

F. BARKER  
EDITOR

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TRONDHJEMITES,  
DACITES, AND  
RELATED ROCKS

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6  
DEVELOPMENTS IN PETROLOGY

## TRONDHJEMITES, DACITES, AND RELATED ROCKS

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# TRONDHJEMITES, DACITES, AND RELATED ROCKS

Edited by

F. BARKER

*U.S. Geological Survey, Denver, Colorado, U.S.A.*



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## PREFACE

Siliceous igneous rocks of low potassium content, although mapped in the field and described by geologists for many years, were largely neglected by geochemists and petrologists until the late 1960's. These rocks have been termed trondhjemite, tonalite, soda granite, leucogranodiorite, soda rhyolite, high-silica dacite, and other names. Rocks of this general composition and cogenetic, less siliceous and more mafic rocks are now known to be a major component of Archean gneiss terranes, to occur in the volcanic and plutonic parts of Late Archean greenstone-granite terranes, to form widely scattered extrusive and intrusive bodies in plate-tectonic environments of convergent oceanic-continental and oceanic-oceanic types, and to be a prominent if volumetrically minor component of many ophiolites.

The purpose of this book is to give the reader a view, by a diverse and active group of geologists and geochemists, of the geology, geochemistry, and petrology of the several kinds of trondhjemites and dacites, and of the genetically related rocks. Many chapters focus on major and minor elements, isotope geochemistry, or petrology. Others stress the pertinent field relations as well. Individual chapters range from preliminary reports to review articles.

The name trondhjemite comes from the old spelling, "Trondhjem," of Trondheim, Norway. V. M. Goldschmidt originated the term in 1916 in his famous paper on the intrusives of the Trondheim-Oppdal region, in which he defined trondhjemite as holocrystalline, leucocratic rock that consists largely of sodic plagioclase and quartz and contains only minor biotite and potassic feldspar. For at least 40 years thereafter, few geologists outside of Fennoscandia used the term. Even the status of trondhjemite as a magmatic type was in doubt. N. L. Bowen, in his classic The Evolution of the Igneous Rocks, doubted that magmas of this composition existed; and he attributed the formation of such rocks rich in CIPW-normative albite to Na-metasomatism of common potassic granitic rocks. Bowen's point of view, however, was gradually overcome by detailed field, petrographic, and chemical studies. Reports by Hietanen in 1943 on the Proterozoic hornblende gabbro-trondhjemite suite of southwestern Finland and by Hietanen, Compton, Taubeneck, L. H. Larsen and Poldervaart; Davis; Lipman; and others in the period 1951-1965 on Mesozoic intrusives of northern California and Oregon are notable in demonstrating the existence of trondhjemitic magmas. Use of trondhjemite as a rock name by these and other workers and recent sanction of the term by the IUGS Subcommittee on the Systematics of Igneous Rocks indicate that Goldschmidt's term "trondhjemite" now is well established.

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The text was prepared and printed out by a word processor in Denver. The editor apologizes for the undetected, scattered typographical and other errors which, inevitably, seem to be found in material produced by this apparatus.

Fred Barker  
June 1978  
Denver, Colorado

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## TRONDHJEMITE: DEFINITION, ENVIRONMENT AND HYPOTHESES OF ORIGIN

F. Barker

### ABSTRACT

Goldschmidt's definition (1916) of the rock name "trondhjemite," unfortunately, was not quantitative. Furthermore, the trondhjemite intrusives of the type area, south of Trondheim, Norway, have had much of their original mineralogy obliterated by metamorphism to greenschist facies. The author suggests that the IUGS definition of trondhjemite as leucotonalite be followed, except that andesine-bearing leucotonalite be termed calcic trondhjemite, and that albite-bearing leucotonalite, as well as the oligoclase variety, be termed trondhjemite.

Major-element characteristics of trondhjemite, which of course are dependent on the petrographic limits as defined and on the chemistry of the constituent mineral phases, include:

1.  $\text{SiO}_2$  > ca. 68 percent, usually <75 percent;
2.  $\text{Al}_2\text{O}_3$  typically >15 percent @ 70 percent  $\text{SiO}_2$  and <14 percent @ 75 percent  $\text{SiO}_2$ ;
3.  $(\text{FeO}^* + \text{MgO})$  <3.4 percent, and  $\text{FeO}^*:\text{MgO}$  commonly is 2-3;
4. CaO ranges from 4.4-4.5 percent in calcic trondhjemite to typical values of 1.5-3.0 percent;
5.  $\text{Na}_2\text{O}$  typically is 4.0-5.5 percent; and
6.  $\text{K}_2\text{O}$  <ca. 2.5 percent, and typically <2 percent.

The separation of trondhjemites into low- $\text{Al}_2\text{O}_3$  and high- $\text{Al}_2\text{O}_3$  types should be made at 15 percent  $\text{Al}_2\text{O}_3$  at 70 percent  $\text{SiO}_2$ .

Most suites of trondhjemite and genetically related tonalite plot as calc-alkalic, but should be considered as a specific type of low K/Na ratio and of low  $(\text{FeO}^* + \text{MgO})$  abundance.

Generation of trondhjemite-tonalitic liquids is briefly reviewed in terms of fractionation of wet basaltic and dry low-K tholeiitic or andesitic liquid and of partial melting of quartz eclogite, amphibolite and gabbro.

Trondhjemite-tonalite suites occur largely in: (1) Archean gray gneiss terranes; (2) peripheries of Archean greenstone belts; (3a) Proterozoic and Paleozoic continental margins; and (3b) Mesozoic and Cenozoic continental margins. Trondhjemites of slightly different character are found in: (4) subvolcanic regions of island arcs; and (5) ophiolites.

The spatial relations between trondhjemite-tonalite suites and subduction zones in environments (3b) and probably (3a) are very close. The actual methods of generation of magmas of this type at or near subduction zones, however, in spite of much work and speculation are not well known.

