Table 1, takes place at approximately 750°C. The transformation zoisite \rightarrow Al-epidote indicates a decrease of temperature. The change in the chemistry of secondary epidote has been related to a decrease in pressure-temperature and/or to an increase in $f(O_2)$ by Raith (1976). In the present case, it can be related to the retrogressive metamorphism.

Garnet has reacted not only with kyanite, as described above, but also with quartz to produce a corona of oligoclase and green hornblende (reaction 6). This reaction may be the equivalent, in the stability field of amphibole, to the classical reaction: garnet + quartz \rightarrow orthopyroxene + plagioclase, which separates the intermediate and high pressure granulite facies (Green and Ringwood, 1967).

Muscovite is replaced by biotite or by a symplectitic intergrowth of biotite + plagioclase (reaction 7). Such textural relationships are commonly observed in eclogites during the kelyphitization processes (Briere, 1920; De Wit and Strong, 1975; etc.).

Rutile is altered to ilmenite and/or sphene (reaction 8).

Thus, all these retrogressive transformations have produced low pressure mineralogical assemblages typical of the amphibolite facies which are similar to those commonly found in the leptynites of the leptyno-amphibolitic complex in Europe. The main retrograde transformations associated with the various primary assemblages are summarized as follows:

Initial assemblages	Retrogressive assemblages	Involved reactions
a	b, c	1, 3, 4, 5, 6, 8, 9
d	e	3, 5, 6, 8, 9
f	g	5, 7, 8, 9
h	i	5, 6, 8, 9
j	k	1, 5, 6, 8, 9
l	m	4, 6, 8, 9

CHEMISTRY

Chemical analyses carried out by Coffrant and Piboule (1975), Piboule (1977), Piboule and Pontier (1977), have shown that the basic rocks of the leptyno-amphibolitic complex have both calc-alkaline and tholeiitic (oceanic) affinities. Our analyses (Table 2) on some eclogites and amphibolites are in agreement with their conclusions. This paper, however, concerns only the chemistry of the leucocratic layers.

Major Elements

Sixteen samples of acidic rocks have been analyzed for major elements. Average contents are reported on Table 2. These rocks present high silica (71-83%) and relatively low Al_2O_3 content (8.7-13%). They are usually depleted in K_2O (<0.64%). In contrast, the concentration of femic elements, Ca and Na, are in the range generally registered for common acidic rocks. These chemical

characteristics are quite different from those of metasediments but close to those of continental trondhjemites and more specifically the oceanic plagiogranites studied by Coleman (1977). One of these characteristics appears by plotting SiO_2 against K_2O . The high silica associated with relatively low total alkalis explains the presence of normative corundum. Normative orthoclase is less than 4 mol % (muscovite rich layer excepted) and the normative An content of the plagioclase ranges from An_4 to An_{56} . This wide range contrasts with the relative homogeneity of the bulk chemical analyses (Tables 2 and 3) and favours the hypothesis of a complex petrogenetic history for these leucocratic layers.

On the graph Ab-Or-An-normative (Fig. 7), these rocks plot within the low pressure one feldspar field (trondhjemite and tonalites; O'Connor, 1965). But the high silica content excludes any affinity with tonalites. No differentiation trend toward a ternary minimum is observed. The evolution displayed in the AFM diagram (Fig. 8) is similar to that reported for trondhjemites by Coleman (1977, fig. 18). The leucocratic layers can be considered as low Al trondhjemites. They have affinities with oceanic plagiogranites (Moore and Vines, 1971; Barker et al., 1976; Parrot, 1976; Payne and Strong, this volume; etc.) and differ from continental granophyres (Coleman, 1977) by a lower K content.

Trace Elements

Alkali, alkali-earth, Th, Hf.--The rocks studied are depleted in Rb and Cs as in K (Table 3). Their low Rb/Sr ratios (0.001-0.04) are similar to those reported by Coleman and Peterman (1975) for oceanic plagiogranites. In contrast, their Ba, Th, Hf content is quite high and in the same range as the concentrations published for leucogranites and rhyolites (Taylor et al., 1968).

Some Sr values are similar to those of Barker et al. (1976) for the low Al_2O_3 trondhjemites; others are higher. All these elements vary and generally display a good correlation between themselves (Sr excepted). A correlation also appears between K-Rb with moderately high K/Rb ratio ranging between 350-700. Then values are comparable to those of Ishizaka and Yanagi (1977) for the plagiogranites.

