GEOLOGY AND GEOCHEMISTRY OF EARLY PROTEROZOIC SUPRACRUSTAL ROCKS FROM THE WESTERN DOS CABEZAS MOUNTAINS, COCHISE COUNTY, ARIZONA

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ABSTRACT

Early Proterozoic supracrustal rocks in the Dos Cabezas Mountains in southeastern Arizona occur in three geographically separate areas. Despite greenschist facies metamorphism, primary textures are preserved in places. Foliation generally appears to be parallel to bedding. The Eastern Terrane (ET) is comprised of a succession of predominantly coarse-grained, quartzofeldspathic, clastic sediments with minor amounts of mafic and felsic volcanic and hypabyssal rocks whereas the Southern Terrane (ST) is composed wholly of quartzites and subordinate phyllite. In contrast, the Western Terrane (WT), the focus of this study, is dominated by felsic volcanic and subvolcanic rocks. The supracrustal sequences are also intruded by various syntectonic to post-tectonic granitic plutons.

Early Proterozoic supracrustal rocks in WT consist of a sequence of intercalated felsic tuffs and associated volcaniclastic sediments, mafic rocks (amphibolites) and minor amounts of epiclastic and chemical sediments. A large, possibly hypabyssal body of rhyodacite porphyry also occurs in WT. In addition, the rocks are intruded by mafic dikes and two granitic plutons. Preliminary structural data indicate the supracrustal rocks have undergone two periods of deformation.

Compositionally similar volcanic rocks in WT and ET

suggest the successions may be related but their relationship to ST is obscured by faulting. Conventionally, the early Proterozoic sequences in the Dos Cabezas Mountains are regarded as Pinal Schist (~1700 Ma) although the abundance of felsic volcanics in WT and conglomerates in ET are unlike "typical" Pinal Schist successions. In addition, Erickson (1969) has speculated that the quartzites of ST may be correlative with the Mazatzal Quartzite of central Arizona.

Volcanic and subvolcanic rocks from WT and ET define a bimodal suite. Tholeiitic amphibolites are characterized by light-REE and HFSE enrichmment but also exhibit a subduction zone component. Geochemically, amphibolites are similar to basalts from active continental margins or within-plate tectonic settings. Geochemical modeling suggests that amphibolites can be produced by chiefly olivine fractionation of a 10-20 % partial melt of incompatible element enriched lherzolite in the upper mantle. Calc-alkaline felsic volcanics are subdivided into rhyodacites, quartz latites and rhyolites. The felsic rocks have light-REE enriched patterns with variable negative Eu anomalies. Overall, the felsic volcanics are compositionally similar to modern felsic volcanics from continental-margin arcs or continental rifts. Geochemical modeling indicates that the felsic volcanics are probably not related to the amphibolites by fractional crystallization. Rhyodacites can be produced by ~20 % partial melting of an undepleted felsic granulite probably at mid-crustal levels. Quartz latites and rhyolites can be generated by progressive differentiation of rhyodacite magma.

Minor but notable occurrences of dark-colored, spheroidal rocks (possibly oolitic ferruginous cherts) exhibit moderate Fe contents and extreme enrichments in REE and HFSE. This enrichment may be due to the presence of minor mineral phases that concentrate trace elements or modification by fluids.

Available geologic and geochemical data for the WT-ET successions are most consistent with formation in a continental-margin arc system rather than an oceanic arc setting. This material is part of juvenile crust accreted to the Archean Wyoming craton during the early Proterozoic.

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INTRODUCTION

The Dos Cabezas Mountains, located in southeastern Arizona, are a northwest trending Basin and Range uplift. Proterozoic supracrustal rocks occur in three separate areas of the range. The purpose of this study is to examine, describe and geochemically characterize the Precambrian supracrustal succession in the western part of the range and to relate it to what is known about Precambrian tectonics and crustal evolution in the southwestern United States.

Geologic mapping at the 1:24,000 scale was carried out using U.S.G.S. topographic quadrangles as base maps. Orthophotoquads of the area also proved to be somewhat helpful. Field work was initiated in June 1982 and was finished in the latter part of 1983. Major units were sampled for petrographic examination and whole-rock chemical analyses. While this study focuses on Proterozoic rocks in the western part of the range, data concerning the Precambrian rocks in the eastern part of the range (Vance, 1983) are utilized for geochemical modeling and tectonic interpretations.

GEOGRAPHIC SETTING

The Dos Cabezas Mountains lie in the north-central part of Cochise County in southeastern Arizona (Figure 1).

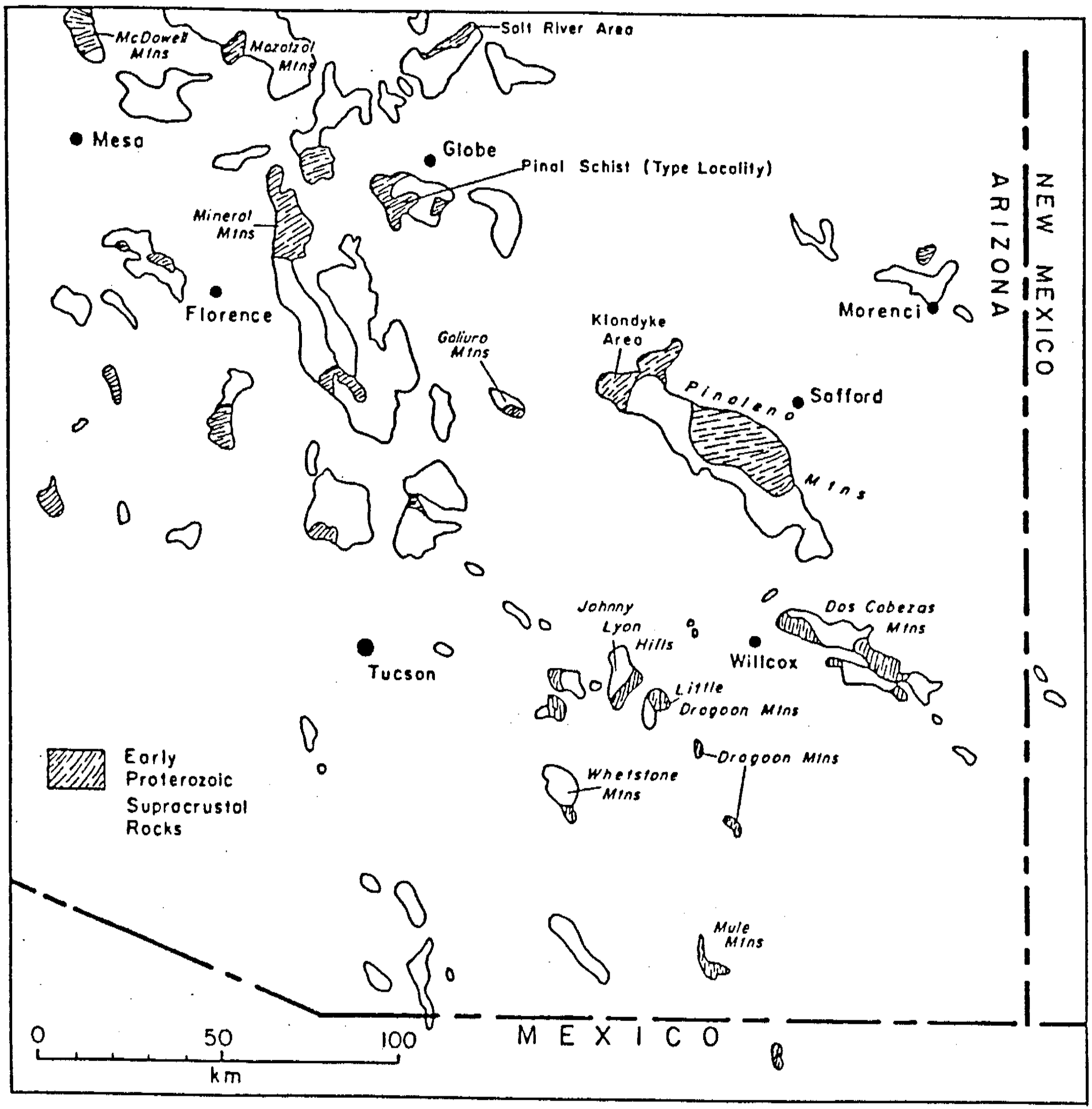

Figure 1. Early Proterozoic supracrustal rocks in southeastern Arizona (after Condie and De Melas, 1985).

Physiographically, the range is in the Eastern Mountain Region of the Basin and Range Province. The Dos Cabezas are bounded to the northeast and southeast by unconsolidated basin-fill of the San Simon and Sulphur Spring Valleys, respectively. To the south, the range is separated from the Chiricahua Mountains by a small divide known as Apache Pass.

The northwestern part of the range comprises the study area and only a few primitive roads exist there. At Exit 344 of Interstate 10, a graded dirt road leaves the highway and provides access to the northern foothills of the range. A few jeep trails depart from this road and lead into the mountains. Jeep trails are also present on the more rugged southern side of the range which may be accessed from State Route 186. The field area is covered by the Willcox 15 minute and Railroad Pass 7.5 minute topographic quadrangles.

The topography of the study area ranges from small rounded hills in the extreme northwestern part to higher and somewhat steeper ridges and saddles in the southern portion. Relief is generally moderate throughout the study area with a maximum of about 518 meters (~1700 feet) in the vicinity of Camels Back. Elevations in the area range from 1311 to 1921 m (4300 to 6300 ft).

The climate of this area is typically hot and arid in the summer and cool in the winter. It is drained by the San

Simon River system and all waterways in the study area are ephemeral. The vast majority of the study area receives less than 41 cm (16 in) of precipitation per year (Vogt, 1980). The area, for the most part, is sparsely vegetated with cacti, desert shrubs and grasses predominating. The area is also sparsely populated and most of the land is used for rangeland. The majority of the land area is controlled by the Bureau of Land Management but some parts are privately owned.

Despite the paucity of vegetation, rock exposures are generally poor to fair due to deep and extensive weathering and colluvial and alluvial cover. Exposures are generally better on hillsides and ridgetops.

PREVIOUS INVESTIGATIONS

A reconnaissance geologic map of an area including most of the Dos Cabezas Mountains was made by Cooper (1960). He includes the Precambrian supracrustal rocks in the Dos Cabezas as part of the Pinal Schist. Sabins (1955; 1957a; 1957b) worked in the northern Chirichahuas and southern Dos Cabezas but focused mainly on Phanerozoic stratigraphic relationships. The most extensive treatment of Precambrian rocks in the Dos Cabezas is by Erickson (1968; 1969) who made a detailed investigation of the entire range. He describes different lithologies within the supracrustal successions and includes petrographic descriptions and geochronologic data which was later revised and updated (Erickson, 1981). A discussion of the Precambrian rocks in Cochise County was prepared by Silver (1978) for a New Mexico Geological Society Guidebook. Calder (1982) compiled a brief overview of the known mineral occurrences within the Dos Cabezas. Vance (1983) mapped the Precambrian supracrustal rocks in the eastern part of the range and chemically analyzed some metavolcanic rocks. More recently, geologic maps of quadrangles within the Dos Cabezas have become available (Drewes, 1984; 1985a; 1985b; Erickson and Drewes, 1984b) including the Railroad Pass 7.5 minute quadrangle (Erickson and Drewes, 1984a). Also, a paper dealing with the preliminary findings of this study has been published (Condie et al., 1985).

On a regional scale, Drewes (1980; 1981) has synthesized a tectonic framework for southeastern Arizona. Conway and Silver (1986) have summarized the geology of early Proterozoic rocks in central and southeastern Arizona. In addition, Copeland (1986) recently completed a geochemical study of early Proterozoic supracrustal rocks in southeastern Arizona.

GEOLOGIC SETTING

INTRODUCTION

Proterozoic rocks in Arizona occur predominantly in a broad northwest-trending belt that runs nearly diagonally across the state. Archean rocks have not been reported in Arizona. In general, the rocks are younger in the southeastern part of the state than in the central and western parts (Condie, 1982). In the northwestern part of the state, the supracrustal rocks are chiefly amphibolite facies paragneisses (Anderson, 1986). Metavolcanic rocks and quartzites comprise most of the supracrustal rocks in central Arizona (Anderson, 1986; Conway and Silver, 1984; 1986), while in the southeastern part, meta-quartz wackes predominate (Condie and De Melas, 1985; Copeland, 1986). In addition, various plutonic bodies of mainly granitic composition intrude the supracrustal successions (Anderson, 1986; Conway and Silver, 1986).

REGIONAL GEOLOGY

Early Proterozoic supracrustal rocks occur sporadically in most of the tectonically complex Basin and Range uplifts of southeastern Arizona (Fig. 1). These rocks conventionally have been assigned to the Pinal Schist, the oldest known stratigraphic unit in southeastern Arizona (Silver, 1978). Unconformably overlying the Pinal is the middle Proterozoic Apache Group, which is present in only a few places in southeastern Arizona (Silver, 1978). Ransome (1903; 1904) first used the term Pinal Schist to describe sequences of generally fine-grained quartz-mica schists of sedimentary parentage and minor amounts of amphibolites in the Pinal and Mule Mountains. Since then, the name has been applied throughout southeastern Arizona to the metamorphosed supracrustal successions older than the ~1000 Ma Apache Group (Cooper, 1960; Erickson, 1969; Silver, 1978; Conway and Silver, 1986; Copeland, 1986). Because the Proterozoic supracrustal rocks in the Dos Cabezas Mountains contain significant amounts of metaconglomerate and metavolcanics and are thus lithologically distinct from the "typical" sequences in the Pinal Mountains, it may not be appropriate to use the name Pinal Schist in the Dos Cabezas Mountains (Condie et al., 1985).