#### TRONDHJEMITE: DEFINITION

Goldschmidt originally defined the term trondhjemite (1916), giving the type area as the "Trondhjem-Gebiet." He stated that the rock is leucocratic, that the plagioclase is in the range oligoclase-andesine, that biotite is the typical dark phase, and that amphibole or, rarely, diopsidic pyroxene may occur in place of biotite. Unfortunately, the type plutons in the region south of Trondheim have been metamorphosed to greenschist facies (Goldschmidt, 1916; Barker and Millard, this volume), the feldspars of liquidus crystallization mostly are altered to felted aggregates of albite, epidote, and muscovite, and only a trace of potassic feldspar is present. These rocks are not suitable for giving us a strict petrographic definition of the term trondhjemite. Goldschmidt's inclusion of andesine as a possible constituent also presents a difficulty: a tonalitic rock containing the percentage of CaO (usually more than 4) and the relatively high ratio of  $\text{CaO}:\text{Na}_2\text{O}$  necessary to form plagioclase more calcic than  $\text{An}_{30}$  usually contains so much  $(\text{FeO}^* + \text{MgO})$ , where  $\text{FeO}^* = \text{FeO} + 0.9 \text{Fe}_2\text{O}_3$ , that the rock contains more than 10 percent dark minerals. Thus the rock is not leucocratic and cannot be termed trondhjemite. But andesine-bearing leucotonalites are found, and Davis (1963) gave the mode and major-element analysis of one from the Trinity Alps, California, and suggested it be called calcic trondhjemite.

The recent IUGS classification of igneous rocks (Streckeisen, 1976) defines trondhjemite as leucotonalite whose plagioclase is oligoclase or andesine. This definition also specifies that quartz content be 20 percent or more of the leucocratic minerals, that alkali feldspar constitute 10 percent or less of the total feldspar, and color index be 10 or less. For the most part this is an excellent definition. The writer suggests, however, that Davis' term calcic trondhjemite be used for andesine-bearing trondhjemite, and that albite-bearing ( $\text{Ab}_{90}\text{-Ab}_{100}$ ) leucotonalites as well as oligoclase-bearing varieties be termed trondhjemite. These albite-bearing rocks are better referred to as "trondhjemite" than as "alkali-feldspar granite."

An approximate definition of trondhjemite also can be given in terms of major elements. The most important of these in distinguishing trondhjemite from tonalite and granodiorite are  $(\text{FeO}^* + \text{MgO})$ , which is involved in determining proportions of mafic minerals and hence color index, and  $\text{K}_2\text{O}$ , a determining constituent of potassic feldspar and biotite. Analyses of biotite and hornblende from the hornblende gabbro-trondhjemite suite of southwest Finland (Arth et al., in press) show that the  $(\text{FeO}^* + \text{MgO})$  content of biotite is 28-30 percent, and that of hornblende is 27-28 percent. Thus, keeping in mind that biotite and hornblende are denser than quartz and feldspars, about 3.3 weight percent  $(\text{FeO}^* + \text{MgO})$  is contained in 10 volume percent biotite and about 3.4 percent in hornblende. Magnetite and ilmenite, of course, contain much higher percentages of  $\text{FeO}^*$  than do the two mafic silicates and these two oxide minerals are much denser. Most trondhjemites, however, contain only a trace of magnetite or ilmenite and only 0.1-0.3 percent or less of the  $\text{FeO}^*$  of the rock is contained in these phases. Epidote may contain a few tenths to as much as 1 percent of  $\text{FeO}^*$  in altered trondhjemite. The limit of  $(\text{FeO}^* + \text{MgO})$  in trondhjemite may be taken at about 3.4 percent.  $\text{K}_2\text{O}$  comprises 10-12 percent of potassic feldspar, 9-10 percent of biotite, 0.5-0.6 percent of hornblende and approximately 0.15-0.4 percent of plagioclase, as estimated from analyses of these phases as found in calc-alkaline intrusives (Deer et al., 1963) and from analyses of biotite and hornblende (Arth et al., in press). Thus, a trondhjemite containing the maximum 10 percent each of biotite and potassic feldspar, as well as 50-60 percent of plagioclase, would contain 2.3-2.55 percent of  $\text{K}_2\text{O}$ . The maximum percentage of  $\text{K}_2\text{O}$  in trondhjemite may be taken as about 2.5 percent.

The major-element contents of trondhjemites, either as limits or as typical concentrations (Fig. 1), are:

1.  $\text{SiO}_2$  >ca. 68 percent, usually <75 percent;
2.  $\text{Al}_2\text{O}_3$  typically >15 percent @ 70 percent  $\text{SiO}_2$  and <14 percent @ 75 percent  $\text{SiO}_2$ ;
3.  $(\text{FeO}^* + \text{MgO})$  <3.4 percent, and  $\text{FeO}^*:\text{MgO}$  commonly is 2-3;
4.  $\text{CaO}$  ranges from 4.4-4.5 percent in calcic trondhjemite to typical values of 1.5-3.0 percent;
5.  $\text{Na}_2\text{O}$  typically is 4.0-5.5 percent; and
6.  $\text{K}_2\text{O}$  <ca. 2.5 percent, and typically <2 percent.