Sc-Co-Cr.--The content of transition elements is low and similar to those encountered in common acidic rocks (e.g., granite and leucogranites, Kolbe and Taylor, 1966; dacite and rhyolite, Taylor et al., 1969), and in plagiogranites (Coleman and Peterman, 1975). A correlation appears between Cr and Co but not between these elements and Sc. Sc is nicely correlated with La/Yb ratio (sample 6 excepted) (Fig. 9). Furthermore, Cr and Co are correlated with some incompatible elements and more especially with Ba. This anomalous correlation is not common in magmatic processes.

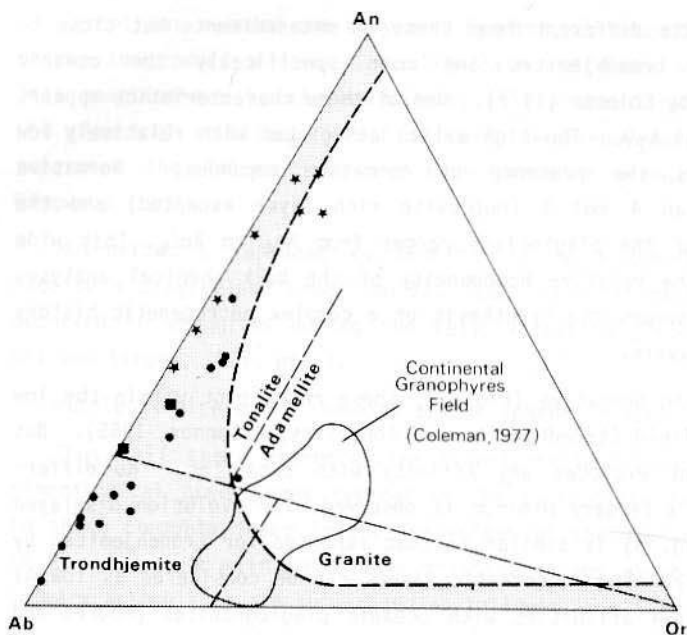


Figure 7.--An-Ab-Or normative triangular plot. Shaded area, low pressure feldspar field ($< 5 \text{ Kb}$). Separate various rock types according to O'Connor (1965). Stars: eclogites; squares, garnet-clinopyroxene amphibolites; spots, trondhjemitic layers.

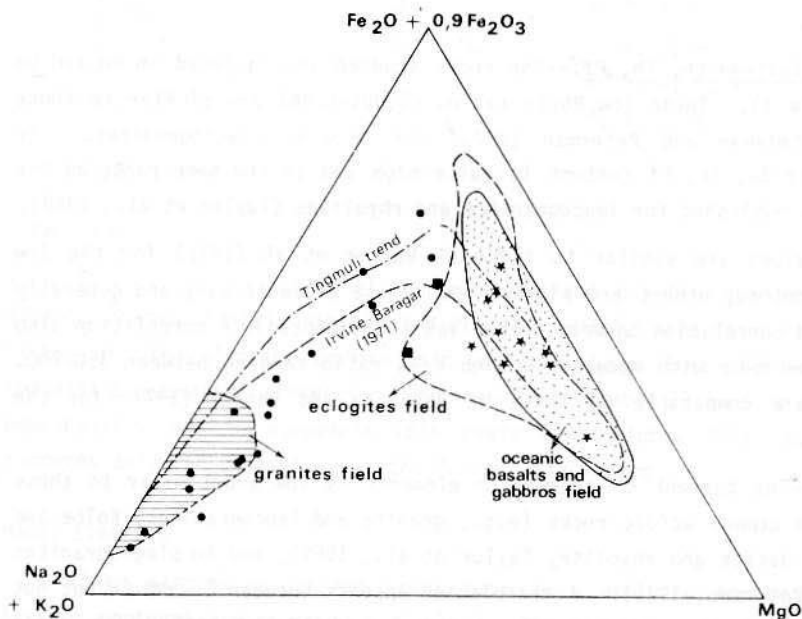


Figure 8.--A.F.M. triangular plot. Eclogitic field after Wager and Brown (1968). Oceanic rocks after Mottana et al. (1968). Symbols as on Figure 7.