The metamorphic grade of the Pinal Schist is predominantly the upper-greenschist facies and primary features are still evident in many places (Erickson, 1969; Silver, 1978; Condie and De Melas, 1985; Copeland, 1986). These rocks exhibit the effects of at least one metamorphic-deformational event and in many places the foliation appears to be parallel to bedding (Cooper and Silver, 1964; Erickson, 1969; Silver, 1978; Condie and De Melas, 1985). Consequently, the rocks are generally regarded as a layered stratigraphic sequence estimated to be about 6 km thick in places (Cooper and Silver, 1964) and many of the metasedimentary sections appear to represent turbidites (Silver, 1978; Condie and De Melas, 1985; Copeland, 1986). Only detailed structural analyses will reveal whether the Pinal Schist has been subjected to polyphase deformation similar to that of other Proterozoic terranes in the southwestern United States (Callender, 1983; Karlstrom and O'Hara, 1984) which could invalidate the simple layered statigraphic sequence interpretation.

Proterozoic supracrustal rocks in the Dos Cabezas Mountains include metamorphosed felsic volcanic and subvolcanic rocks, feldspathic quartzites, arkose, conglomerate, quartzite, shale and amphibolite (Erickson, 1968; 1969; Condie, et al., 1985). The large amounts of felsic metavolcanics and the diverse character of the metasediments appear to be unique to the Dos Cabezas when compared to the Pinal Schist in nearby mountain ranges (Erickson, 1969; Copeland, 1986). About 40 km to the southwest, major exposures of the Pinal Schist occur in the Johnny Lyon Hills and Little Dragoon Mountains (Fig. 1). In the Johnny Lyon Hills, the Pinal Schist is represented by thick turbidite sequences of interlayered, graded beds of volcaniclastic graywacke and slate with some conglomerate, chert and thick sheets of intrusive rhyodacite in places (Silver, 1978). The Pinal is lithologically more diverse in the Little Dragoons where it is comprised of graded beds of graywacke and slate plus lenses of tuff, amphibolite, sandstones, rhyolite flows, chert and intrusive rhyodacite porphyry (Silver, 1978). Recent work by Swift (1986) indicates the presence of melange deformation zones within some of the metasediments in the Little Dragoons and Johnny Lyon Hills. Southeast of the Little Dragoons, scattered small exposures of Pinal crop out in the Dragoon Mountains where the rocks are predominantly pelitic schists and amphibolite but have been overprinted by younger structural features (Gilluly, 1956). Drewes (1981) indicates that the metasediments in the Dragoons include arkose, arkosic conglomerate and phyllite. In the northern Chiricahuas, the Pinal Schist is predominantly quartzite, which is occasionally cross-stratified, with minor amounts of phyllite, (felsic ?) metavolcanics and amphibolite (Sabins, 1957b; Erickson, 1969; Drewes, 1981; Copeland, 1986). The strike of foliation generally trends northeasterly for most of the early Proterozoic supracrustal rocks in southeastern Arizona (Gilluly, 1956; Erickson, 1969; Silver, 1978).

The age of the Pinal Schist is not well defined but Silver (1978) suggests the Precambrian supracrustal rocks in the Dragoon quadrangle were deposited in the interval 1680 to 1700 Ma ago and deformed during a major orogenic event 1625 to 1680 Ma ago based on a few U-Pb zircon dates. In addition to at least one Proterozoic deformational event, the Pinal Schist has been overprinted by several Phanerozoic deformational events (Drewes, 1981). These structural complexities along with the lack of abundant geochronological information, discontinuous exposure and absence of distinctive marker units prohibit stratigraphic correlation of Precambrian units between mountain ranges in southeastern Arizona.

While the Pinal Schist is a lithologically diverse assemblage and occurs over a fairly large area, the succession is believed to be genetically related (Copeland, 1986; Conway and Silver, 1986). Various tectonic settings have been proposed for the Pinal Schist. Among them are "a classic eugeosynclinal setting" (Silver, 1978), a continental rift (Condie and De Melas, 1985; Condie et al., 1985) and various continental margin scenarios (De Melas, 1983; Conway and Silver, 1986; Copeland, 1986; Swift, 1986). This supracrustal package is envisaged as being part of the new crust that was accreted to the Wyoming Archean province via arc collisions and related processes during the early Proterozoic (Condie, 1982; 1986; Patchett and Arndt, 1986).

THE DOS CABEZAS MOUNTAINS

Introduction

The Dos Cabezas Mountains are comprised chiefly of Precambrian igneous and metamorphic rocks and a Cretaceous volcanic-hypabyssal complex. Minor amounts of Paleozoic and

Mesozoic sedimentary units as well as Laramide and Tertiary intrusive rocks also occur within the range (Cooper, 1960; Erickson, 1969). The geologic history of the range is summarized by Erickson (1968; 1969) and Sabins (1955). It is noteworthy that the entire sequence of rocks within the Dos Cabezas record at least four periods of tectonic activity.

The Precambrian rocks can be divided into two groups, supracrustal rocks and plutonic rocks. The supracrustal rocks consist of weakly to moderately metamorphosed volcanic and sedimentary rocks which occur in three geographically separate areas of the range. Following Erickson's convention (1969), these areas (Fig. 2) will be referred to as the Eastern (ET), the Southern (ST) and the Western Terranes (WT). Clastic sediments with minor amounts of volcanic and subvolcanic rocks comprise ET, whereas ST is composed wholly of sediments (Vance, 1983; Erickson, 1969). Volcanic, volcaniclastic and hypabyssal rocks predominate in WT, which is the main focus of this investigation. While supracrustal rocks in the Dos Cabezas Mountains have not been dated, similar rocks in the Johnny Lyons Hills (Fig. 1) provide an age around 1690 Ma based on U-Pb zircon dating (Silver, 1963; 1978).

The plutonic rocks (Fig. 2) are granitic, variably foliated late syntectonic to post-tectonic intrusions. Erickson (1968; 1969; 1981) has informally named these

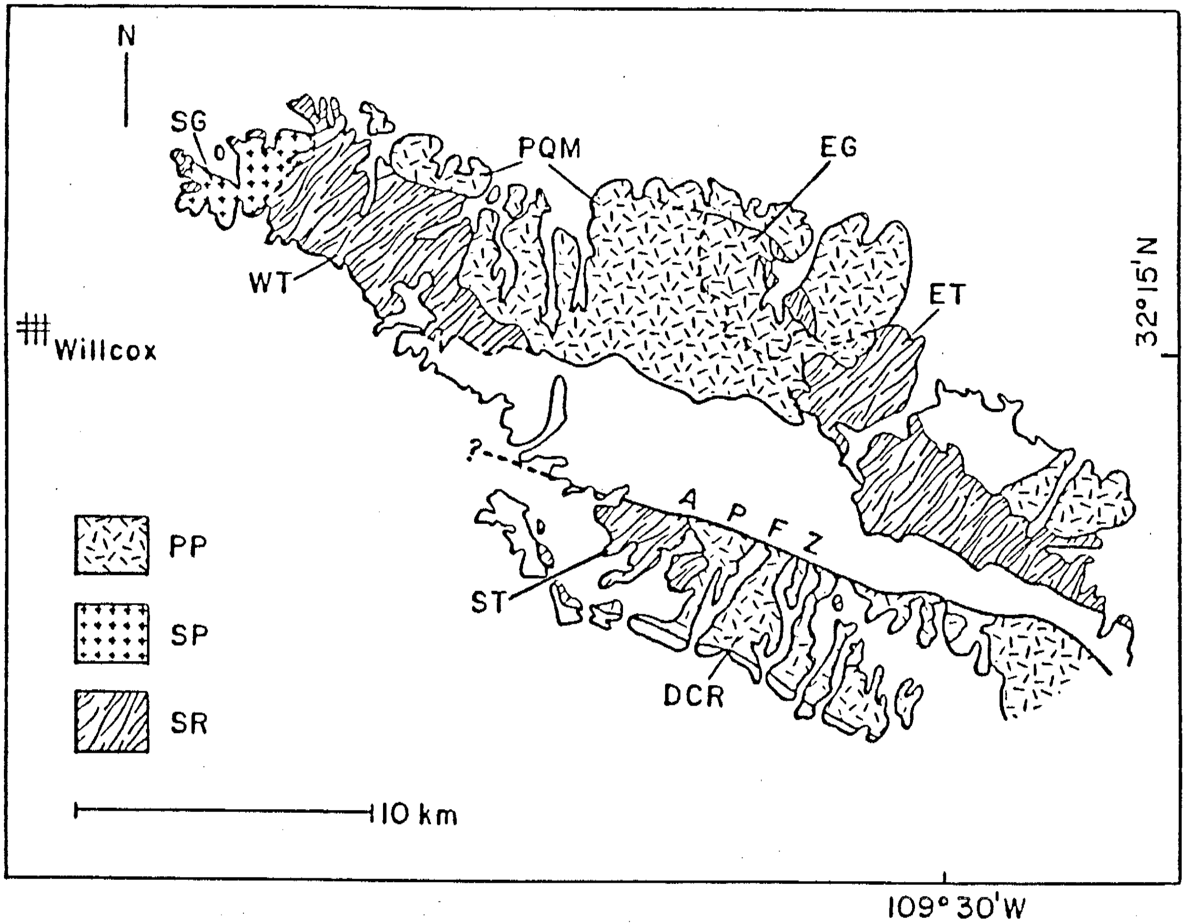

Figure 2. Precambrian rocks in the Dos Cabezas Mountains. PP, post-tectonic plutons; SP, syntectonic pluton; SR, supracrustal rocks; WT, Western Terrane (this study); ST, Southern Terrane; ET, Eastern Terrane; SG, Sommer gneiss; PQM, Polecat quartz monzonite; EG, Eaton granite (1464 Ma); DCR, Dos Cabezas rapakivi quartz monzonite (1381 Ma); APFZ, Apache Pass Fault Zone (after Erickson, 1969).

plutons and his terminology will be adopted here. The following discussion of these rocks is derived mainly from Erickson (1969). All of these plutonic bodies post-date the supracrustal rocks and can generally be described as porphyritic, coarse-grained rocks of quartz monzonitic to granitic composition. Of the seven plutons, all are foliated to some degree except the Polecat quartz monzonite and the Dos Cabezas rapakivi quartz monzonite (Fig. 2). The contacts between plutons and supracrustals are locally discordant and xenolithic blocks of metamorphosed supracrustal rocks occur in some of the plutons. The Sommer gneiss (Fig. 2) is the only syntectonic intrusion in the Dos Cabezas and is inferred to be the oldest plutonic body. Erickson (1981) reports whole-rock Rb-Sr isochron ages of 1381 +/- 28 Ma for the Dos Cabezas rapakivi quartz monzonite and 1464 +/- 29 Ma for the Eaton granite (Fig. 2). The other plutons are thought to have been emplaced between 1400 and 1450 Ma based on field relations. These plutons, with the possible exception of the Sommer gneiss, may be part of the broad belt of granitic and anorthosite plutons that extends from the southwestern United States to Labrador and Greenland (Emslie, 1978; Anderson, 1983).

The metamorphic grade of the Precambrian rocks does not exceed the upper greenschist facies (Erickson, 1969) and primary textures are preserved in the supracrustal rocks in some places. Consequently, the prefix meta- will be dropped and the name of the protolith will be used throughout this work. In order to more fully understand the WT sequence, the ET and ST will be briefly discussed. The WT will be described in the next chapter.

The Eastern Terrane

The Proterozoic supracrustal rocks in ET are predominantly a succession of clastic sedimentary rocks with variable amounts of volcanic, volcaniclastic and intrusive rocks (Fig. 3). The sediments, which become coarse-grained towards the west, include conglomerates, arkoses, cross-bedded feldspathic quartzites and argillaceous quartzites that interfinger with phyllites (Erickson, 1969; Vance, 1983). Provenance studies of the arkoses and conglomerates indicate granitic and felsic volcanic sources (Vance, 1983; Condie et al., 1985). In addition to the clastic sediments, Vance (1983) reports the presence of a thin discontinuous marble bed.

The remaining supracrustal rocks in ET include metamorphosed fine and coarse-grained volcaniclastic units, some of which appear to contain flattened pumice fragments; volcanic breccia, amphibolites and various felsic tuffs and intrusive porphyries (Vance, 1983; Drewes, 1985b). Amphibolites occur as variably foliated sills and dikes which intrude the other supracrustal rocks. The felsic rocks include homogeneous rhyodacite porphyry, which has

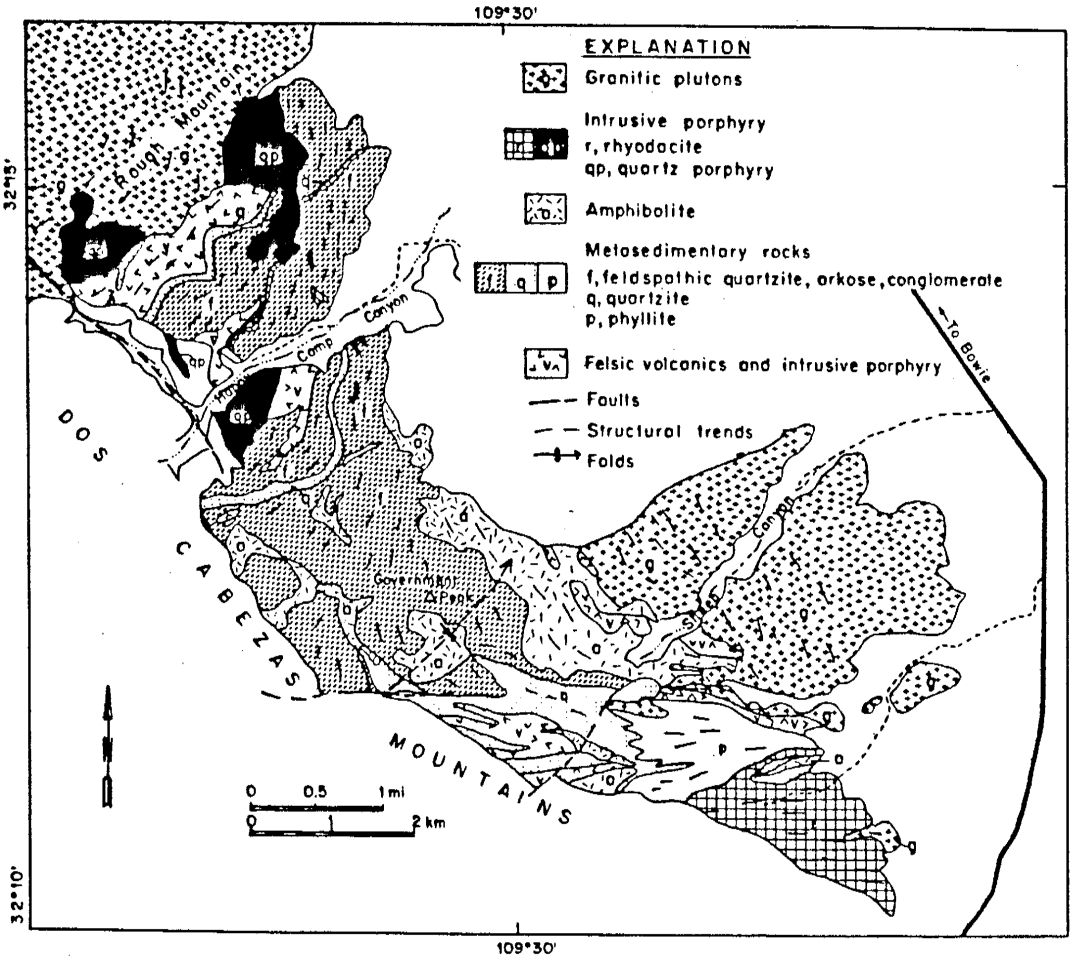

Figure 3. Geologic map of ET (from Condie et al., 1985).

been interpreted as a flow (Erickson, 1969) and as a hypabyssal intrusion (Vance, 1983), intrusive quartz latite porphyry and rhyolitic rocks which occur as intrusive bodies and tuffs (Vance, 1983). As discussed later, the volcanic supracrustal rocks from this terrane have similar geochemical characteristics when compared to rocks from WT.