The writer stresses that trondhjemites and tonalites, like many other plutonic rocks, often do not show a one-to-one correspondence of major-element contents to volumetric percentages of minerals (modal analyses determined by

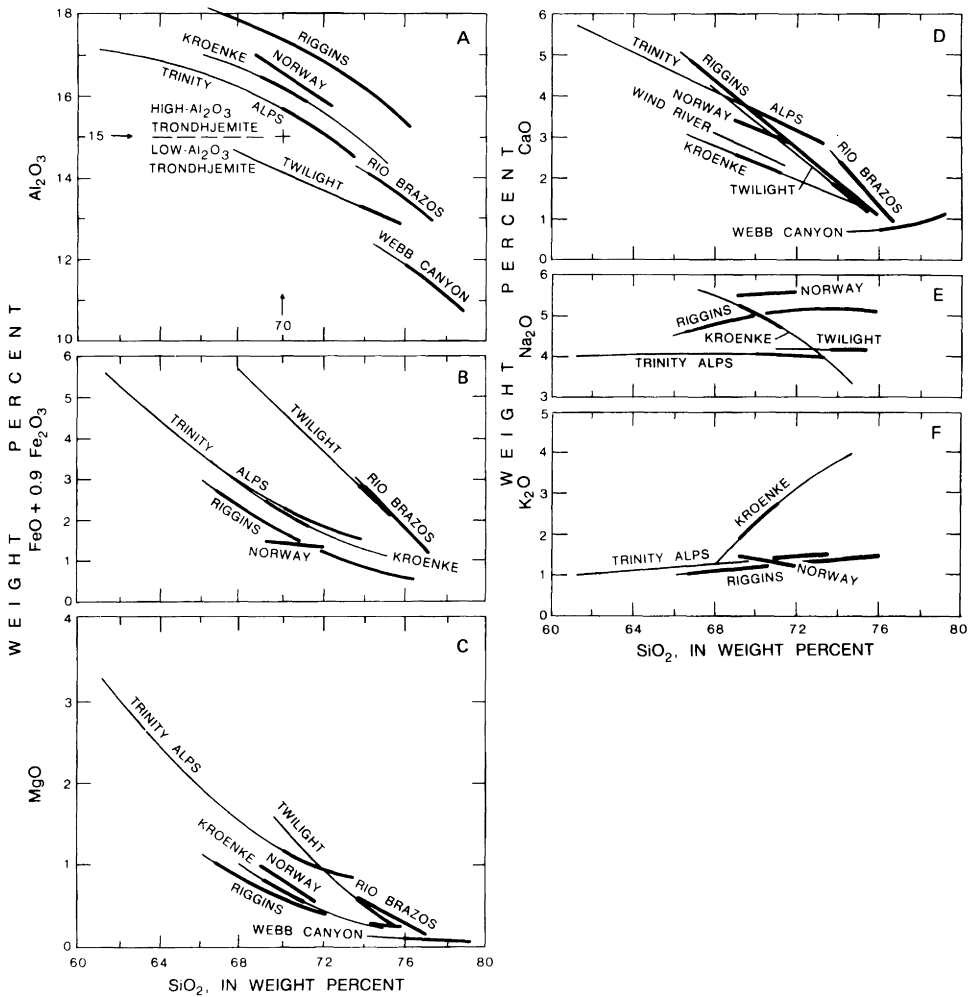


Figure 1.--Harker diagrams for the Kroenke Granodiorite, trondhjemite of Rio Brazos and Twilight Gneiss of Colorado and New Mexico (Barker et al., 1976; Barker and Millard, this volume); and gneisses of the Wilson Creek area, Wind River Mountains, Wyoming, trondhjemite and pegmatite of Riggins area, Idaho, quartz diorite-trondhjemite intrusives of the Trinity Alps, California, and Webb Canyon Gneiss, Teton Range, Wyoming (Barker et al., this volume). Note that not all suites are represented in some of the diagrams because the data points did not fall near or on smooth curves. Heavier line segments indicate rock type is trondhjemite.

one or two thin sections), considering the compositions and densities of those mineral phases. These discrepancies presumably are due to modal inhomogeneities of the rocks that are not discernable to the eye. Thus, some rocks are more accurately classified as trondhjemite or not by means of major elements rather than by modal analysis.

Classification of common siliceous igneous rocks by proportions of normative Ab, Or, and An was proposed by O'Connor (1965). His diagram is given in Figure 2A. O'Connor's plot separates trondhjemites from tonalite, granodiorite, and granite rather well, even though this type of classification does not consider mafic constituents or color index. However, some trondhjemites fall in the tonalite field of this diagram. Also, because the ratio Ab/An generally increases from tonalitic to granitic compositions, the author suggests a modification in which the boundary separating trondhjemite from tonalite and from granodiorite extends from  $Ab_{30}Or_{70}-An_{100}$ . These modifications are shown in Figure 2B.

Cawthorn et al. (1976) have discussed the corundum-normative character of calc-alkaline magmas, especially in relation to hornblende fractionation. Most trondhjemites and many of the associated tonalites are corundum-normative, irrespective of whether they are of the low- or high- $Al_2O_3$  type; e.g., the low- $Al_2O_3$  trondhjemite of Rio Brazos, New Mexico (Barker et al., 1976), shows as much as 5 percent normative corundum; the Twilight Gneiss of Colorado, also the low- $Al_2O_3$  type, shows as much as 3.6 percent. High- $Al_2O_3$  types, such as the Kroenke Granodiorite of Colorado and the trondhjemite of Riggins, Idaho (Barker and Millard, this volume), typically show from a fraction of a percent to about 2 percent of normative corundum. As Cawthorn et al. point out, calc-alkaline rock suites typically change from diopside-normative to corundum-normative at  $SiO_2$  contents in the middle to high 60's. A prominent exception to this, however, is found in the gabbro-diorite-tonalite-trondhjemite suite of SW Finland (Arth et al., in press); this suite becomes corundum-normative at 57 percent  $SiO_2$ .

#### MAJOR-ELEMENT CHARACTER

Major-element compositions of some tonalite-trondhjemite suites are shown in the Harker diagrams of Figure 1. The superposed dashed lines in that figure show approximately which compositional region of each suite is trondhjemite. Plots of some of the constituents of the eight suites of Figure 1 do not give smooth curves and are not shown.  $K_2O$  is prominent in this regard, and curves for only four of the suites are given (Fig. 1F).