TABLE 3 : Major and trace element contents of selected trondhjemitic samples.

Major elements (%)	1	2	3	4	5	6
SiO ₂	83.55	78.38	74.15	73.24	80.09	78.79
TiO ₂	0.22	0.25	0.25	0.55	0.10	0.37
Al ₂ O ₃	8.73	12.16	13.49	13.70	11.73	13.47
Fe ₂ O ₃	0.91	1.75	1.59	2.51	0.00	1.08
FeO	0.89	1.29	1.29	2.21	0.66	1.81
MnO	0.02	0.05	0.02	0.07	0.02	0.06
MgO	0.47	0.60	0.48	1.45	0.19	0.97
CaO	2.25	3.01	2.04	1.91	0.38	1.09
Na ₂ O	1.49	1.41	5.16	2.43	5.16	0.75
K ₂ O	0.34	0.17	0.07	0.36	0.03	0.17
H ₂ O ⁺	0.08	0.09	0.06	0.07	0.03	0.04
H ₂ O ⁻	0.90	0.57	0.31	0.60	0.30	0.44
Trace elements (p.p.m.)						
Li	21	6	5	9	5	6
Rb	8	4	1	5	1	2
Cs	0.5	0.3	0.2	0.27	0.16	0.25
Sr	445	455	710	80	225	55
Ba	785	333	129	140	77	550
Hf	16.8	8.4	5.0	5.2	3.1	4.5
Th	22.5	13.4	6.3	8.9	10.3	6.3
La	87.9	36.5	21.9	10.1	11.5	2.7
Ce	178.1	74.5	47.6	24.1	32.4	4.8
Nd	115	44.9	28.0	10.3	13.8	2.9
Sm	24.0	10.2	5.4	2.4	3.5	1.1
Eu	2.83	1.46	1.16	0.46	0.13	0.32
Tb	3.6	1.7	0.98	0.55	0.63	0.74
Yb	11.7	8.60	5.11	3.68	1.85	3.92
Lu	1.73	1.36	0.84	0.66	0.31	0.70
Sc	4.8	11.8	10.8	14.5	7	14.9
Co	12.1	6.8	3.2	6.3	1	4.3
Cr	10.7	9.2	2.8	5.9	2.6	7.1

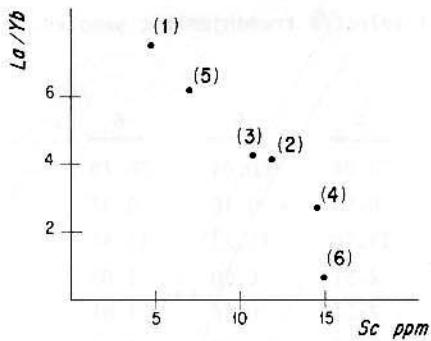


Figure 9.--Variations of La/Yb ratios against Sc in trondhjemites. The numbers are the reference samples reported in Table 3.

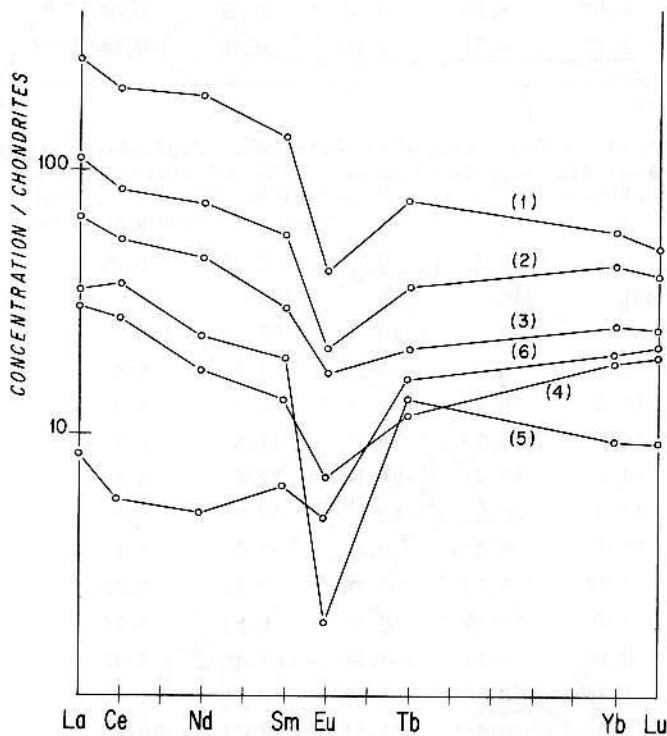


Figure 10.--Rare earth element abundances in trondhjemites normalized to a chondritic average (Frey et al., 1968). Numbers 1 to 6 refer to samples of Table 3.