Most of the metamorphic foliation in ET appears to be parallel to bedding, dips steeply and generally trends northeasterly except for the area southeast of Government Peak where it swings to the east (Erickson, 1969; Vance, 1983; Drewes, 1984; 1985b). However, two directions of foliation are present in the phyllites in the southern part of ET; the more typical roughly east-west trend and a north-northeast trend (Erickson, 1969; Vance, 1983). Drewes (1985b) and Erickson (1969) indicate that the sedimentary sequence is right side up based on preserved primary sedimentary structures. Both Vance (1983) and Erickson (1969) envisage the major structural pattern for ET as that of a broad, open synclinal fold, plunging to the northeast (Fig. 3). In addition, Vance (1983) reports the presence of smaller, tight, northwest-trending folds in phyllites in the southern part of the area and while some of these are rather tight, no sign of major transposition of units was observed. Vance (1983) suggests that at least two periods of deformation have affected the phyllites and their general outcrop pattern is a result of superimposed folds.

A few northeast to northwest-trending faults occur in ET, but the displacement is probably not great (Erickson, 1969; Vance, 1983; Drewes, 1985b).

The Southern Terrane

The supracrustal rocks in ST are comprised of a sequence of predominantly clean, thick-bedded quartzites with minor interbeds of argillaceous quartzite and phyllite with graded bedding and cross-bedding occasionally still recognizable (Erickson, 1969; Drewes, 1985b). Erickson (1969) states that neither felsic volcanic rocks nor amphibolites are present in this terrane and that the quartzites appear to be similar to those in the northern Chiricahuas.

Foliation in this terrane is generally parallel to bedding with steep to vertical dips and the structure of these rocks can be described as a series of tight, vertically plunging folds with axes trending to the northwest (Erickson, 1969; Drewes, 1985b). Drewes (1985b) also shows some small northwest-trending faults in this terrane.

The rocks of ST, unlike those of WT and ET, occur on the southern side of the Apache Pass Fault Zone (Fig. 2). The Apache Pass Fault Zone is a northwest-trending complex fault system, that may have been active since Precambrian time, with the major movement strike-slip with a minor dipslip component (Erickson, 1969; Drewes, 1985b). The massive quartzites and tight folding of ST are in distinct contrast to the diverse clastic sediments, volcanic rocks and broad, open folds of ET and WT. These lithologic and structural differences suggest considerable displacement along this fault and Erickson (1969) has speculated that the ST quartzites may actually correlate with the younger Mazatzal Quartzite of central Arizona but data are not available to support this idea.

GEOLOGY OF THE WESTERN TERRANE

INTRODUCTION

Proterozoic supracrustal rocks occur in the western Dos Cabezas Mountains in an area about 30 square km (Fig. 2). The supracrustal rocks in WT consist of a sequence of felsic tuffs, associated volcaniclastics, mafic rocks and minor amounts of epiclastic sediment intruded by a large hypabyssal body of porphyritc rhyodacite. Mafic dikes also occur throughout the succession (Plate 1). In addition, two granitic plutons, one of which is syntectonic, intrude the supracrustal succession. The Proterozoic rocks are unconformably overlain and intruded by Phanerozoic sedimentary rocks and igneous bodies. Most of the peripheral portions on Plate 1 are from Cooper (1960) and/or Erickson (1969).

The Proterozoic supracrustal rocks in WT are strikingly different from the typical Pinal Schist in that the WT succession contains a large amount of felsic volcanic and subvolcanic rocks. Also, as pointed out by Erickson (1969), the majority of the rocks in WT are not sufficiently metamorphosed to be classified as "schists".

DESCRIPTION OF PROTEROZOIC MAP UNITS

In addition to two plutonic units, six major lithologic units within the supracrustal sequence are recognized in the field (amphibolites, rhyodacite porphyry, felsic tuff, conglomerate, tuffs and sediments undivided, and rhyolite tuff). Erickson (1969) has determined the metamorphic grade of WT to be of the greenschist facies (chlorite and biotite zones). Foliation is present in all of the supracrustal rocks and appears to be parallel to bedding in most instances and generally dips steeply. The laminated rocks appear to represent a layered stratigraphic sequence and no evidence of major transposition was observed as many units can be traced along strike for considerable distances.

Virtually all of WT is moderately weathered and with the exception of the amphibolites, the volcanic rocks and sediments weather in a similar manner. Also, in many places, the rocks are moderately to strongly sheared in many places and alteration associated with Tertiary igneous bodies and quartz veins occurs in some areas. In addition, lithologic contacts frequently are not exposed. Hence, despite overall mild metamorphism, the reconstruction of protoliths at some outcrops is problematic.

Since a thorough structural treatment of WT is beyond the scope of this investigation, it is imprudent to assign a numerical value to the thickness of the supracrustal sequence. If the succession is treated as a simple stratigraphic sequence, a considerable vertical thickness (at least a few kilometers) is implied. Structural features will be briefly discussed in a later section.

The map units are based on lithologies that may transgress time boundaries. Interbedding of lithologies is common, particularly volcaniclastic tuffs with epiclastic sediments. Age relations for the six supracrustal units are not well established other than that some of the amphibolite dikes are the youngest and the large rhyodacite porphyry may be younger than the laminated rocks. These units will be individually described in the next sections.

Rhyolite Tuff (Map Unit rt)

The predominate rock type of this unit is rhyolite tuff (~75 per cent of unit) with subordinate amounts of intercalated sediments (20 %) and thin amphibolite layers (5 %). Major outcrops of the unit occur in the west-central part of the study area with some exposure in the vicinity of Zeits Canyon. Minor amounts are also present to the east and west of Zeits Canyon. For the most part, this unit, like the majority of the strongly foliated rocks, is confined to the lower elevations (Plate 1).

The contact between the rhyolite tuff and the Sommer gneiss is gradational. Most of the gneiss, especially near map unit rt, is sheared and looks like the tuff although the tuff is generally not as orange-colored as the gneiss. To the east, white rhyolite tuffs grade into thinly-bedded, diverse tuffs and sediments of unit ts. Within unit rt, contacts between sediment and tuff are generally gradational whereas those with amphibolite layers are sharp.

The tuff occurs as both continuous beds and lenses of thickly bedded to very fissile, white to gray, foliated porphyritic rocks that weather grayish-green to brown. In hand specimen, the tuffs are composed of phenocrysts of quartz and feldspar in a fine-grained groundmass of sericite, quartz and feldspar (Fig. 4). Phenocrysts vary in size from ~1 to ~5 mm and abundance ranges from ~10 to 30 %. Silicified zones within the tuff are not uncommon.

Thin sections of the tuff reveal anhedral to subhedral phenocrysts of predominantly quartz with subordinate amounts of plagioclase and K-feldspar. The quartz generally has undulatory extinction and occasionally exhibits mortar texture. Uncommonly, quartz crystals display what appears to be resorption embayments. Small veinlets of quartz are sometimes observed. Plagioclase and K-feldspar phenocrysts are generally subhedral to euhedral in shape. Occasionally, plagioclase twins are broken, deformed or obliterated. Sericite occurs as parallel stringers that define the foliation and wrap around crystals. The groundmass is composed of very fine-grained quartz and feldspar and mica. Common accessory phases are opaques and trace amounts of zircon. Retrograde or alteration products include epidote and possibly chlorite. For the most part, these rocks are well layered and may have been water-lain tuffs.

Variably foliated, interbedded sediments include

Figure 4. A slab of rhyolite tuff. A nickel is shown for scale.

roughly equal amounts of fine-grained sandstones and phyllitic rocks and very minor amounts of hematitic quartzite. The sandstones and phyllites occur as generally thin, continuous beds whereas the quartzites occur as thin lensoid bodies.

In the field, sandstones are greenish-gray, mostly fine-grained sediments that weather brownish-red to buff. Occasionally these rocks exhibit graded bedding or cross-laminations defined by magnetite accumulation. Foliation is not well developed in the rocks. Petrographic examination indicates that the sandstones are arkosic and they display a detrital texture of fine-grained, sub-rounded to rounded, irregular to equidimensional grains of feldspar with lesser quartz in a quartz matrix. Most of the feldspar appears to be sausseritized plagioclase, although twinning is generally obliterated. Quartz grains display undulatory extinction and sometimes mortar texture. Opaque phases are present as euhedral cubes and irregular patches and may be concentrated in bands a few millimeters thick. Some small (<1 mm) euhedral zircon grains are also observed. Retrograde/alteration products include chlorite, epidote, calcite and possibly actinolite.

Phyllites occur as thinly bedded to very fissile, grey to tan, well foliated, very fine-grained micaceous rocks. Occasionally, these rocks are feldspathic containing up to ~10 % subhedral crystals of plagioclase (?) in an argillitic groundmass. The rocks probably represent shales and mudstones with a minor component of volcanic detritus. Alternatively, the fine-grained rocks may have resulted from air-fall tephra, but there is no evidence to substaniate a pyroclastic origin.

Thin lenses of purple to gray, locally hematitic, fine-grained dirty quartzites occur as a minor constituent of the rt unit. These concordant bodies commonly lack foliation or internal structure. Where they are interbedded with the rhyolitic tuffs, the quartzites generally are less hematitic near tuff contacts.

Amphibolites occur as thin (a few meters thick) units too small to map at the 1:24,000 scale. These units are fine-grained, greenish-colored and are interbedded with tuffs. These rocks may represent mafic flows or sills or volcaniclastic material. While none of these amphibolites were sampled, they appear to be similar to the amphibolites of map unit a.

Tuffs and Sediments Undivided (Map Unit ts)

This unit consists of a sequence of variably foliated, interbedded volcanic and sedimentary rocks. The volcanic rocks occur as volcaniclastic tuffs and comprise ~70 % of the unit. Sedimentary rocks are represented by arkoses, siltstones, phyllites (shales) and very minor but notable occurrences of limestone and ferruginous chert. Most of the unit occurs in the north-central part of the study area and areally is the second most extensive supracrustal unit (Plate 1). Individual layers commonly grade into each other and are from < 1 m to ~3 m thick. Shearing and weathering are common in the unit.

Two main varieties of felsic volcaniclastic tuffs occur within this sequence in roughly equal proportions. One type is light-gray to brown with 10-25 % subhedral phenocrysts of mostly plagioclase and subordinate quartz and K-feldspar in a foliated, micaceous groundmass. Typically, phenocrysts can be up to 3 mm in size and subhedral to euhedral megacrysts of K-feldspar (?) up to 10 mm are occasionally present. Chemically, some of these tuffs are similar to quartz latites in ET. The other type of tuff is a greenish-gray porphyritic rock composed of predominantly subhedral, broken plagioclase and lesser quartz crystals that sometimes exhibit evidence of resorption in a groundmass of sericite and quartz. Phenocryst abundances range from 5 to ~25 % and occasionally they occur in thin layers in the rock indicating subaqueous reworking. Chemically, these rocks are very similar to the rhyodacite porphyry (map unit rp).

In addition to the felsic varieties, green-colored, fine-grained to porphyritic, layered mafic volcaniclastics are a minor component in this unit. Petrographically, most of these rocks are recrystallized into chlorite schists and secondary products such as carbonate and epidote are abundant.

The interbedded sediments are commonly finely laminated, green-gray to tan, arkosic sandstone, feldspathic siltstones and phyllitic rocks (shales). Graded bedding is common in the coarser varieties. A small body ($<$ 0.5 m thick) of foliated, white, fine to medium-grained marble also occurs in the sequence in the western part of the study area (Plate 1). The rock appears to be a recrystallized carbonate bed containing a few very thin chlorite layers. Although contacts are not exposed, it is a very minor component of the sequence and is the only known carbonate in WT.