The earlier division of trondhjemites into low  $Al_2O_3$  and high- $Al_2O_3$  types (Barker et al., 1976) needs to be qualified as shown in Figure 1A, the depend-

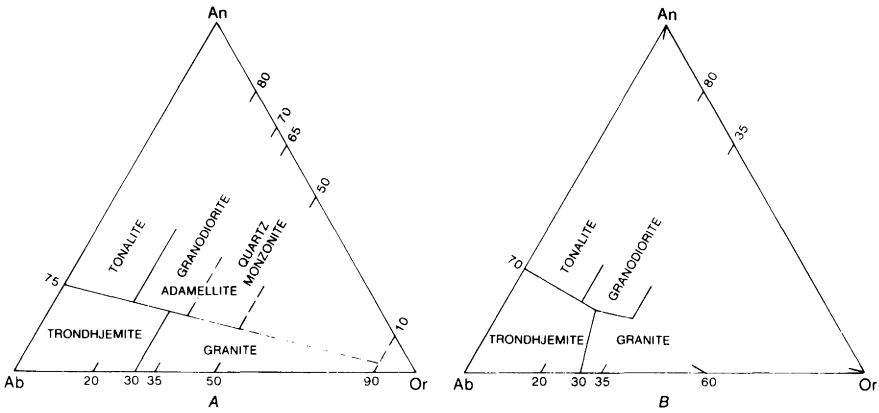


Figure 2.--Normative plots of Ab-Or-An showing fields of some siliceous plutonic rocks. A, after O'Connor, 1965; B, suggested modification.

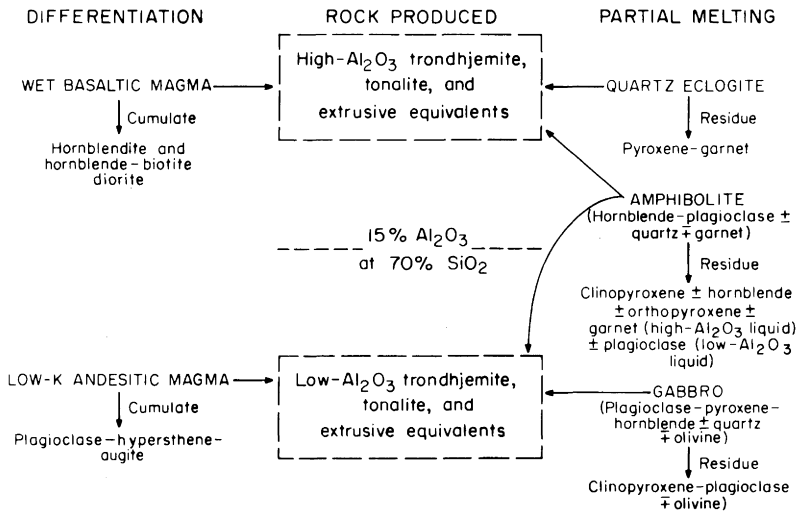


Figure 3.--Schematic diagram showing generation of high- $\text{Al}_2\text{O}_3$  and low- $\text{Al}_2\text{O}_3$  trondhjemitic-tonalitic liquids by differentiation and partial melting, modified from Barker and Arth (1976).

ence of  $Al_2O_3$  contents on  $SiO_2$  is rather pronounced, and so the author suggests that the two suites be separated into low- $Al_2O_3$  and high- $Al_2O_3$  types at 15 percent  $Al_2O_3$  and 70 percent  $SiO_2$ . There is a continuum of  $Al_2O_3$  compositions of trondhjemites, and so the separation as suggested is done for convenience. Implications of  $Al_2O_3$  contents are discussed in the following section.

Most trondhjemite-tonalite suites, including those having dioritic or gabbroic end members, plot as calc-alkaline in terms of  $(Na_2O + K_2O)-SiO_2$  and  $(Na_2O + K_2O)-FeO^*-MgO$  (Barker and Arth, 1976). By this definition, and also by use of  $CaO$  versus  $(Na_2O + K_2O)$  on a Harker plot, the gabbro-trondhjemite suite of southwestern Finland, at least, is calc-alkaline (Barker and Arth, 1976). However, plots such as  $K-Na-Ca$ , or normative ones including  $Ab$  and  $Or$  in which  $Na_2O$  and  $K_2O$ , or derivative parameters, are separated, show that trondhjemites should be considered as a low- $Na/K$ -ratio type of calc-alkaline rock (Barker and Arth, 1976). They also should be described as a low- $(FeO^* + MgO)$  type. Thus, the calc-alkaline quartz diorite-tonalite-granodiorite-granite suites that form the bulk of the Mesozoic circum-Pacific batholiths are rather different from trondhjemite-tonalite suites. And, even though trondhjemite-tonalite suites in some cases are found only 5-50 km oceanward of the great batholiths, there apparently is not a compositional continuum between the two.

#### OCCURRENCE

The trondhjemitic-tonalitic suite (not including many of the compositionally similar dacitic suites, which are considered by other contributors to this volume) is found mostly in four geologic environments, two of which are similar:

1) Archean gray gneiss terranes, as a major rock type, often in association with basaltic rocks, and, in some cases with komatiitic rocks, to give a compositionally bimodal or trimodal suite; these rocks mostly are intrusive but some are volcanic--many original features of emplacement have been obliterated by shearing and metamorphism in most of these terranes; usually metamorphosed to amphibolite or granulite facies, and commonly retrograded to greenschist facies; relatively potassic intrusives are specially associated in some of these terranes; see Barker and Arth, Barker and Millard, Collerson and Bridgewater, Hunter, McGregor, and Tarney in this volume,

2) Peripheries of Archean greenstone belts, as emplaced during or just after buckling of those belts; usually accompanied by plutons of granodiorite and granite; see Ermanovics et al., Hunter, and Longstaffe in this volume.

3a) Along margins of Proterozoic and Paleozoic continental margins, that apparently are related to subduction or to subsidiary back-arc spreading; the



Proterozoic occurrences, at least, typically are accompanied by much greater volumes of the suite quartz diorite-tonalite-granodiorite-granite; see Arth, Barker and Millard; Malpas; and Payne and Strong in this volume; and

3b) Along margins of Mesozoic and Cenozoic continental margins, that almost certainly are related to subduction; of relatively small volume; partly as composite intrusives oceanward of large calc-alkaline batholiths; see Arth, Barker et. al., in this volume.