R.E.E.--The R.E.E. patterns (Fig. 10) are characterized by a negative Eu anomaly and generally light RE enrichment relative to the chondrite average. These features are commonly observed in granites (s.l.) (Haskin et al., 1966; Nagasawa, 1970; Taylor et al., 1968; etc.) and differ markedly from the trend displayed either by dacite and rhyolites related to orogenic calc-alkali magmatism (Gill, 1974; Lopez-Escobar et al., 1977; Ewart et al., 1973; Dostal et al., 1977) or by oceanic plagiogranites (Kay and Senechal, 1976).

According to their La/Yb ratios, the analyzed rocks may be subdivided:

-The two samples (nos. 1 and 5) with the highest La/Yb ratios (6) are the most siliceous and display a slight heavy RE fractionation; their pattern is quite similar to those of the granophyre from Ardnamurchan (Walsh and Henderson, 1977).

-The three samples (nos. 2, 3, 4) with lower La/Yb (4.5) show very similar patterns to those reported by Barker et al. (1976) for the trondhjemites of Rio Brazos.

-Sample no. 6-- its trend is characterized by a depletion of light R.E.E. Such a pattern is generally registered by the albitized riebeckite granites in relation to secondary alteration process (Mineyev, 1963). Sample 6 has the lowest Na₂O content and does not display any trace of albitization. Metasomatic processes advocated for the generation of trondhjemites (e.g., Hughes, 1973) cannot produce such a trend (Floyd, 1977). Furthermore, it has been demonstrated (Nicollet and Leyreloup, 1978) that this alteration process is unlikely in the present case.

ORIGIN

The three main processes that have been proposed for the origin of trondhjemites are considered here. The particular chemical trend of the Rouergue trondhjemites, however, requires a fourth hypothesis implying a two-stage evolution model.

Fractional crystallization--The origin of trondhjemites by low pressure fractional crystallization from a basic magma is the most frequently suggested hypothesis (Kay and Senechal, 1976); Coleman, 1977; Erickson, 1977). A low K andesitic magma (Barker and Arth, 1976) cannot be a source for our trondhjemites because dacites and rhyolites produced from such a source (Yajima et al., 1972; Ewart et al., 1973) have a very different REE pattern and different absolute trace element contents.

A basic magma source such as those generating oceanic plagiogranites (Coleman and Peterman, 1975) and trondhjemites associated with ophiolites (Kay and Senechal, 1976; Coleman, 1977) produces a residual liquid with a lithophile

element content much lower (K, Rb, Cs excepted) than those reported in Table 3. Furthermore, no low pressure fractionation process from a unique source rock may explain the geochemical characteristics of the studied trondhjemites (e.g., correlation La/Yb-Sc or Cr-Ba). This hypothesis is definitely unacceptable since four trondhjemite samples with large REE range are collected in a very small area (few square meters).

Anatexis of metasediments (Barth, 1962).--Contrary to the observations of Bryhni et al. (1970) and Green and Mysen (1972) in the Caledonian of Norway, the trondhjemites layers are exclusively located among basic rocks which are surrounded by fine-grained pelitic gneisses devoid of any trace of mobilization. Consequently, it is most unlikely that the trondhjemites were derived from the metasediments. Furthermore, the partial fusion of these gneisses cannot generate a liquid with such trace element content.