A dense, purple to dark-gray, spheroidal, fine-grained cherty rock occurs in the central portion of this map unit (Plate 1). Erickson (1969) first described this body as an oolitic ferruginous shale. The body is conformable with the surrounding tuffs and sediments and no shearing was observed in the rock. The body is $\leq$ 1 m thick and can be traced for a few hundred meters along strike. The rock will attract a magnet and is graded with spheroids $\sim$1 mm in diameter concentrated near the bottom of the layer. Thin bands ($<$ 2 mm thick) become pronounced near the top. Spheroids typically comprise $\sim$35 % of the rock and generally are not deformed although some are congealed together. As pointed out by Reimer (1983a; 1983b), spheroidal rocks in non-carbonate environments may actually be accretionary lapilli tuffs and not oolitic rocks. Petrographic characteristics of accretionary lappilli tuffs in Archean rocks from South Africa include the presence of poorly sorted volcanic debris, ash particles, angular fragments of volcanic quartz and altered ophitic volcanic fragments; a large range in spheroid size (~1-15 mm); lithic fragments as cores; concentric rings of lithic fragments and phenocrysts; frequently deformed spheroids; perlitic cracks; possible glass shards and primary flow texture in the groundmass which commonly contains remnant phenocrysts of quartz and plagioclase (Reimer, 1983a; 1983b). In thin section, the spheroidal rocks from unit ts do not possess most of the above features. Petrographically, the rocks are composed of well-rounded, 1-2 mm size, crudely concentric ooids generally rimmed by magnetite (Fig. 5). The ooids are comprised of very fine-grained sericite and quartz with small needles of magnetite. The matrix is composed of essentially the same very fine-grained minerals but also includes irregular patches of chlorite and sphene. The lack of volcanic components in these rocks and the similarity in appearance to oolitic rocks suggests to this investigator that they are probably oolitic rocks and not accretionary lapilli tuffs.

Overall, map unit ts appears to represent a layered, dominantly volcanic sequence with minor amounts of epiclastic and chemical sediments. The pronounced layering

Figure 5. Photomicrograph of oolitic ferruginous chert. Plane-polarized light, 5x, width of photo covers 6.5 mm.

in the volcanics suggest they were reworked in a subaqueous environment. The presence of carbonate indicates that there may have been short periods of quiesence whereas the oolitic rocks suggest there may also have been shallow water, high-energy environments.

Conglomerate (Map Unit c)

This unit is composed of variably stretched quartz-pebble conglomerates and volcaniclastic rocks in roughly equal proportions. The rocks are foliated and silicified zones are not uncommon. The conglomerate unit occurs in the topographically moderate area in the southeastern part of WT (Plate 1).

Dense, dark-gray to brown, thick-bedded, quartz-pebble conglomerates are matrix supported with some pebbles up to 3 cm long (Fig. 6). Most pebbles are subrounded to subangular clasts of very fine-grained quartz. In some outcrops, pebbles are stretched with some elongated as much as 5:1. In thin section, oblong-shaped, undulatory quartz pebbles and very minor amounts of subhedral plagioclase and K-feldspar crystals up to 2 mm long occur in a matrix of fine-grained quartz, plagioclase, sericite and epidote. Trace amounts of opaques, chlorite and sphene (?) are usually present. Foliation is defined by micas which wrap around crystals.

Gradationally interbedded with the quartz-pebble

Figure 6. A slab of quartz pebble conglomerate.

conglomerates are various foliated, presumed volcaniclastic layers. Dark-gray to brown, fine-grained varieties may sometimes contain crude layers of subhedral to euhedral, mostly K-feldspar phenocrysts up to 3 mm long. The phenocrysts generally comprise 15 % or less of the rock. The predominant coarser varieties contain variably stretched, subrounded clasts ($\leq$ 1 cm in size) of quartz, fine-grained amphibolite (?) and possibly granitic rocks along with lesser amounts of euhedral feldspar phenocrysts.

The contact between this unit and the rhyodacite porphyry is not well exposed. To the east, the unit grades into felsic tuffs. This unit may represent a mixture of stream gravels and volcaniclastic material in a fluvial environment.

Felsic Tuff (Map Unit ft)

The ft unit is composed of foliated, gray to brown, felsic tuff and is a minor rock type in the southeastern part of the study area (Plate 1). These rocks are silicified and appear to be baked by adjacent igneous bodies. Consequently, fresh exposures of these rocks are essentially nonexistent but the weathered surfaces generally retain a relict eutaxitic texture (Fig. 7). The rock is composed of small (~1 mm or less) plagioclase phenocrysts and flattened relict pumice fragments (?) and rarely, lithic fragments in a fine-grained matrix. The texture in this

Figure 7. Eutaxitic texture in felsic tuff.

tuff is similar to textures dispalyed by modern ash-flow tuffs and this unit may represent a pyroclastic flow deposit.

This unit marks the easternmost exposure of WT and is terminated to the north by a middle Proterozoic granitic pluton and to the south by Phanerozoic igneous rocks.

Rhyodacite Porphyry (Map Unit rp)

Areally, the predominant rock type in WT is weakly foliated to massive, gray to black porphyritic rhyodacite that weathers gray to reddish-brown. This unit occurs in the central and eastern part of the study area and is generally confined to the higher elevations. It is irregular shaped and may be quite thick as its outcrop width excceds 7 km (Plate 1).

Overall, the rhyodacite lacks intercalated rock types although it is cut by amphibolite dikes and is quite homogeneous in terms of texture and phenocryst abundance. It also seems to be less weathered than the other map units. In hand specimen, the rocks are composed of 25-35 % phenocrysts of chiefly plagioclase in a fine-grained, dark-colored, micaceous groundmass (Fig. 8). Phenocryst sizes are typically 2-3 mm but can be up to ~5 mm. Infrequently, biotite or small cubes of pyrite are present. For the most part, the rhyodacite is only weakly foliated with the foliation surface defined by alignment of platy minerals in

Figure 8. A hand specimen of rhyodacite porphyry.

the groundmass.

In thin section, the rhyodacites are composed of subhedral phenocrysts of commonly sausseritized plagioclase and quartz with the plagioclase comprising at least 75 % of the phenocryst phases. Rarely, K-feldspar and remnants of clinopyroxene crystals being replaced by chlorite or actinolite are also present. Deformational effects are more evident at the microscopic scale as plagioclase crystals may be cracked, broken or display deformed twin lamallae and quartz crystals generally exhibit undulatory extinction and mortar texture. Some phenocrysts are deformed into augen shapes. The groundmass is composed mostly of fine-grained quartz and sericite needles with minor amounts of chlorite, opaques and possibly sphene and actinolite. Foliation is defined by sericite and chlorite which wrap around crystals. Common alteration products include epidote and carbonate.

The inferred contact between this unit and other units in WT may be of an intrusive nature as the rhyodacite porphyry in the west-central portion of the area appears to be an intrusive arm from the main body (Plate 1, sec. 18, 19, T13S, R26E). Also, it is observed that the massive, homogeneous, porphyritic rhyodacite is confined to the higher ridges and hills whereas the porphyritic rocks in the lower elevations are thinly interbedded with various lithologies, more fissile and seem to represent a layered stratigraphic sequence. Erickson (1969) considers most of rp in the study area as extrusive volcanics. However, the lack of interbedded tuffs, the lack of eutaxitic and similar pyroclastic textures, the lack of autobrecciated and vitrophyric zones (if they were flows) and the massive, homogeneous nature of the unit suggests to this investigator that the rhyodacite porphyry is of a hypabyssal origin although some of the layered sequence apparently contains similar volcaniclastic rocks. Since this rock probably intrudes the layered sequence, the rhyodacite porphyry is inferred to be younger than the volcaniclastic and epiclastic rocks.

Amphibolite (Map Unit a)

This unit is comprised of fine to medium-grained, green amphibolite which weathers blue-gray to orange-brown. The amphibolites occur as variably foliated sills, dikes and at least one flow. Dikes are distributed sporadically throughout WT while the sills are mostly limited to the central portion of the study area (Plate 1). The width of these bodies ranges from 150 m for sills to ~1 m for dikes. Sharp contacts exist between the amphibolites and surrounding supracrustal rocks. Small (~1 m or less), irregular to ellipsoidal pods of amphibolite, which may be brecciated, are also observed. In addition, amphibolites occur as fine-grained, foliated dikes within the Sommer gneiss and as unfoliated pods with diabasic texture in the post-tectonic Polecat quartz monzonite. These bodies were not examined in detail.

Although metamorphism has obscured primary features in most outcrops, diabasic, porphyritic and possibly amygdaloidal textures occur in a few places. Amphibolite dikes are generally finer grained than sills but both are similar mineralogically. Petrographically, the amphibolites display foliation marked by chlorite and/or actinolite and stringers of magnetite. Mylonitic texture is sometimes observed in the more sheared varieties and infrequently, relict diabasic or porphyritic textures can be observed. The essential phases in these rocks include amphibole (generally actinolite but may also be hornblende or tremolite) 45 %; subhedral and occasionally partially digested plagioclase, sometimes with deformed twins, 20 %; epidote 20 %; chlorite 10 % and magnetite 5 %. Also, quartz is sometimes observed in the groundmass, especially in the cataclastic varieties. Accessory minerals include apatite, sericite, sphene (?) and a small (< 0.5 mm), anhedral, blood-red, isotropic mineral with high relief (spinel or garnet ?). In addition, secondary calcite is observed.

Additionally, one outcrop in the foothills of the northwestern part of the range (Plate 1) appears to be a fragmental pillow breccia which indicates a submarine flow origin for this particular body. Macroscopically, the rock is dense and composed of dark gray, fine-grained pillow fragments in a light gray to green, heterogeneous matrix (Fig. 9). In thin section, the rock appears altered with secondary minerals comprising a significant portion of the rock. The clasts are composed of chiefly magnetite and chlorite in roughly equal amounts with subordinate epidote and actinolite and subhedral plagioclase laths about 1 mm long (~5-10 %). Also, as with other amphibolites examined petrographically, trace amounts of a blood-red, isotropic mineral (spinel or garnet ?) was observed. The matrix is mostly fine-grained quartz, epidote and chlorite.

For the most part, the amphibolites seem to represent mafic intrusive rocks although there is evidence for at least one submarine extrusive flow. Erickson (1981) reports a seemingly reset K-Ar date of 1190 +/- 35 Ma for an amphibolite from WT. Based on the field relations of the amphibolites and the presence of similar mafic dikes in the syntectonic Sommer gneiss, at least some of the amphibolites are regarded as the youngest early Proterozoic supracrustal rocks in WT.

Granitic Plutons

Portions of two granitic plutons peripheral to WT were briefly examined in the field (Plate 1). The Sommer gneiss (map unit grl) is syntectonic, variably foliated, slightly porphyritic to equigranular, gray, granitic rock that

Figure 9. A slab of fragmental pillow breccia.

weathers red to orange. The rock is composed of generally medium-grained plagioclase, quartz and K-feldspar in a sericitic groundmass with elongated clots of chlorite and biotite. Frequently, this unit is badly sheared resulting in cataclastic rocks of granular quartz and feldspar in a fine-grained micaceous groundmass with a pronounced internal foliation. Also included in this unit are zones of aplite and felsite.

This unit is generally foliated parallel to the surrounding supracrustal rocks. This feature and the similarity in appearance of the sheared gneiss to the adjacent supracrustal rocks make it difficult to distinguish protoliths. The contact with the supracrustal sequence is at least locally discordant as apophyses and small pods of the granitic rocks cross into the supracrustal rocks.

Post-tectonic Polecat quartz monzonite (map unit gr2) is one of the largest Precambrian plutons in the Dos Cabezas Mountains. Typically, it is a non-foliated, porphyritc, gray, granitic rock that weathers buff to red-brown. It is composed of mostly coarse-grained K-feldspar up to 3 cm in a medium-grained groundmass of quartz, plagioclase, K-feldspar and biotite. Shearing is generally absent in this body but it is badly weathered in places. The contact between this pluton and adjacent supracrustal rocks is generally discordant and appears to be a fault boundary in the north-central part of the study area.

STRUCTURAL FEATURES

Obvious structural features include metamorphic foliation, small shear zones, small to large-scale folds and a few faults with little net displacement. No obvious evidence for transposition or isoclinal folding is observed.

Foliation is generally parallel to bedding in the layered rocks and cross-bedded arkoses in unit rt indicate the rocks are not overturned (up is to the southeast) at least in the vicinity of Zeits Canyon. The strike of foliation trends roughly east-west in the western part of the study area and swings to the northeast in the central and eastern parts (Plate 1). The foliation dip also progresses from ~30 degrees in the western part to vertical in the eastern part. In addition to bedding-plane foliation, pronounced lineation of parallel mineral streaks within foliation planes is present in some rocks. The lineation generally trends north to northwesterly and plunges steeply to the southeast. Phyllitic rocks are occasionally crenulated with small fold axes parallel to the general lineation trend.

Small scale folding varies from chevron folds in phyllites (hand specimen size) to occasional kinks or S-folds (~2 m or less wavelengths). Also, drag folding apparently associated with fault movement is observed. The only large scale fold is in the northwestern part of WT where intrusion of the Sommer gneiss may have folded the supracrustal rocks into a somewhat tight anticlinal structure plunging ~55 degrees to the east (Plate 1).

Two poorly exposed east-west trending faults displaying apparent left-lateral separation occur within WT. While they cut only Precambrian units, the ages of these faults cannot be established. The westernmost fault exhibits ~1 km of left-lateral displacement of the Sommer gneiss-rhyolite tuff contact and an amphibolite sill (Plate 1). This fault appears to be nearly vertical and it is brecciated with altered and shear zones occurring along its inferred trace. Left-lateral strike-slip or normal faulting with the northern block downthrown can explain the observed offset. The other east-west trending fault occurs in the north-central part of the study area where it marks the boundary between the Polecat quartz monzonite on the north and supracrustal rocks to the south (Plate 1). This fault is inferred on the basis of the linear character of the Polecat quartz monzonite-ts contact, the presence of brecciation around the contact and the apparent left-lateral offset of ~2 km from the main portion of the pluton. The type of movement along this fault is not known but left-lateral strike-slip motion can produce the observed offset. The relationship between the two faults where they meet is obscured by alluvial cover. In addition, a few very small, northwest to northeast trending, probable normal faults also occur in WT (Plate 1).