Trondhjemites also are found either separately or as members of rock suites that differ from the common trondhjemite-tonalite suite in:

4) Subvolcanic regions of island arcs, either as parts of arc-tholeiitic or calc-alkaline suites; derived from the same magma system as the much better known dacitic rocks considered in this volume by Barker and Millard, Gill, Malpas, Payne and Strong, Phelps, and Tomblin in this volume; and

5) Ophiolites, as a member of the plagiogranite suite of Coleman and Peterman (1975) and as considered by Coleman and Donato in this volume, which includes diorite, quartz diorite, tonalite and albite-quartz rocks as well as trondhjemite proper.

Other environments may contain minor trondhjemitic rocks; one example is high-rank metamorphic terranes in which metabasalt has been partially melted or dissolved and precipitated to give trondhjemitic pegmatites or aplites (see Nicollet et al., this volume).

#### HYPOTHESES OF ORIGIN

Most workers follow Hanson and his coworkers (Hanson and Goldich, 1972; Arth and Hanson, 1972, 1975) in believing that trondhjemitic-tonalitic liquids form from basaltic sources. Other sources, such as graywacke, dacitic volcanic rocks, plutonic rocks of low K/Na ratio, and others, cannot be excluded a priori as possible parents for such liquids, but in many cases their involvement is ruled out by geochemical or petrological considerations. The generation of trondhjemitic-tonalitic liquids was briefly summarized by Barker and Arth (1976). Their schematic diagram showing four general modes of origin from basaltic rock or liquid--differentiation by crustal-liquid fractionation and partial melting under both relatively dry and relatively wet conditions--is reproduced here (Fig. 3). The reader will find more discussion on origins in this volume and in Arth et al. (in press).

Processes of fractionation and of partial melting involve such a variety of cumulate or residual minerals that liquids of all  $Al_2O_3$  compositions may be produced by either process; that is, there is a continuum between high- $Al_2O_3$  and low- $Al_2O_3$  trondhjemitic liquids.

## COMMENTS ON ARCHEAN GRAY GNEISS COMPLEXES

Trondhjemite is a major rock type or is abundant only in the Archean gray gneiss complexes. These gneiss complexes comprise much of the Earth's oldest known rocks, which are 2.8 to 3.8 b.y. old. The common association of trondhjemite and tonalite gneiss and metabasalt--and the general absence of andesitic rocks--led Barker and Arth (1976) to "suggest a variation of Green and Ringwood's second model (1968), involving partial melting of amphibolite under wet conditions. The first event in this two-stage model consists of mantle upwelling, generation of basaltic liquid by partial melting of mantle material, volcanism (probably in rift zones), and accumulation of thick piles of basalt. The lower parts of these accumulating piles were metamorphosed to hornblende-plagioclase  $\pm$  quartz amphibolite, the necessary water coming from interstitial sources. Along relatively steep Archean geotherms (see discussion of Green, 1975), partial melting commenced at less than 10-kb total pressure and second-stage siliceous magmas were produced. At 15 to 30 percent fractional melting in the range 850<sup>o</sup> to 1000<sup>o</sup>C and at  $a_{H_2O} > 0.6$ , the liquids were trondhjemitic to tonalitic (Holloway and Burnham, 1972; Helz, 1973, 1976), and the residue was largely hornblende, varietal clinopyroxene, and minor magnetite and olivine. At relatively low total pressure,  $a_{H_2O}$ , and percentage of partial melting, the residue contained plagioclase and the liquid was of the low-Al<sub>2</sub>O<sub>3</sub> type (Fig. 3). Typically, however, we infer that plagioclase was not a residual phase and that the liquids were of high-Al<sub>2</sub>O<sub>3</sub> type (Fig. 3). As the lower part of the basaltic pile reached higher pressures and temperatures, it was progressively dehydrated largely by the upward removal of the trondhjemitic-tonalitic liquids, so that conditions were reached where the hornblende-bearing residue became unstable and reacted to pyroxene, olivine, and other minerals. This dehydrated residue was below its solidus and did not undergo further fractional melting. The critical factor in this model, obviously, is that the siliceous liquid must have been removed from the residue before the fraction of melting reached about 40 percent or more and before the liquid phase became andesitic. Basaltic volcanism of the first stage continued as the trondhjemitic-tonalitic liquids rose through the basaltic pile, and so bimodal volcanism occurred in the upper parts of the pile. The ratio of basalt to dacitic rocks thus depended on two loosely related processes and so varied widely..."

These two authors further suggested that "Models of genesis of trondhjemitic-tonalitic liquids involving quartz eclogite probably are not pertinent for Archean rocks. Early Archean terranes apparently contain no eclogite, at least in present exposures. Amphibolite is ubiquitous. Many workers have suggested that heat flow was significantly higher in Archean time

than at present (see, for example, Daly, 1933; Brooks and Hart, 1972, 1974). The crust and lithosphere in the early Archean also may have been thinner than at present (Daly, 1933; Green, 1975). D. H. Green also has suggested that Archean geotherms may have been so steep that they did not pass through an eclogite region, and so eclogite was absent. Even if Archean geotherms were not so steep as to obviate a stability field for eclogite, they presumably would have been sufficiently steep that the 15 to 30 percent of partial melting required to generate trondhjemitic-tonalitic liquids would have occurred well before the parental amphibolite reached the depths (50 to 60 km) where garnet would form (Wyllie, 1971; Lambert and Wyllie, 1972). Thus we propose that common amphibolite, rather than quartz eclogite or garnet amphibolite, was the predominant parental material of the bimodal Archean trondhjemitic and tonalitic liquids.