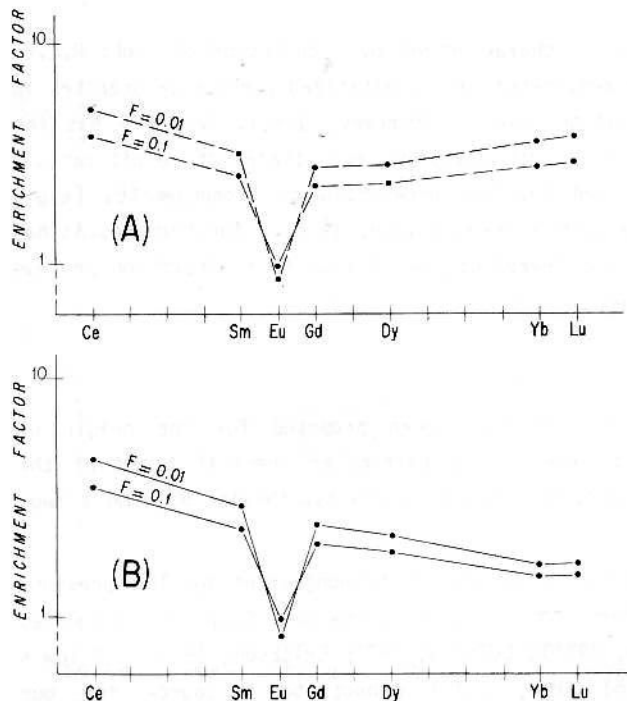


Figure 11.--Enrichment factor Cl/Co for REE in melts produced by partial melting of amphibolites. Using equation is of Shaw (1970) and the partition coefficient values compiled by Arth and Hanson (1975). Two mineralogical assemblages are considered: (A) Parent: 0.5 hb; 0.4 pl, 0.1 cpx, melt; 0.2 nb, 0.8 pl. (B) Parent: 0.5 hb; 0.4 pl, 0.05 cpx, 0.05 ga melt; 0.2 hb; 0.8 pl. The calculation has been done for variable degrees of partial melting (F). Only those for F = 1% and F = 10% are reported. The incongruent fusion of hornblende does not disturb the REE pattern in the resulting liquid.

Partial melting of the metabasic rocks (Arth and Hanson, 1972; Barker et al., 1976; Barker and Arth, 1976; Payne, 1973).--The partial fusion of eclogites or garnet granulites produces a strong RE fractionation in the resulting liquid with pattern very different from those shown by the trondhjemites (Gill, 1974; Arth and Hanson, 1975). On the other hand, the surrounding amphibolitic rocks with the mineralogical assemblages--hornblende + plagioclase \pm clinopyroxene \pm garnet--could be a source of the trondhjemites. The calculation of the partial fusion model of such a mineralogical assemblage (Fig. 11) explains the REE pattern of the trondhjemites (Fig. 10). It implies plagioclase as a residual phase since the trondhjemites display negative Eu anomalies and no correlation between Sr and other incompatible elements such as Ba and K. According to the partition coefficient value used for the calculation, the samples with the highest La/Yb ratio and with a slight H.R.E.E. fractionation (samples 1 and 5) imply also garnet as residuum.

The large range of R.E.E. content cannot be explained only by a variable degree of partial melting. This large range of variation implies a source rock with variable chemical and mineralogical composition. The variable mineralogical assemblage in the source rocks may easily explain the negative correlation between Sc and La/Yb ratio as shown by the calculations reported graphically in Figure 12. Samples 1 and 5 with the lowest Sc content and highest La/Yb ratio imply in agreement with the previous observation that garnet would occur in the residuum mineral assemblage. This hypothesis explains all the geochemical characteristics of the trondhjemites if quartz is present in the source rocks, in order to explain the high silica content. However, the distinctive REE pattern of sample no. 6 and the positive correlation between Cr and Ba put some constraint on this model. In sample no. 6, devoid of zoisite, a consecutive fractionation of this mineral may justify its R.E.E. trend (if we accept relative light R.E.E. enrichment in zoisite similar to those published for allanite; e.g., Adams and Sharp, 1972). But this fact cannot explain the content of other elements (for instance, the low Na₂O concentration).

Two-stage evolution model.--The partial fusion of an igneous acidic parent (Fig. 13), with a trondhjemitic mineral assemblage (quartz-oligoclase-biotite), accounts for most of the geochemical observations, even the correlation Cr-Ba and the peculiar trend of the sample (Fig. 10) The calculations reported on Figure 13 suggest that the studied rocks are partly refractory residuum and partly differentiated product. This hypothesis is sustained by the observation of thin sections; the squelettic kyanite in sample no. 6 represents remelting textures similar to those described by Busch et al. (1974). But this conclusion raises the question of the parental material of these trondhjemites. If lithophile element enrichment by some alteration process is excluded, the