This author concurs with Erickson (1969) that WT seems to be a large block whose structural pattern is most readily accommodated as representing the outer axial region and southeastern limb of a large anticline with a northeast trending axis just to the west of WT. This block is locally refolded and broken by a few faults. This interpretation also implies a great original stratigraphic thickness. The presence of a lineation/crenulation trend in addition to bedding-plane foliation suggests these rocks have undergone at least two periods of deformation.

GEOCHEMISTRY OF PROTEROZOIC SUPRACRUSTAL ROCKS

INTRODUCTION

Of approximately 90 samples collected in WT, 22 were selected for bulk chemical analysis utilizing XRF and INAA. Major oxide and trace element analyses and CIPW norms for rocks from WT are presented in Table 1. Sample preparation, analytical procedures and typical machine precision estimates may be found in Allen (1985) and Copeland (1986). Sample locations are found in Appendix A. It should be noted that obtaining a fresh, unaltered specimen for analysis is problematic as evidenced by the high LOIs of some samples. In addition, analyses of 16 samples from ET (Vance, 1983) are reported in Table 2 for comparison and to expand the data base for tectonomagmatic discrimination diagrams and geochemical modeling.

Analyzed rocks from WT include 3 rhyolitic tuffs from map unit rt; 1 felsic tuff, 1 volcaniclastic lapilli tuff, 1 greenstone and 2 oolitic ferruginous cherty rocks from unit ts; 5 rhyodacites; 8 amphibolites and 1 sample of Sommer gneiss. Samples from ET include 2 rhyolitic tuffs, 3 intrusive rhyolites, 3 intrusive quartz latites, 5 rhyodacites and 3 amphibolites. Although these rocks include hypabyssal and volcaniclastic varieties, for brevity the term Dos Cabezas volcanics will hereafter be used to refer to any of the early Proterozoic volcanic and

TABLE 1. CHEMICAL ANALYSES AND CIPW NORMS OF WT ROCKS

Rock Type	Rhyol.	Rhyol.	Rhyol.	Qt.lat.	Rhyod.	Rhyod.
SAMPLE	8A-DC	10-DC	X7	X18	DC-5	DC-6
SiO2	79.3	79.7	79.0	73.9	66.1	66.7
TiO2	0.10	0.15	0.12	0.34	0.80	0.83
Al2O3	11.7	11.4	12.5	12.6	13.5	14.3
Fe2O3-T	0.89	1.00	1.2	2.14	5.47	5.71
MgO	0.15	0.07	0.095	0.40	1.40	1.44
CaO	0.095	0.13	0.48	1.83	3.21	2.78
Na2O	2.80	3.46	1.75	2.41	2.52	3.08
K2O	3.92	3.97	3.54	4.06	3.34	3.33
MnO	0.005	0.007	0.012	0.047	0.097	0.097
P2O5	0.013	0.02	0.008	0.057	0.19	0.19
LOI	0.68	0.37	1.63	2.52	3.02	1.54
TOTAL	99.65	100.28	100.35	100.30	99.65	100.00
Rb	157	123	154	173	149	129
Ba	548	983	525	670	621	744
Cs	4.7	3.7	4.8	4.3	4.6	2.8
Sr	26	28	18	46	136	171
Pb	12	16	15	30	21	22
Th	13	13	18	17	14	15
U	2.8	3.5	3.2	7.3	3.5	3.7
Sc	2.6	5.7	3.1	8.4	17.3	17.6
V	2.7	5.1	2.9	25	72	72
Cr	0.6	0.7	0.1	8.1	26	25
Co	0.5	0.6	0.5	4.6	13	13
Ni	ND	ND	0.8	0.9	18	14
Cu	-	-	-	-	11	12
Zn	20	20	-	-	81	89
Ga	-	-	-	-	17	16
Y	70.8	48.4	84.9	53.9	54.2	55.1
Zr	143	165	152	156	264	267
Nb	16	13	14	12	16	15
Hf	5.5	5.8	7.8	5.9	9.0	8.3
Ta	1.2	0.99	1.6	1.1	1.2	1.3
La	18	39	46	37	48	50
Ce	63	86	106	86	108	106
Sm	4.3	7.9	12.2	7.7	9.1	9.4
Eu	0.38	1.1	0.83	1.0	1.9	2.0
Tb	1.4	1.3	2.4	1.4	1.4	1.5
Yb	6.3	4.8	9.5	5.7	5.1	5.2
Lu	1.1	0.80	1.56	0.97	0.84	0.86
Mg Number	-	-	-	-	-	-

TABLE 1 (continued)

Rock Type	Rhyol.	Rhyol.	Rhyol.	Qt.lat.	Rhyod.	Rhyod.
SAMPLE	8A-DC	10-DC	X7	X18	DC-5	DC-6
CIPW Norms						
Qtz	47.83	43.83	54.46	40.30	29.66	27.25
Cor	2.72	1.23	5.01	1.08	0.37	1.05
Or	23.42	23.50	21.21	24.57	20.50	20.07
Ab	23.95	29.32	15.01	20.88	22.15	26.58
An	0.44	0.52	2.35	8.90	15.26	12.80
Ne	-	-	-	-	-	-
Di	-	-	-	-	-	-
Hy	1.02	0.83	1.15	2.48	7.47	7.59
Ol	-	-	-	-	-	-
Mt	0.41	0.45	0.56	0.98	2.56	2.62
Ilm	0.19	0.29	0.23	0.66	1.58	1.61
Ap	0.02	0.05	0.02	0.14	0.46	0.45
SUM	100.0	100.0	100.0	100.0	100.0	100.0

Explanation at end of Table 2.

TABLE 1 (continued)

Rock Type	Rhyod.	Rhyod.	Rhyod.	Amph.	Amph.	Amph.
SAMPLE	6A-DC	23-DC	29-DC	AZ-2	AZ-6	DC-2
SiO2	66.6	66.3	66.8	42.6	45.1	47.0
TiO2	0.82	0.83	0.77	1.42	2.96	1.99
Al2O3	14.5	14.5	14.1	14.8	16.2	14.9
Fe2O3-T	5.66	5.82	5.23	12.7	16.2	14.1
MgO	1.41	1.41	1.34	7.58	4.53	6.61
CaO	2.28	2.63	2.66	9.60	6.74	8.25
Na2O	3.14	2.91	3.68	1.67	3.25	1.09
K2O	3.59	3.80	2.73	0.049	1.89	0.18
MnO	0.10	0.10	0.087	0.19	0.19	0.20
P2O5	0.19	0.19	0.17	0.18	0.37	0.30
LOI	1.87	1.66	2.87	9.17	2.58	5.45
TOTAL	100.16	100.15	100.44	99.96	100.01	100.07
Rb	160	162	119	3.9	131	5.3
Ba	754	749	611	17	476	149
Cs	9.5	4.7	5.1	0.4	15	0.3
Sr	151	170	131	205	590	193
Pb	19	26	17	25	3.7	5.6
Th	14	14	13	0.7	2.3	1.7
U	3.6	3.8	2.8	0.1	0.5	0.4
Sc	17.3	17.8	14.5	45.0	21.6	42.4
V	85	87	80	272	197	258
Cr	27	25	21	243	8.0	188
Co	13	13	11	49	59	55
Ni	16	11	16	59	72	98
Cu	19	-	-	20	51	49
Zn	87	87	77	143	121	149
Ga	17	-	-	18	23	20
Y	56.7	55.5	52.3	34.1	33.8	47.2
Zr	277	273	253	120	212	203
Nb	15	15	15	6.8	21	9.3
Hf	8.8	9.0	7.6	3.1	5.4	5.4
Ta	1.2	1.2	1.1	0.23	1.5	0.34
La	50	50	43	8.4	26	17
Ce	104	106	89	19	62	43
Sm	9.4	9.9	8.6	4.1	8.0	7.0
Eu	2.0	2.0	2.0	1.4	2.4	2.1
Tb	1.5	1.7	1.5	0.95	1.1	1.4
Yb	5.3	5.2	4.6	3.1	2.4	4.4
Lu	0.87	0.84	0.77	0.51	0.40	0.72
Mg Number	-	-	-	57.3	38.6	51.3

TABLE 1 (continued)

Rock Type	Rhyod.	Rhyod.	Rhyod.	Amph.	Amph.	Amph.
SAMPLE	6A-DC	23-DC	29-DC	AZ-2	AZ-6	DC-2
CIPW Norms						
Qtz	26.97	26.34	26.88	-	-	7.19
Cor	1.80	1.30	0.68	-	-	-
Or	21.67	22.89	16.60	0.33	11.63	1.14
Ab	27.14	25.10	32.03	15.76	26.32	9.88
An	10.29	12.04	12.43	36.52	25.02	37.72
Ne	-	-	-	-	1.25	-
Di	-	-	-	12.57	6.11	3.31
Hy	7.49	7.61	7.06	20.81	-	33.35
Ol	-	-	-	8.15	19.94	-
Mt	2.61	2.68	2.42	2.44	2.91	2.61
Ilm	1.59	1.61	1.50	2.97	5.93	4.07
Ap	0.45	0.45	0.41	0.47	0.89	0.74
SUM	100.0	100.0	100.0	100.0	100.0	100.0

Explanation at end of Table 2.

TABLE 1 (continued)

Rock Type	Amph.	Amph.	Amph.	Amph.	Amph.	And.
SAMPLE	DC-3	5ADC	12-DC	Y7	18-A	17-L
SiO2	46.4	48.8	49.9	43.7	43.6	56.2
TiO2	2.15	1.49	2.38	1.48	0.72	0.75
Al2O3	15.0	15.1	11.6	14.5	16.7	16.0
Fe2O3-T	14.3	12.6	16.7	11.9	10.6	8.13
MgO	6.59	6.39	5.47	5.92	6.38	3.45
CaO	9.33	9.97	6.24	8.68	9.56	7.52
Na2O	1.32	1.92	1.96	1.15	1.50	3.95
K2O	0.56	0.50	0.013	1.68	1.63	0.24
MnO	0.20	0.19	0.32	0.14	0.23	0.14
P2O5	0.34	0.20	0.45	0.20	0.073	0.10
LOI	3.27	2.78	5.33	11.10	9.18	4.18
TOTAL	99.46	99.94	100.36	100.45	100.17	100.66
Rb	17	20	1.4	106	100	14
Ba	166	127	45	240	180	42
Cs	0.3	0.6	0.2	9.8	2.8	0.6
Sr	226	209	121	87	93	199
Pb	6.4	9.2	8.8	17	8.9	13
Th	1.2	1.3	2.9	0.9	0.7	4.0
U	0.3	0.3	0.8	0.3	0.2	0.9
Sc	37.7	44.5	52.7	32.1	38.2	24.1
V	268	294	441	262	234	155
Cr	256	206	18	206	34	98
Co	53	40	50	46	59	33
Ni	112	60	39	131	109	76
Cu	51	64	26	66	52	30
Zn	112	121	199	166	136	73
Ga	20	17	24	16	14	14
Y	45.6	40.5	55.4	36.2	23.1	27.7
Zr	216	141	166	132	54.5	120
Nb	6.2	6.9	10	7.6	4.0	7.4
Hf	5.2	3.7	4.7	3.5	1.8	3.3
Ta	0.41	0.25	0.42	0.25	0.10	0.36
La	17	11	20	11	4.3	14
Ce	41	25	47	28	11	36
Sm	6.9	4.9	7.8	5.0	2.1	4.0
Eu	2.0	1.5	2.4	1.4	0.81	1.0
Tb	1.3	1.1	1.6	0.98	0.53	0.74
Yb	3.8	3.3	5.8	3.4	2.2	3.0
Lu	0.66	0.55	0.94	0.56	0.38	0.51
Mg Number	50.9	53.3	42.4	52.8	57.5	48.8

TABLE 1 (continued)

Rock Type	Amph.	Amph.	Amph.	Amph.	Amph.	And.
SAMPLE	DC-3	5ADC	12-DC	Y7	18-A	17-L
CIPW Norms						
Qtz	2.82	2.35	11.25	0.02	-	9.63
Cor	-	-	-	-	-	-
Or	3.48	3.08	0.06	11.24	10.70	1.48
Ab	11.76	16.91	17.72	11.02	14.09	34.90
An	35.11	32.38	24.39	33.34	37.77	26.33
Ne	-	-	-	-	-	-
Di	9.33	14.65	4.65	11.52	11.84	9.93
Hy	29.67	24.92	32.87	26.83	7.88	14.53
Ol	-	-	-	-	14.00	-
Mt	2.60	2.26	3.08	2.33	2.03	1.47
Ilm	4.40	2.97	4.87	3.18	1.52	1.49
Ap	0.83	0.48	1.11	0.52	0.18	0.24
SUM	100.0	100.0	100.0	100.0	100.0	100.0

Explanation at end of Table 2.