Differentiation suites of the Finnish type (Arth et al., in press), important as they may be in terranes of late Archean and younger age, are not reported to occur in the earlier parts of Archean gray gneiss complexes. Identification of the mode of generation of individual bodies of trondhjemitic or tonalite, occurring in the field without closely associated diorite and gabbro, is difficult. The systematics of REE patterns with  $\text{SiO}_2$  may be the key to distinguishing rocks formed by fractionation of basaltic liquid from those formed by partial melting."

Cawthorn and coworkers (Cawthorn and Brown, 1976; Cawthorn et al., 1976) have independently discussed the role of hornblende in the fractionation of calc-alkaline magmas.

The chapters of Collerson and Bridgewater, McGregor, and Tarney et al. in this volume consider the origin of Archean gneiss terranes in much detail.

#### RELATION TO SUBDUCTION

Many Phanerozoic and some Proterozoic trondhjemitic bodies can reasonably be related to subduction, excepting those in ophiolites and in several minor environments. However, the actual processes of generation of trondhjemitic liquids at or above subducted oceanic crust and lithosphere remain an outstanding problem. In many publications and discussions various workers have suggested several processes by which trondhjemitic-tonalitic liquids may be formed: (1) partial melting of the basaltic part of subducted oceanic crust; (2) partial melting of scattered masses or inclusions of eclogite in the subducted lithosphere; (3) water vapor produced by dehydration reactions in the subducted slab streaming upward into the overlying partial wedge of mantle or even into the lower crust and there causing of rock of basaltic composition; (4) basaltic liquid, generated by partial melting of peridotite, fractionating

by separation of hornblende and other liquidus phases; or (5) by other means. Certainly all of these processes are plausible. Much work, though, remains to be done to enable us to determine which process occurs for a given occurrence, details of that process, and which geologic, petrologic, and chemical parameters are diagnostic or indicative of process.

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#### REFERENCES

- Arth, J. G. and Hanson, G. N., 1972. Quartz diorites derived by partial melting of eclogite or amphibolite at mantle depths. *Contrib. Miner. Pet.*, 37: 161-174.
- Arth, J. G. and Hanson, G. N., 1975. Geochemistry and origin of the Early Precambrian crust of northeastern Minnesota. *Geochim. Cosmochim. Acta*, 39: 325-362.
- Arth, J. G., Barker, F., Peterman, Z. E. and Friedman, I., Geochemistry of the gabbro-diorite-tonalite-trondhjemite suite of southwest Finland and its implications for the origin of tonalitic and trondhjemitic magmas. *J. Pet.*, (in press)
- Barker, F., Arth, J. G., Peterman, Z. E. and Friedman, I., 1976. The 1.7- to 1.8-b.y. old trondhjemites of southwestern Colorado and northern New Mexico: Geochemistry and depths of genesis. *Geol. Soc. Am. Bull.*, 87: 189-198.
- Barker, F. and Arth, J. G., 1976. Generation of trondhjemitic-tonalitic liquids and Archean bimodal trondhjemite-basalt suites. *Geology*, 4: 596-600.
- Barker, F. and Arth, J. G., 1974, On the significance of komatiite. *Geology*, 2: 107-110.
- Cawthorn, R. G., Strong, D. F. and Brown, P. A., 1976. Origin of corundum-normative intrusive and extrusive magmas. *Nature*, 259: 102-104.
- Cawthorn, R. G. and Brown, P. A., 1976. A model for the formation and crystallization of corundum-normative calc-alkaline magmas through amphibole fractionation. *J. Geol.*, 84: 467-476.
- Coleman, R. G. and Peterman, Z. E., 1975. Oceanic plagiogranite. *J. Geophys. Res.*, 80: 1099-1108.

- Daly, R. A., 1933. *Igneous rocks and the depts of the Earth*: New York and London, McGraw-Hill Book Co., Inc., 598 pp.
- Davis, G. A., 1963. Structure and mode of emplacement of Caribou Mountain pluton, Klamath Mountains, California. *Geol. Soc. Am. Bull.*, 74: 331-348.
- Deer, W. A., Howie, R. A. and Zussman, J., 1963. *Rock-forming minerals*, Vol. 4, Framework silicates. Longmans, Green and Co., London: 435 pp.
- Goldschmidt, V. M., 1916. Geologisch-petrographische studien im hochgebirge des südlichen Norwegens, IV. Übersicht der eruptivgesteine im Kaledonischen Gebirge zwischen Stavanger und Trondhjem. *Vid. Skr. I. Mat.-Nat. Klasse*, 2: 75-112.
- Green, D. H., 1975. Genesis of Archean peridotitic magmas and constraints on Archean geothermal gradients and tectonics. *Geology*, 3: 15-18.
- Green, T. H. and Ringwood, A. E., 1968. Genesis of the calc-alkaline igneous rock suite. *Contr. Miner. Pet.*, 18: 105-162.
- Hanson, G.N. and Goldich, S. S., 1972. Early Precambrian rocks in the Saganaga Lake-Northern Light Lake area, Minnesota-Ontario--Pt. 2, Petrogenesis. In: B. R. Doe and D. K. Smith (Eds.), *Studies in mineralogy and Precambrian geology*. *Geol. Soc. Am. Mem.* 135: 179-192.
- Helz, R. T., 1973. Phase relations of basalts in their melting range at  $P_{H_2O} = 5$  kb as a function of oxygen fugacity. Pt. I. Mafic phases. *J. Pet.*, 14: 249-302.
- Helz, R. T., 1976. Phase relations of basalts in their melting ranges at  $P_{H_2O} = 5$  kb. Pt. II. Melt compositions. *J. Pet.*, 17: 139-193.
- Hietanen, Anna, 1943. Über das Grundgebirge des Kalantigebietes im südwestlichen Finnland: *Finlande Comm. Geol. Bull.*, 130, 105 pp.
- Holloway, J. R. and Burnham, C. W., 1972. Melting relations of basalt with equilibrium water pressure less than total pressure. *J. Pet.*, 13: 1-29.
- Lambert, I. B. and Wyllie, P.J., 1972. Melting of gabbro (quartz eclogite) with excess water to 35 kilobars, with geological applications: *J. Geol.*, 80: 693-708.
- O'Connor, J. T., 1965. A classification for quartz-rich igneous rocks based on feldspar ratios. *U.S. Geol. Surv. Prof. Pap.*, 525-B: 79-84.
- Streckeisen, A., 1976. To each plutoic rock its proper name. *Earth Sci. Rev.*, 12: 1-33.
- Wyllie, P. J., 1971. Experimental limits for melting in the Earth's crust and upper mantle, in Heacock, J. G., ed., *The structure and physical properties of the Earth's crust*. *Am. Geophys. Union Geophys. Mon.* 14: 279-301.