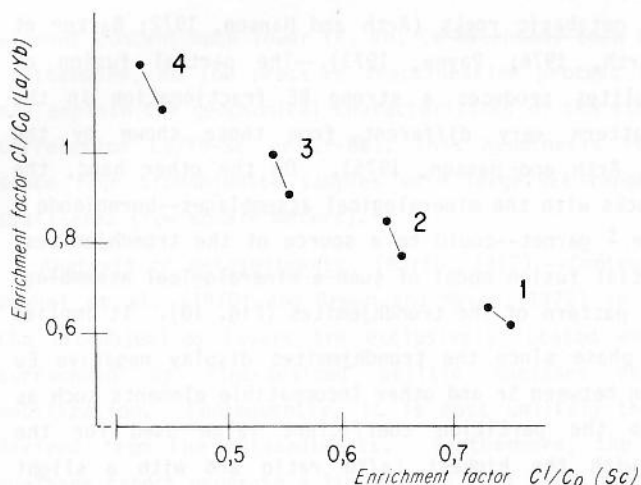


Figure 12.--Variations of La/Yb ratios against Sc (expressed as Cl/Co during partial melting of the amphibolites using equation 15 of Shaw (1970). Four mineral assemblages are considered:

1. 0.4 pl; 0.5 hb; 0.1 cpx
2. 0.3 pl; 0.6 hb; 0.1 cpx
3. 0.25 pl; 0.65 hb; 0.07 cpx; 0.03 ga
4. 0.20 pl; 0.70 hb; 0.03 cpx; 0.07 ga

In every case the fractional melt was formed from 0.8 pl and 0.2 hb. The calculation is done for F comprised between 5% and 10% with partition coefficient values of Arth and Hanson (1975) for REE and of Lopez-Escobar et al. (1977) for Sc.

plagiogranite with the composition reported by several authors (e.g., Coleman, 1977) cannot generate the acidic rocks during anatexis because of their high REE, Ba, etc., content. Continental granophyres or various acid volcanics (Barker, pers. comm.) may be in this respect a preferred source material but they imply an escape of alkali (K, Rb, Cs) during prograde metamorphism. The parental acidic rock may have been a trondhjemite produced by partial fusion of amphibolite. This last hypothesis excludes an escape of alkali but implies two successive phases of anatexis.

In any case, whatever the nature of the acidic parent rock, the trace element chemistry of the studied trondhjemites suggests a final stage of anatexis.

ORIGIN OF THE KYANITE-ZOISITE-GARNET-QUARTZ-OLIGOCLASE (MATRIX AND CORONA) ASSEMBLAGE

The P.T. stability conditions of the high pressure assemblage (Kyanite, zoisite, garnet, quartz) are bounded towards low temperature and pressure by the transition zoisite to Al-epidote, appearance of plagioclase and by the inversion kyanite-sillimanite. Consequently, this assemblage was formed at

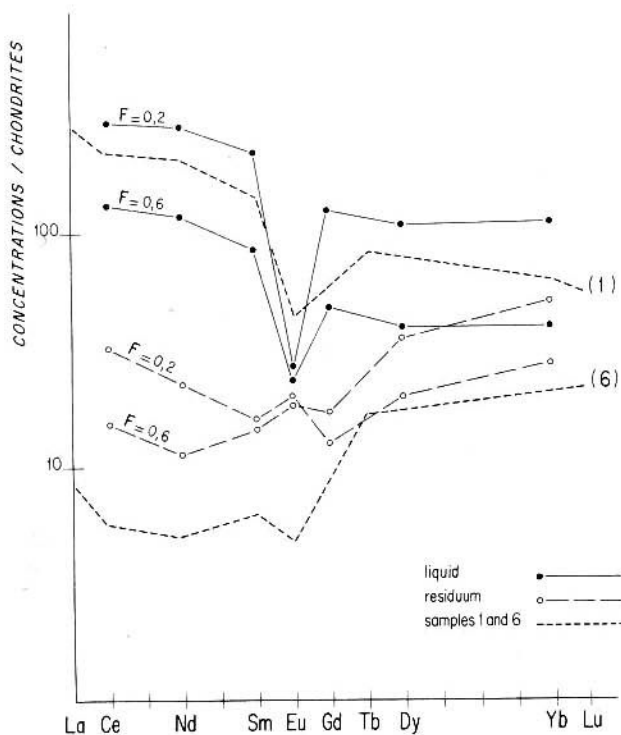


Figure 13.--Chondrite normalized rare earth abundances in theoretical liquid and corresponding residuum derived by melting of a trondhjemitic parent rock (0.5 qz; 0.44 pl; 0.6 bi) assuming incongruent fusion of biotite (1 bi 0.25 ga + 0.75 L). The calculations have been done for $F = 20\%$ and $F = 60\%$ using partition coefficients of Arth and Hanson (1975) and incongruent melting equation of Shaw (1977). Samples 1 and 6 are reported for comparison. Initial rare earth element concentrations (C_0) are those of sample 2.