TABLE 1 (continued)

Rock Type	And.	Gneiss	Chert	Chert
SAMPLE	DC-8	SG-313	OI-1	DC-10B
SiO2	60.1	75.8	59.3	60.8
TiO2	0.35	0.26	0.97	0.96
Al2O3	14.3	12.6	15.4	15.4
Fe2O3-T	4.51	1.67	12.4	11.3
MgO	3.18	0.20	1.17	0.78
CaO	6.84	0.38	1.80	1.68
Na2O	4.62	2.95	4.42	4.12
K2O	0.74	4.77	2.45	2.99
MnO	0.079	0.041	0.15	0.081
P2O5	0.11	0.041	0.46	0.45
LOI	5.61	0.85	1.52	1.58
TOTAL	100.44	99.56	100.04	100.14
Rb	23	212	86	108
Ba	240	730	840	787
Cs	0.9	5.6	6.8	-
Sr	460	51	157	135
Pb	8.8	23	19	14
Th	2.2	17	5.2	-
U	0.6	3.1	1.8	-
Sc	13.2	6.9	20.6	-
V	-	11	ND	ND
Cr	109	3.5	0.3	-
Co	16	3.0	7.7	-
Ni	65	1.9	5.0	1.6
Cu	-	-	ND	ND
Zn	54	-	202	93
Ga	-	-	39	35
Y	7.2	56.9	111	110
Zr	70	149	1517	1500
Nb	3.1	12	51	50
Hf	1.9	5.8	41	-
Ta	0.14	1.2	3.0	-
La	11	36	115	-
Ce	21	82	290	-
Sm	2.1	7.9	31.5	-
Eu	0.66	0.9	7.1	-
Tb	0.29	1.5	3.7	-
Yb	0.75	5.8	12.2	-
Lu	0.15	0.98	1.99	-
Mg Number	61.3	-	-	-

TABLE 1 (continued)

Rock Type	And.	Gneiss	Chert	Chert
SAMPLE	DC-8	SG-313	OI-1	DC-10B
CIPW Norms				
Qtz	13.15	39.43	-	-
Cor	-	2.02	-	-
Or	4.63	28.59	-	-
Ab	41.39	25.32	-	-
An	17.04	1.65	-	-
Ne	-	-	-	-
Di	14.84	-	-	-
Hy	7.15	1.65	-	-
Ol	-	-	-	-
Mt	0.83	0.77	-	-
Ilm	0.70	0.50	-	-
Ap	0.27	0.09	-	-
SUM	100.0	100.0	-	-

Explanation at end of Table 2.

TABLE 2. CHEMICAL ANALYSES AND CIPW NORMS OF ET ROCKS

Rock Type	Rhyol.	Rhyol.	Rhyol.	Rhyol.	Rhyol.	Qt.lat.
SAMPLE	GT-2	GT-3	QP-3	QP-5	QP-7	P-2
SiO2	81.6	78.9	81.8	82.4	79.1	74.1
TiO2	0.18	0.22	0.17	0.17	0.20	0.35
Al2O3	11.5	12.3	11.5	11.6	12.0	13.1
Fe2O3-T	1.28	1.68	1.17	1.52	1.40	2.59
MgO	0.25	0.58	0.19	0.13	0.15	0.27
CaO	0.20	0.51	0.19	0.03	0.28	1.26
Na2O	1.69	1.07	0.14	0.12	1.24	2.77
K2O	3.66	4.64	4.48	3.81	5.91	4.74
MnO	0.02	0.05	0.02	0.02	0.02	0.04
P2O5	0.02	0.03	0.02	0.02	0.04	0.06
LOI	0.63	0.58	0.70	0.93	0.09	0.84
TOTAL	101.03	100.56	100.38	100.75	100.43	100.12
Rb	113	165	206	207	254	167
Ba	525	1234	407	223	453	937
Cs	1.8	3.2	7.3	13	5.2	9.0
Sr	96	142	23	5.3	56	127
Pb	44	98	12	9.3	21	23
Th	23	23	24	22	24	19
U	5.1	5.0	4.5	3.9	4.4	4.5
Sc	5.1	5.6	5.2	5.3	5.4	7.4
V	-	7.8	2.9	4.9	-	18
Cr	1.9	2.0	0.3	0.4	1.7	3.1
Co	1.2	1.7	0.8	0.8	1.4	3.6
Ni	3.1	7.5	ND	ND	4.4	ND
Cu	-	-	-	-	-	-
Zn	49	72	20	25	24	39
Ga	-	-	-	-	-	-
Y	56.2	75.4	46.7	30.4	62.5	59.7
Zr	149	180	151	150	166	281
Nb	14	15	14	14	15	15
Hf	5.3	6.0	5.5	5.6	5.8	7.9
Ta	1.3	1.4	1.3	1.4	1.4	1.2
La	42	55	44	30	47	41
Ce	89	115	87	67	98	90
Sm	7.5	11.4	7.9	5.9	8.9	8.1
Eu	0.58	0.94	0.60	0.47	0.72	1.4
Tb	1.7	2.1	1.3	0.93	1.8	1.5
Yb	5.1	6.1	4.7	4.0	5.1	5.3
Lu	0.81	0.99	0.82	0.71	0.89	0.87
Mg Number	-	-	-	-	-	-

TABLE 2 (continued)

Rock Type	Rhyol.	Rhyol.	Rhyol.	Rhyol.	Rhyol.	Qt.lat.
SAMPLE	GT-2	GT-3	QP-3	QP-5	QP-7	P-2
CIPW Norms						
Qtz	56.45	52.57	63.10	66.62	48.01	36.43
Cor	4.43	4.67	6.15	7.29	3.14	1.28
Or	21.56	27.46	26.58	22.58	34.84	28.26
Ab	14.26	9.01	1.19	1.02	10.47	23.65
An	0.86	2.34	0.82	0.02	1.13	5.91
Ne	-	-	-	-	-	-
Di	-	-	-	-	-	-
Hy	1.48	2.66	1.28	1.42	1.32	2.49
Ol	-	-	-	-	-	-
Mt	0.58	0.76	0.52	0.68	0.62	1.17
Ilm	0.34	0.42	0.32	0.32	0.38	0.67
Ap	0.05	0.07	0.05	0.05	0.09	0.14
SUM	100.0	100.0	100.0	100.0	100.0	100.0

Explanation at end of Table 2.

TABLE 2 (continued)

Rock Type	Qt.lat.	Qt.lat.	Rhyod.	Rhyod.	Rhyod.	Rhyod.
SAMPLE	P-4	P-7	BT-1	BT-3	BT-8	BT-9
SiO2	73.1	71.2	68.1	66.9	68.5	67.3
TiO2	0.41	0.42	0.83	0.87	0.81	0.84
Al2O3	13.3	13.6	14.8	14.8	14.5	14.7
Fe2O3-T	3.08	2.96	5.74	6.14	5.65	6.04
MgO	0.45	0.38	1.81	1.72	1.38	1.86
CaO	1.53	1.38	2.12	2.29	2.68	2.42
Na2O	2.28	2.50	2.70	3.44	3.08	3.24
K2O	4.75	5.09	4.58	3.57	3.06	3.27
MnO	0.06	0.05	0.09	0.10	0.10	0.11
P2O5	0.08	0.08	0.19	0.19	0.18	0.21
LOI	1.26	0.59	0.57	0.61	0.32	0.32
TOTAL	100.30	98.25	101.53	100.63	100.26	100.31
Rb	208	191	161	190	120	137
Ba	963	961	859	916	739	850
Cs	19	11	13	12	5.1	7.4
Sr	88	117	159	104	168	133
Pb	23	27	17	25	21	20
Th	19	18	14	13	14	14
U	4.7	5.0	3.4	3.4	3.9	3.7
Sc	9.5	9.6	17.6	16.1	17.0	17.1
V	19	-	-	-	79	84
Cr	5.9	6.7	24	24	26	25
Co	4.4	4.3	13	13	13	13
Ni	3.9	ND	24	19	23	17
Cu	-	-	-	-	18	13
Zn	57	46	90	80	75	85
Ga	-	-	-	-	15	15
Y	68.0	66.7	56.5	56.8	54.5	55.9
Zr	302	297	270	272	252	266
Nb	15	16	14	15	15	16
Hf	9.4	8.8	8.7	8.1	7.8	8.3
Ta	1.3	1.2	1.2	1.2	1.3	1.3
La	49	42	50	45	48	48
Ce	98	88	104	91	98	99
Sm	10.2	8.4	9.4	8.8	10.0	9.8
Eu	1.6	1.6	2.0	1.8	1.8	1.9
Tb	1.6	1.3	1.7	1.5	1.5	1.7
Yb	6.0	5.9	4.9	4.5	4.8	4.8
Lu	1.0	1.0	0.76	0.77	0.81	0.76
Mg Number	-	-	-	-	-	-

TABLE 2 (continued)

Rock Type	Qt.lat.	Qt.lat.	Rhyod.	Rhyod.	Rhyod.	Rhyod.
SAMPLE	P-4	P-7	BT-1	BT-3	BT-8	BT-9
CIPW Norms						
Qtz	37.40	33.82	26.26	24.50	29.97	26.80
Cor	1.84	1.70	1.99	1.57	1.69	1.94
Or	28.40	30.86	26.91	21.18	18.16	19.41
Ab	19.52	21.70	22.72	29.22	26.18	27.53
An	7.15	6.49	9.23	10.16	12.18	10.68
Ne	–	–	–	–	–	–
Di	–	–	–	–	–	–
Hy	3.31	3.04	8.32	8.49	7.32	8.83
Ol	–	–	–	–	–	–
Mt	1.41	1.37	2.57	2.78	2.55	2.72
Ilm	0.79	0.82	1.57	1.66	1.55	1.60
Ap	0.19	0.19	0.44	0.44	0.42	0.49
SUM	100.0	100.0	100.0	100.0	100.0	100.0

Explanation at end of Table 2.

TABLE 2 (continued)

Rock Type	Rhyod.	Amph.	Amph.	Amph.
SAMPLE	BT-10	A-1	A-2	A-3
SiO2	67.9	45.2	47.9	47.8
TiO2	0.84	1.94	2.03	1.87
Al203	14.6	16.6	16.3	15.7
Fe2O3-T	5.90	15.8	15.1	14.8
MgO	1.53	7.53	7.14	7.47
CaO	2.26	8.77	7.62	8.39
Na2O	3.48	2.30	2.63	2.34
K2O	3.23	0.15	0.88	0.25
MnO	0.11	0.24	0.20	0.21
P2O5	0.19	0.22	0.27	0.22
LOI	1.44	1.40	1.00	1.35
TOTAL	101.48	100.15	101.07	100.40
Rb	139	7.7	38	22
Ba	751	57	76	83
Cs	8.6	0.1	4.5	1.6
Sr	147	171	280	208
Pb	20	6.0	8.2	8.5
Th	14	1.3	1.8	1.4
U	3.8	0.4	0.6	0.6
Sc	17.0	48.5	36.5	42.1
V	-	296	-	239
Cr	25	128	171	277
Co	13	74	51	67
Ni	15	118	100	119
Cu	-	85	-	48
Zn	82	172	134	166
Ga	-	26	-	20
Y	55.4	39.9	46.3	46.5
Zr	264	150	180	176
Nb	15	7.9	8.1	7.9
Hf	8.4	4.3	4.2	5.3
Ta	1.3	0.30	0.39	0.44
La	48	12	15	14
Ce	101	31	35	36
Sm	9.4	5.9	6.2	6.5
Eu	1.9	1.9	1.9	2.0
Tb	1.4	1.1	1.2	1.3
Yb	4.8	3.8	3.7	3.9
Lu	0.82	0.68	0.63	0.73
Mg Number	-	51.7	51.5	53.1

TABLE 2 (continued)

Rock Type	Rhyod.	Amph.	Amph.	Amph.
SAMPLE	BT-10	A-1	A-2	A-3
CIPW Norms				
Qtz	26.98	-	-	-
Cor	1.73	-	-	-
Or	19.16	0.91	5.27	1.51
Ab	29.55	19.99	22.54	20.25
An	10.01	35.46	30.46	32.31
Ne	-	-	-	-
Di	-	6.41	5.00	7.25
Hy	7.87	15.68	19.19	28.15
Ol	-	14.44	10.41	3.71
Mt	2.66	2.80	2.64	2.61
Ilm	1.60	3.78	3.85	3.69
Ap	0.44	0.52	0.63	0.52
SUM	100.0	100.0	100.0	100.0

Explanation at end of Table 2.

EXPLANATION FOR TABLES 1 AND 2

Major element oxides and CIPW norms in weight percent, trace elements in parts per million (ppm). Fe2O3-T is total Fe as Fe2O3. LOI is loss on ignition. ND is not detectable, a dash (-) means not determined or zero.

Since FeO was not analytically determined, it is estimated as follows: For mafic and andesitic rocks, FeO calculated using the ratio Fe2O3/FeO = 0.15 for CIPW norms and Mg Number. Mg Number calculated using [MgO/MgO+FeO (molecular proportions)]*100. For felsic rocks, FeO calculated using the ratio Fe2O3/FeO = 0.5 for CIPW norms. CIPW norms determined by recalculating chemical analyses to 100 % on a volatile-free basis.

Major element oxides, Rb, Sr, Pb, V, Y, Zr, Nb, Cu, and Ga were analyzed by XRF; Ba, Cs, Th, U, Sc, Cr, Co, Ni, Hf, Ta REE and Zn were analyzed by INAA (except Zn for samples Y7, 18-A, 17-L, OI-1 and DC-10B and Ba and Ni for DC-10B which were analyzed by XRF).

For WT rocks: P. Bowling, analyst; For ET rocks: K. Vance, analyst.

Rhyol. = Rhyolites, Qt.lat. = Quartz latites, Rhyod. = Rhyodacites, And. = Andesite, Amph. = Amphibolite subvolcanic rocks of the Dos Cabezas Mountains.

ALTERATION

Before the composition of these rocks is discussed, it is necessary to address the problem of alteration. In addition to metamorphism, various secondary processes such as halmyrolysis, weathering, hydrothermal alteration and metasomatism may play a role in perturbing the original chemical composition of a rock. While these processes can affect both major and trace element concentrations, various studies have suggested that the heavy rare earth elements (REE) and the high field strength elements (HFSE, i.e. Ti, Y, Zr, Nb, Hf and Ta) are the least susceptible to mobilization during alteration and are considered "relatively immobile" (Cann, 1970; Nicholls and Islam, 1971; Condie et al., 1977) although under certain circumstances they can be mobilized (Hynes, 1980; MacGeehan and MacLean, 1980). Consequently, these immobile elements should be the best to use for tectonic discrimination and geochemical modeling.