## A REVIEW OF THE MINERALOGY AND CHEMISTRY OF TERTIARY-RECENT DACITIC, LATITIC, RHYOLITIC, AND RELATED SALIC VOLCANIC ROCKS

A. Ewart

### ABSTRACT

This paper attempts to review those salic eruptives in which  $\text{SiO}_2 > 60\%$ , but specifically excluding peralkaline and silica-undersaturated types. The approach is based on a compilation of major and trace elements, plus phenocryst occurrence and phenocryst modal data; some 2,890 sets of rock data are included. The data are tabulated into five chemical groupings (60-63, 63-66, 66-69, 69-72,  $>73\% \text{SiO}_2$ ); further breakdown of data is based on geographic and/or tectonic subregions, and further chemical subdivision into low-K, calc-alkaline, and high-K series from each subregion. In this paper, the general terms siliceous andesite, dacite, and rhyolite are applied to volcanic rocks with  $\text{SiO}_2\%$  of 60-63, 63-69, and  $>69\%$ , respectively, except lavas specified as trachytes, for which a separate set of data are compiled.

The majority of salic volcanic magmas have been erupted within orogenic zones; i.e., the circum-Pacific regions, Indonesia, the Mediterranean arcs, and to a lesser extent, the Caribbean and Scotia arcs. An additional group of silicic magmas, dominated by rhyolites, are those of the bimodal mafic-silicic magma associations; examples are drawn from Yellowstone, Mono, Medicine Lake, and Salton Sea in the western U.S.A.; Iceland; western Scotland; and southern Queensland (Australia). Further comparative data are provided from the Hawaiian, Galapagos, and Canary Islands, and the unusual high soda-low potash lavas of Deception and Fedarb Islands.

Cluster analyses of averaged data for the various subregions suggest close correlations between the orogenic silicic magmas of the western U.S.A. (excluding Cascades), western South America, and Mediterranean regions. Further clustering is found between the eruptives of the Cascades-Aleutians, Middle Americas, and Indonesian subregions. The clustering tends to separate these orogenic magmas from the oceanic rhyolites and dacites, and the rhyolites of the bimodal associations. The trachytes exhibit no clear correlations with any of these groupings.

Mineralogically, the calc-alkaline orogenic salic volcanics are characterized by phenocryst assemblages comprising plagioclase, quartz, augite, hypersthene, hornblende, cummingtonite, Fe-Ti oxides, biotite, and rarely sanidine. The low-K eruptives lack biotite and sanidine, while the high-K eruptives contain much more abundant sanidine, quartz and biotite, and commonly also sphene and allanite. Detailed phenocryst assemblages are tabulated in the text. Fe-Ti oxide temperatures range from 640-780°C in high-K rhyolites of western U.S.A. (excluding those of the bimodal associations); 725-900°C in calc-alkaline rhyolites from the S.W. Pacific; and 830-1120°C for orogenic dacites from various circum-Pacific regions. These data also suggest that the orogenic silicic magmas from the western U.S.A. have equilibrated on a slightly higher  $f_{O_2}$  buffer (between NNO and HM buffers) than the orogenic magmas from other regions. It is also shown that the averaged compositions of the magmas from western U.S.A., western South America, and Mediterranean regions, and indeed the high-K eruptives from other regions, trend towards and terminate close to the lower pressure "ternary minima" in the quartz-feldspar system, and the 2-feldspar cotectic surface in the feldspar system. This is not found for the calc-alkaline and low-K series.

Rhyolites of bimodal associations often exhibit distinctive phenocryst assemblages and compositions, most notably the progressive development of strongly Fe-enriched pyroxenes, olivines, and where present, amphiboles and biotites. Fe-Ti oxide data indicate relatively high equilibration temperatures (800-985°C), and equilibration between the QFM and NNO  $f_{O_2}$  buffers (i.e., lower than most orogenic salic magmas). These rhyolites also frequently exhibit very fractionated trace element abundance patterns.

## INTRODUCTION

### Classification

Streckeisen (1967, p. 181-185) has summarized the diverse opinions concerning the nomenclature of salic volcanic rocks, and has proposed a very logical classification, based on the parameters Q (silica minerals), A (alkali feldspars including albite), and P (plagioclase  $An_{05-100}$  and scapolite). Unfortunately, this classification necessitates the recalculation of the chemistry of the volcanic rocks into the necessary normative mineralogy; this, of course, results from the typical volcanic two-stage (or more) crystallization history (phenocryst and groundmass) which represent distinct P-T equilibration assemblages. Rittman (1973) has proposed a rather complex system of recalculation of the chemistry into the necessary mineral molecules, but at least to this writer, the calculation procedure still seems often ambiguous and sometimes arbitrary. Nevertheless, it offers an important

approach to the classification of the volcanic rocks being considered in this review.