12.5–20 Kb and 750^o–840^oC (Fig. 14) and is consistent with the stability field of amphibole-quartz-kyanite assemblage of Green and Vernon (1974) although the compositions of the amphiboles are not similar. Furthermore, the corona texture involving oligoclase cannot be satisfactorily explained by the sub-solidus reaction: kyanite + zoisite + quartz \rightarrow anorthite + H₂O vap (Boettcher, 1970) because the three reacting minerals have to be in contact and their reaction products formed at the boundary between them. Our rocks do not show this situation: when kyanite and zoisite are in contact, the oligoclase is found at the boundary between these minerals. Furthermore, this corona appears around kyanite and zoisite when the two minerals are involved in both a quartzose or a plagioclase-rich matrix.

These observations negate a sub-solidus metamorphic transformation in high pressure conditions but favour a direct crystallization of the high pressure

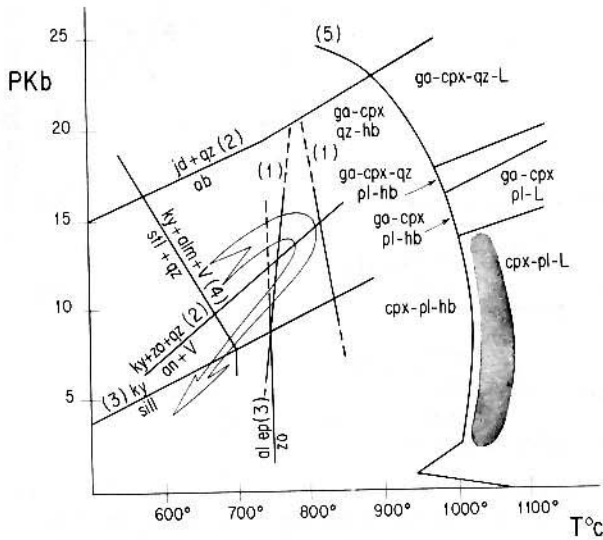


Figure 14.--P.T. crystallization conditions of the high pressure paragenesis (gray shaded area). The dark shaded area delineates the crystallization field of the assumed primary trondhjemitic melt. The arrow indicates the metamorphic evolution of the trondhjemitites. (1) Delineates the stability field of the qz + ky + amph assemblage (Green and Vernon, 1974). (2) According to Boettcher (1970, 1971). (3) Holdaway (1971, 1972). (4) Ganguly (1972). (5) Gabbro solidus at 0.5% H₂O (Wyllie, 1971).

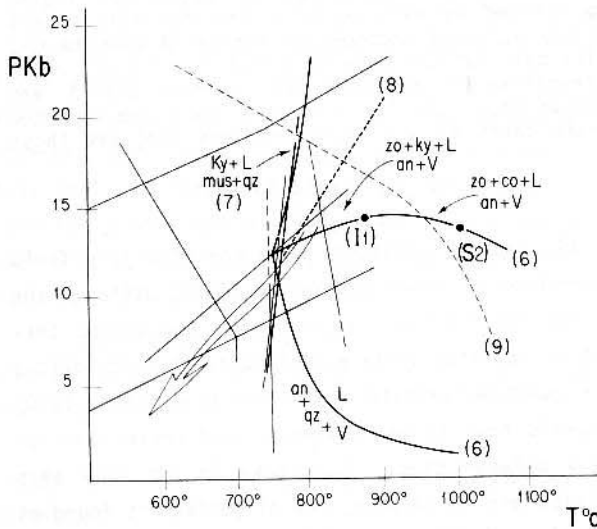


Figure 15.--P.T. crystallization conditions assuming direct crystallization from the trondhjemitic melt (shaded area); arrow, sub-solidus state retrogressive evolution. Fine lines refer to the reaction reported on Figure 14. Invariant point I1, singular point S2, reactions (6): Boettcher (1970, 1971), (7): Storre and Karotke (1972), (8) Gabbro solidus at 7 Kb P H₂O and (9) amphibole stability limit at same P H₂O extrapolated from Bryhni et al. (1970).