Besides macroscopic and microscopic evidence of alteration, various chemical criteria such as high LOI, normative feldspathoids and aberrant chemical analyses (including odd REE patterns) may be used to discern altered samples (Shadel, 1982). In addition, graphical methods utilizing molecular proportion ratios (MPR) have been suggested to detect (and correct for) chemical modifications (Beswick and Soucie, 1978). However, it should be noted that some investigators feel that MPR plots are invalid to use as tests of element mobility because trends on these plots are an artifact of ratio correlation (Rollinson and Roberts, 1986).

Based on the chemical criteria listed above, it is apparent from Table 1 that some of the mafic rocks from WT are altered. These samples (AZ-2, AZ-6, 12-DC, Y7 and 18A) also display petrographic evidence of secondary epidote, chlorite and/or calcite. However, relatively immobile elements in these samples are plotted on geochemical diagrams. They are, however, excluded from geochemical modeling calculations. While the plots of Beswick and Soucie (1978) are not reproduced here, the above samples generally plot in the altered fields. No corrections are applied to these rocks since the procedures proposed by Beswick and Soucie (1978) are for major elements only. Although there appears to be an analytical problem for some major elements, the rocks from ET (Table 2) do not seem to be as altered as some of those from WT. This agrees with the observation of this author and Vance (personal communication) that WT has undergone more extensive shearing and weathering than ET. However, felsic rocks from both areas appear to have had some silica added since some contain around 80 % SiO_2. This is maybe due to the presence of ubiquitous, microscopic quartz veinlets. This is in contrast to the low SiO_2 contents (<45 % SiO_2) of some of the altered mafic rocks, which may reflect silica removal or dilution. In addition, the variation in alkalies within a given rock type may be due to mobilization during secondary processes.

CLASSIFICATION

Several classification schemes involving various combinations of major and/or trace elements are used to categorize the Dos Cabezas volcanic suite. The Nb/Y-SiO_2 plot of Winchester and Floyd (1977) defines the amphibolites as sub-alkaline basalts (tholeiites) and shows three populations within the felsic rocks which are designated rhyodacites, quartz latites and rhyolites (Fig. 10). The paucity of samples between 50 and 66 % SiO_2 may be due to sampling bias; however, rocks of andesitic composition are generally scarce in the Proterozoic of the southwestern United States (Condie and Budding, 1979; Shadel, 1982; Condie, 1986; Copeland, 1986). One of the two samples that plots as an andesite, DC-8, is clearly altered (high LOI, unusual REE pattern) and cannot be considered a "real" andesite. The other sample, 17-L, displays some petrographic evidence of alteration although it is not as chemically aberrant as DC-8. This rock, however, is believed to be volcaniclastic and may represent a mixture of

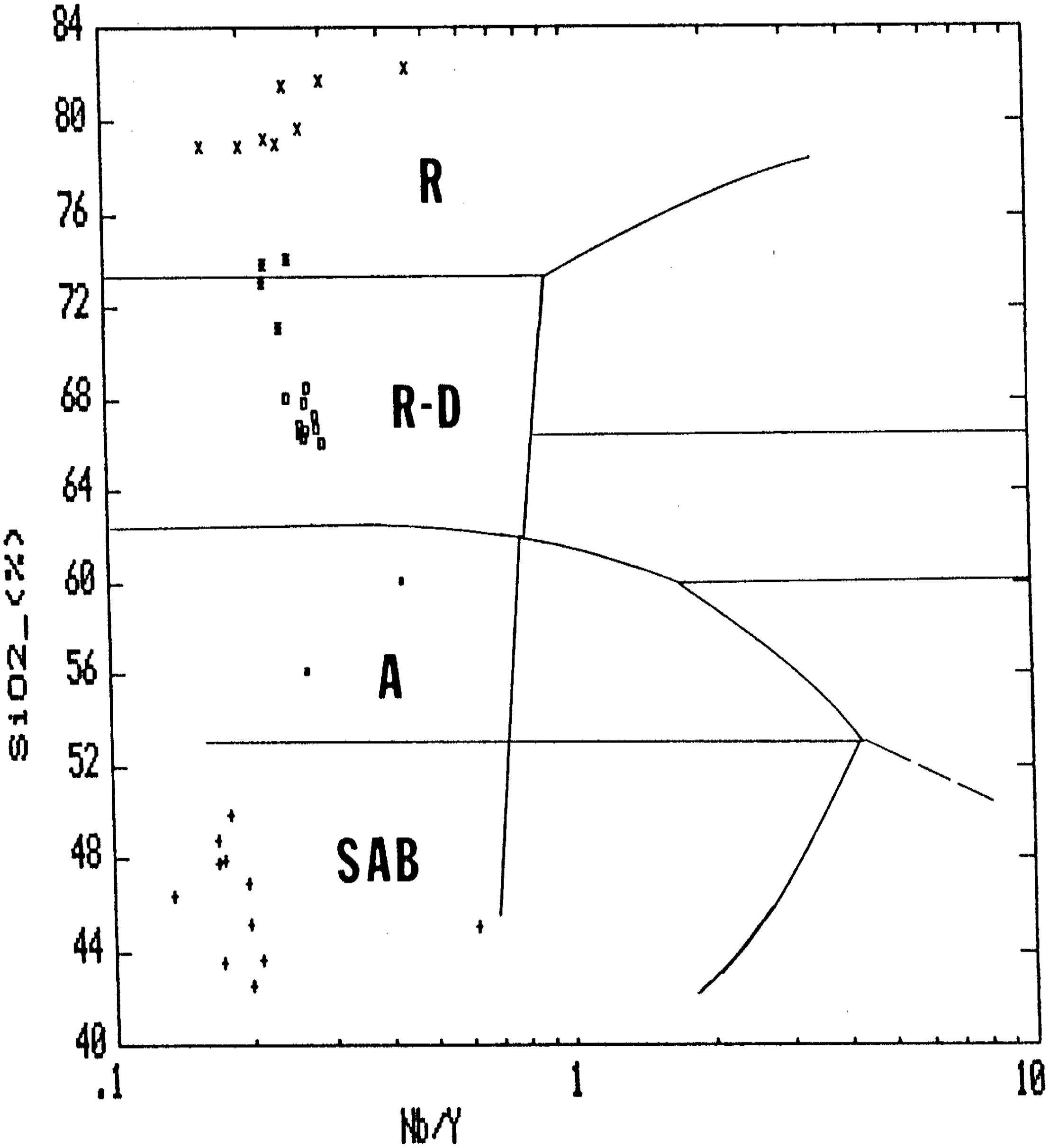

Figure 10. Classification of Dos Cabezas volcanics on Nb/Y-SiO2 diagram, R, rhyolite; R-D, rhyodacite-dacite; A, andesite; SAB, sub-alkaline basalt; fields after Winchester and Floyd (1977). Symbols: +, amphibolite; small filled box, andesite (?); large open box, rhyodacite porphyry; large filled box, quartz latite; x, rhyolite.

felsic and mafic material in the proper proportions to chemically seem andesitic. Alternatively, it may be a chemically modified mafic rock. In any case, the identification of these two samples as andesites is tenuous and they are not shown on subsequent geochemical plots. So for all intents and purposes, the Dos Cabezas suite appears to represent a bimodal igneous series based on the samples represented here.

These populations define coherent geochemical groups and the same classification of the suite is delineated on other Winchester and Floyd (1977) plots with the only notable exception being that the mafic rocks plot chiefly as basaltic andesites on the Nb/Y-Zr/TiO2 plot. The same grouping of the Dos Cabezas volcanics is also evident on the Jensen cation plot (Jensen, 1976; Fig. 11) and the AFM diagram (Irvine and Barager, 1971; Fig. 12). The amphibolites plot as tholeiites on both diagrams whereas the rest of the suite generally displays calc-alkaline affinities (Figs. 11, 12). The Dos Cabezas volcanics do not define a linear trend between mafic and felsic end members on trace element binary plots such as Th-Nb, Ta-Yb or Y-La. The presence of tholeiitic mafic rocks and calc-alkaline felsic rocks and the lack of smooth geochemical covariation between the two groups suggests that they are not genetically related. Consequently, a fractional crystallization origin such as the proposed models for

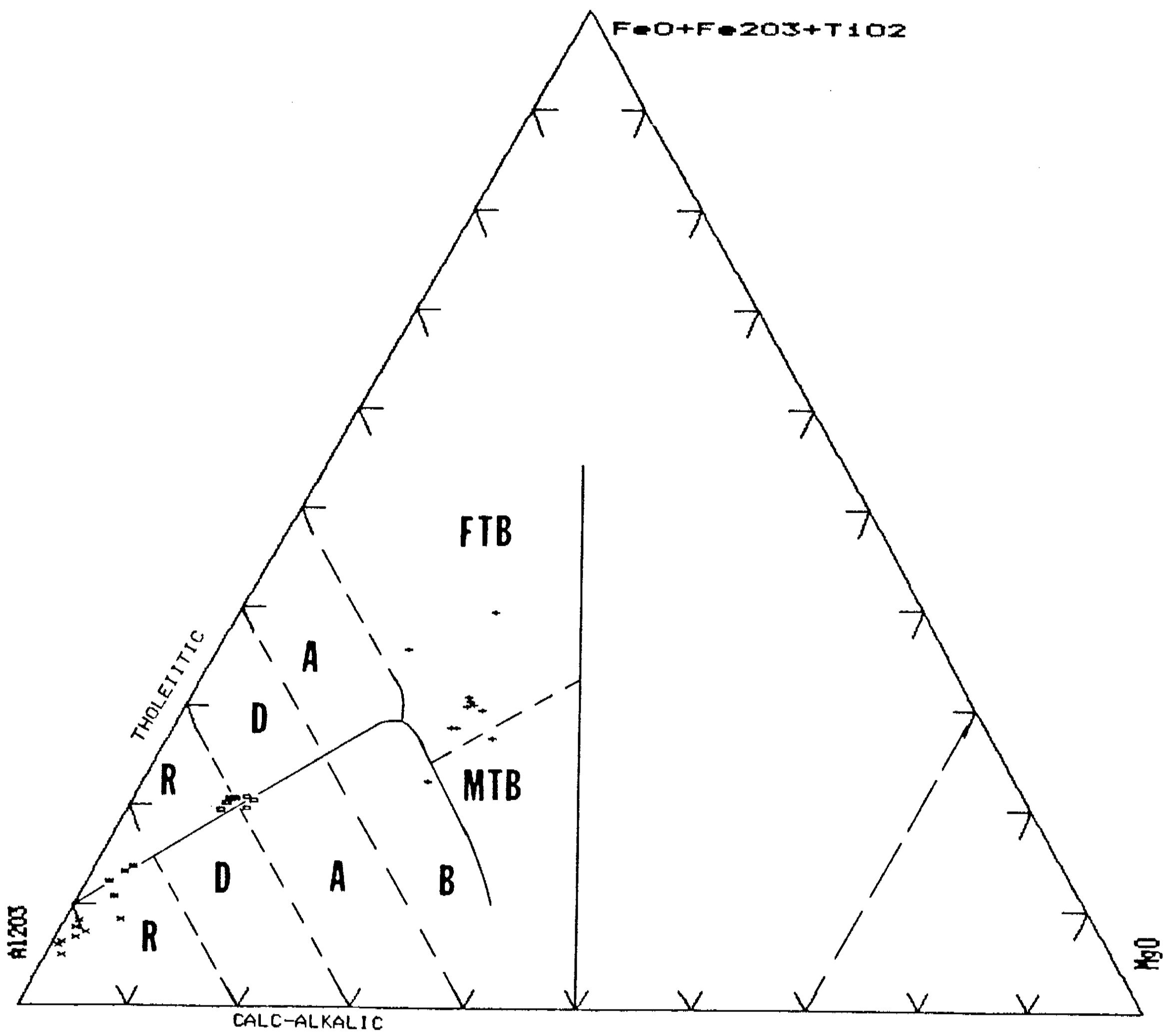

Figure 11. Jensen cation plot showing distribution of Dos Cabezas volcanics. FTB: high-Fe tholeiitic basalt, MTB: high-Mg tholeiitic basalt, B: basalt (calc-alkaline), A: andesite, D: dacite, R: rhyolite, fields after Jensen (1976). Symbols given in Fig. 10.