The occurrence of Tertiary-Recent salic lavas and pyroclastics is predominantly in the island arcs and orogenic (mobile) continental marginal zones, both being regions in which subduction is interpreted to play a key role in magma genesis. Within these regions, well defined geographic and stratigraphic variations of chemistry are often recognized within volcanic sequences (e.g., Jakes and White, 1969), even within a given compositional type (e.g., dacite). Variation of  $K_2O$  is the most significant within the major elements, and three distinct series of volcanic eruptives are commonly distinguished within the subduction tectonic environment; i.e., low-K series, calc-alkali series, and high-K series. Moreover, these three series are not necessarily distinguished by routine petrography. Thus, many current workers, particularly those studying the S.W. Pacific region, prefer a simpler chemical classification scheme, based on a simple plot of  $SiO_2$  versus  $K_2O$  (wt. %, e.g., Mackenzie and Chappell, 1972; Peccerillo and Taylor, 1976). This approach has been adopted in this review for certain aspects of the data reduction and presentation, and the scheme of Peccerillo and Taylor (1976) is followed with minor modification for nomenclature. Thus, throughout this paper, volcanic rocks for which  $SiO_2 > 69\%$  are referred to as rhyolites; 63-69%  $SiO_2$  as dacites; 60-63%  $SiO_2$  as silicic andesites. When necessary, the terms low-K, calc-alkaline, and high-K are added as prefixes.

#### Aims and Methods of Approach of Review

The primary aim is to present comparative data of the chemistry and mineralogy of "dacitoid" and associated magmas from diverse geographic regions. In order to cover a reasonably comprehensive range of salic volcanic rocks, the following procedures for data selection and treatment have been adopted:

(a) With the exception of peralkaline (a recent review of peralkaline volcanic rocks is to be found in Bulletin Volcanologique, Volume 38, 1974) and silica undersaturated types, all data for volcanic lavas and pyroclastics for which  $SiO_2 > 60\%$  (anhydrous basis) are included in the compilations.

(b) No data are included for pre-Tertiary rocks, partly because of increasing problems of secondary alteration, and partly because of increasing ambiguity as to the tectonic environment of these older volcanic series.

(c) In data selection, emphasis has been placed on obtaining both chemical (major and trace elements), mineralogical (phenocryst), and petrographic data for individual samples. Altogether, some 2,890 sets of data are utilized, based on data available to October 1977. The complete list of data sources is



provided in the references. Although the literature search cannot be described as exhaustive, it is intended to provide a reasonably comprehensive coverage of salic volcanic occurrences from diverse geographic and tectonic regions. Data have only been excluded if there is clear evidence (mineralogical or chemical) of modification due to weathering, hydrothermal alteration, or leaching. By far the majority of chemical analyses utilized in the compilations included specific determinations for FeO and Fe<sub>2</sub>O<sub>3</sub>. Where only a total Fe value was published, the FeO and Fe<sub>2</sub>O<sub>3</sub> were calculated according to the method of Le Maitre (1976).

(d) The data have been primarily subdivided on the basis of two criteria: (i) SiO<sub>2</sub> content, and (ii) geographic and/or tectonic region. Chemically, the following five groupings are prepared, based on SiO<sub>2</sub>% (calculated on anhydrous basis): 60-63%; 63-66%; 66-69%; 69-73%; >73%. This procedure partly overcomes ambiguities caused by arbitrary classification divisions. In practice, the 60-63% SiO<sub>2</sub> group corresponds approximately to silicic andesites, the 63-66% and 66-69% divisions to most definitions of dacites and quartz latites, and the >69% divisions to most definitions of rhyodacites and rhyolites.

The geographic and/or tectonic regional groupings are as follows:

Number (Reference to Figs. 1-3,21-22; Tables 1-3; and appendices 1-3)	Regional Grouping
1.	Western (Andean) South America
2.	Middle Americas (Mexico, Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica).
3.	Western U.S.A.--eastern belt (zone), defined on basis of the inferred eastern subduction zone of Lipman, Prostka, and Christiansen (1972, see their Fig. 9, p. 235). The Yellowstone and Snake River plain rhyolites are excluded (see later).
4.	Western U.S.A.--western belt (zone), but excluding the Quaternary Cascades. Boundary defined as in 3 above. The Mono and Salton Sea rhyolites (California) are excluded (see later).
5.	Quaternary High Cascades of northwestern U.S.A. and Canada (including the Medicine Lake and Newberry volcanic centres), Alaska, and Aleutians.

6. Japan (including the southern islands), Taiwan, Kuriles, Kamchatka, and Saipan.
7. Indonesia (Sunda arc).
8. S.W. Pacific, including Papua, New Guinea, Solomon Islands, New Hebrides, Fiji, Tonga-Kermadec Islands and New Zealand.
9. Tonga-Kermadec Islands (considered as a separate subdivision).
10. Mediterranean region, comprising the Eolian and and Aegean island arcs (e.g., Barberi et al., 1974).
11. Caribbean (Lesser Antilles) island arc.
12. South Sandwich Islands (Scotia arc).
13. Deception Island (within South Shetland islands)
14. Western Scotland and Northern Ireland (Slieve Gullion complex).
15. Iceland
16. Galapagos Islands
17. Canary Islands.

The complete averaged data (chemical and mineralogical) divided according to the criteria set out above, are presented in Tables 1-A and 1-B.

(e) For further consideration and discussion of the compilations, the data for the orogenic volcanic sequences have been further divided into "low-K," "calc-alkaline," and "high-K" groupings, based on slightly modified chemical subdivisions proposed by Peccerillo and Taylor (1976), a plot of which is shown in Figure 1. Selected averaged data, subdivided into three chemical series, are presented in Appendices 1, 2, and 3.

(f) Trace and minor element data are also included in the compilations of Tables 1 and Appendices 1, 2, and 3. The average concentrations are based as all available data (for which adequate accompanying major element data are given), irrespective of the analytical technique used. This has the obvious disadvantage that data of variable quality are mixed (e.g., optical spectrographic and isotope dilution data). In the interests of obtaining as wide a coverage as possible, however, this "blanket" approach was preferred.

(g) Petrographic data on phenocryst phases, presented in Tables 1-3 and Appendices 1-3 are based on both modal abundances (only limited data available), and also in terms of the % frequency occurrence of each mineral phase present within a given grouping. This is based on the stated occurrence of a given mineral phase in published petrographic descriptions. It must be noted, however, that many accounts which may present excellent chemical data, are