assemblage from the trondhjemitic melt. Indeed, in the simplified $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-CaO-H}_2\text{O}$ system (Boettcher, 1970), the trondhjemitic melt, under P.T. conditions defined previously, may crystallize first kyanite and zoisite which is in accord with our observations (presence of early corroded kyanite and asymmetrically zoned and truncated zoisite megacrysts). Then both minerals react with the liquid by peritectic reaction (kyanite + zoisite + liquid \rightarrow anorthite + H_2O vap., Boettcher, 1970) to form plagioclase (Fig. 15). In practice, kyanite and zoisite quickly become encapsulated by plagioclase which forms reaction rings (Yeh, 1970; Ehlers, 1972). The reaction is stifled by the need for diffusion through this solid layer (Nicholson and Davies, 1971; St. John and Hogan, 1977). The armoured kyanite and zoisite are then not completely reabsorbed; with decreasing P.T. the residual liquid crosses its solidus curve with secondary precipitation of quartz and plagioclase, their relative proportion and composition dependent on the composition of the residual liquid. Green hornblende forms only in rocks with $\text{Na}_2\text{O} > 3\%$ in agreement with the results of Cawthorn and O'Hara (1976). At this stage, the sub-solidus reactions described above may appear with decreasing P and T conditions (Fig. 15).

The presence of primary garnet in our rocks (e.g., early composite garnet-kyanite megacrysts: Fig. 6, inclusions of garnet in kyanite) cannot be explained by the simplified system of Boettcher (1970). However, the addition of MgO and FeO in this system (Hensen, 1976) increase the stability field of garnet and may reconcile the observations. Furthermore, it has been demonstrated (Green and Ringwood, 1968a, b) that the almandine pyrope is a near liquidus phase and may coexist with kyanite in rhyodacitic liquid. The presence of garnet may also result from the incongruent melting of biotite during the hypothetical high pressure fusion of early trondhjemites as suggested from geochemical considerations (previous section).

Further observations support high pressure crystallization from a liquid. The presence of kyanite in muscovite may imply a peritectic reaction: kyanite + liquid \rightarrow muscovite + quartz (Storre and Karotke, 1972). The bi- or trifid textures (Fig. 5) are compatible with those observed during the solidification of an alloy (Bouchy and Gobin, 1971; Figs. 4-15) and similar to the dendrites commonly found in peritectic reactions (Titchener and Spittle, 1975).

CONCLUSION

The metamorphic evolution of the trondhjemitic layers is indubitably associated with that of the metabasites. However, the successive metamorphic episodes which took place in this region (Nicollet, 1978) strongly complicate the petrogenetic interpretations. The geochemical data on trondhjemites suggest one step of partial fusion from an initial acidic material. In order

to conciliate the analytical data and those established from the calculations, the theoretical model implies a partial fusion under high pressure conditions (appearance of garnet by incongruent fusion of biotite).

Although several hypotheses have been excluded, the problem of primary origin of the trondhjemitic material remains unsolved. Partial fusion of amphibolite or altered plagiogranite associated with an old ophiolitic complex now dismembered are the most plausible source for the acidic layers. But it is impossible to choose, at the present, between the two possibilities. The intimate field association of the trondhjemites and eclogites contrasts with the geochemical considerations which indicate they are not genetically related. Their intimate association may be explained by a process of dehydration of amphibolite during local partial fusion process under high pressure conditions (Fry and Fyfe, 1969; Essene et al., 1970; Bryhni et al., 1970; Green and Mysen, 1972).

The P.T. path of the trondhjemites indicated in Figures 14 and 15 is similar to what might be expected in a subduction zone (Raheim and Green, 1975; Miller, 1977; Reinsch, 1977). The hypothetical prograde course of this path (Fig. 14) may have been generated during burial in a subduction zone, prior to the emplacement of an orogenic belt (Bryhni et al., 1977; O'Hara, personal comm.), while decompression following uplift would be reflected in the quasi-adiabatic retrograde path (Leyreloup et al., 1975; Ernst, 1977).

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