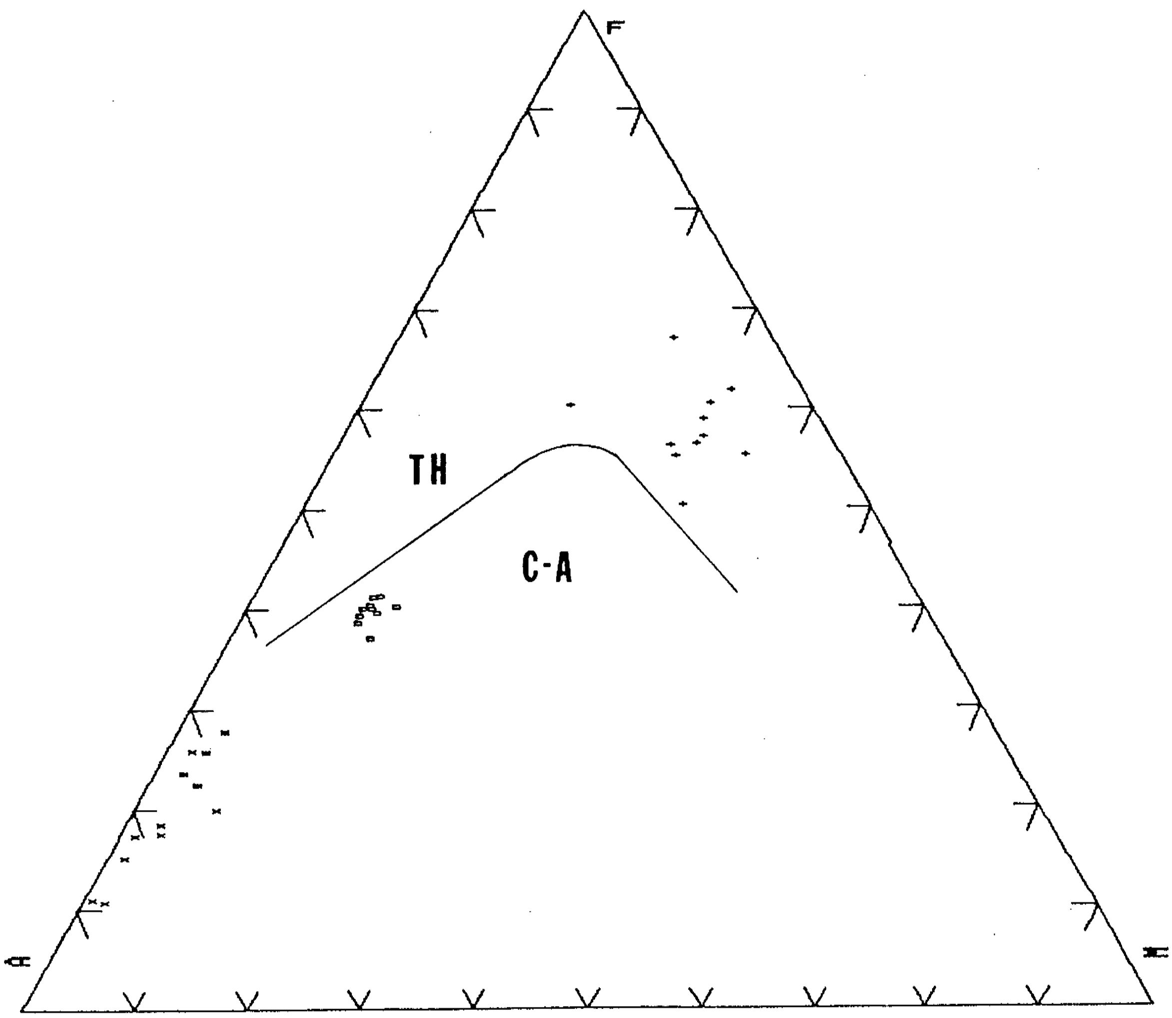

Figure 12. Distribution of Dos Cabezas volcanics on AFM plot. TH: tholeiitic compositions, C-A: calc-alkaline compositions, fields after Irvine and Barager (1971). A=Na2O+K2O, F=FeO+Fe2O3 (FeO/Fe2O3 normalized as in Table 2), M=MgO. Symbols as in Fig. 10.

Proterozoic volcanics in southeastern Wyoming, west-central Colorado and northern New Mexico (Condie and Shadel, 1984; M.W. Knoper and K.C. Condie, unpub. data; Robertson, 1984; McKee and Condie, 1985) is not favored for the Dos Cabezas volcanic suite.

AMPHIBOLITES

Geochemically, amphibolites from WT are indistinguishable from those in ET (Tables 1, 2). Also, there are no differences chemically between amphibolite sills and dikes. Most of the amphibolites are quartz normative, a few are olivine normative and one altered sample (AZ-6) is nepheline normative. In terms of major elements, the four main features characteristic of these mafic rocks are, 1) the relatively high Ti contents with most samples containing ~1.5 to 2.0 % TiO_2; 2) the low Mg Numbers which fall between 50-53 for the least altered samples indicating the rocks are petrologically evolved; 3) the iron-enrichment, which indicates the rocks are tholeiitic (Figs. 11, 12); and 4) the variable K_2O contents that probably reflect alteration.

The amphibolites also exhibit large ranges in Rb, Ba, Cs and to a lesser degree Sr. This also may reflect alteration. Except for some of the clearly altered samples, the amphibolites have moderate amounts of V and Cr but lower (~100 ppm) Ni contents and have relatively high contents of

Y (~45 ppm) and Zr (up to ~200 ppm). Most trace element ratios such as Zr/Y, Nb/Y, La/Ta, La/Th, Th/Yb, La/Yb and Y/Tb fall within limited ranges whereas other ratios such as Ti/V, Nb/Ta, Ti/Zr and those involving alkali metals or alkaline-earth metals exhibit larger variations. Chondrite-normalized REE patterns are similar, displaying light-REE enrichment (up to 50 x chondrites), small negative Eu anomalies and moderate heavy-REE abundances (Fig. 13a). The REE patterns of the amphibolites are similar to the Proterozoic metabasalts in central and southern New Mexico (Condie and Budding, 1979). It is interesting to note that some of the altered amphibolites display the same REE patterns as the least altered varieties but two of the altered group (18-A and AZ-6) are clearly aberrant (Fig. 13b). Overall, the amphibolites have trace element characteristics similar to other early Proterozoic metabasalts in southeastern Arizona such as those in the Dragoons and Chiricahuas (Copeland, 1986).

Geochemical modeling (Appendix B) indicates that the mafic rocks can be produced by predominantly olivine fractionation of a 10-20 % partial melt of an incompatible element enriched upper mantle lherzolite source.

To further characterize these mafic rocks and facilitate comparison with basalts from different tectonic settings, the amphibolites are plotted on mid-ocean ridge basalt (MORB) normalized multi-element diagrams (Pearce,

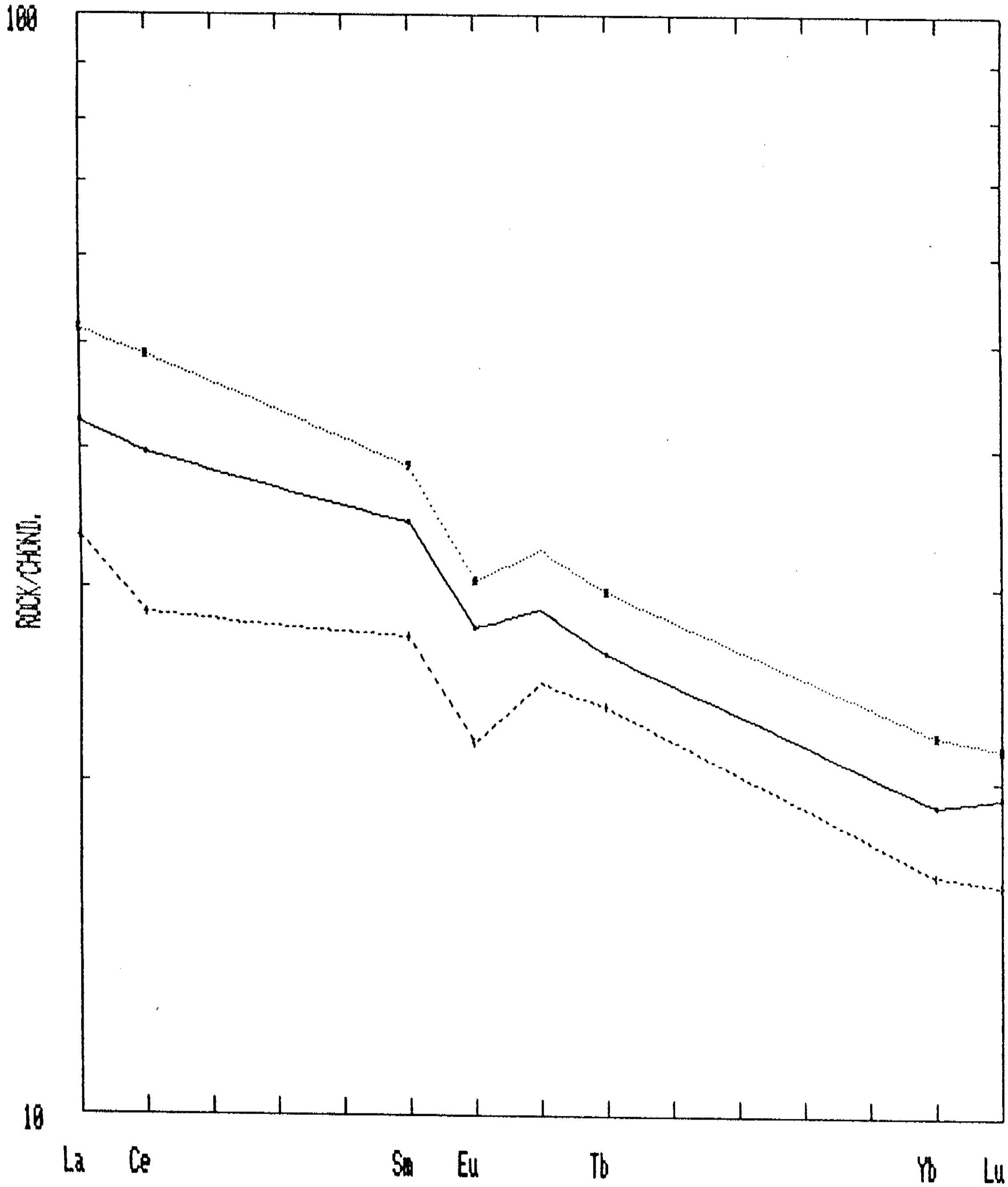

Figure 13a. Chondrite-normalized REE pattern envelope of variation (broken lines) and mean (solid line) for the six least altered amphibolites.

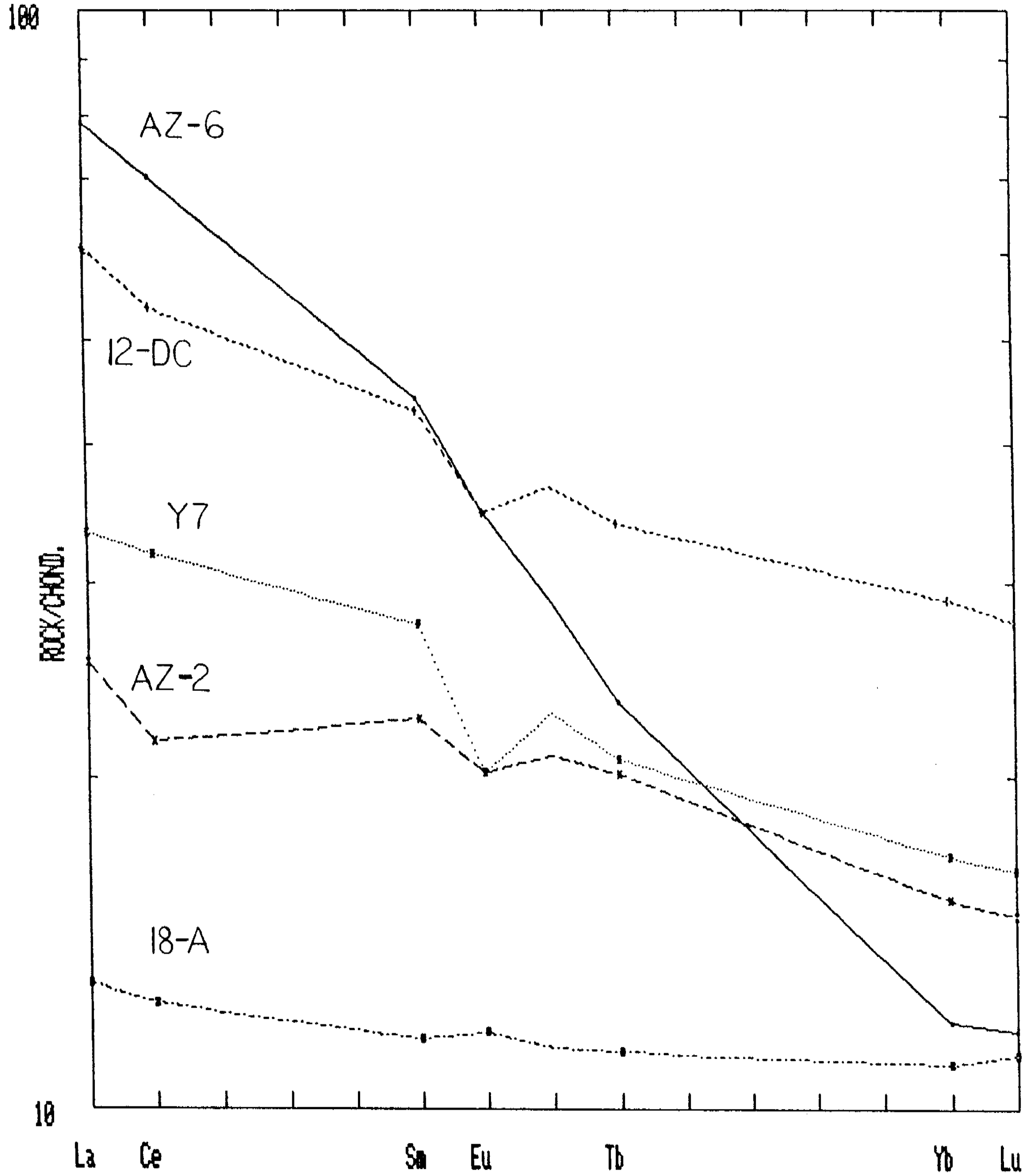

Figure 13b. Chondrite-normalized REE patterns for altered amphibolites.

1982; 1983). The shapes of patterns on these diagrams are a function of the chemical characteristics of the source region and/or crustal contamination of the samples in question (Pearce, 1983). Temporal variations in mantle geochemistry via fractionation and anatexis tend to change the level of the pattern without significantly altering the shape. Hence, it is possible to compare Precambrian trace element patterns to those of Phanerozoic rocks (Pharaoh and Pearce, 1984).

The range of compositions of MORB-normalized trace element patterns for the six least altered amphibolites as well as their mean is plotted in Figure 14a. The amphibolites are enriched relative to MORB in all elements and the pattern reveals that the large ion lithophile elements (LILE - Sr, K, Rb, Ba and Th) and Ce are enriched relative to the HFSE. This selective enrichment of LILE +/- Ce is generally attributed to volatile transfer of these elements from a subducting slab to the mantle wedge whereas the HFSE are retained in the slab. Hence, this selective enrichment is a feature of arc related magmatism (Pearce, 1983; Saunders and Tarney, 1984). When compared to modern arc system basalts, the Dos Cabezas mafic rocks have a pattern similar to island-arc basalts but are much more enriched (Fig. 14b). Especially for the immobile elements, the shape and level of the amphibolite element patterns are most closely approximated by those of continental-margin

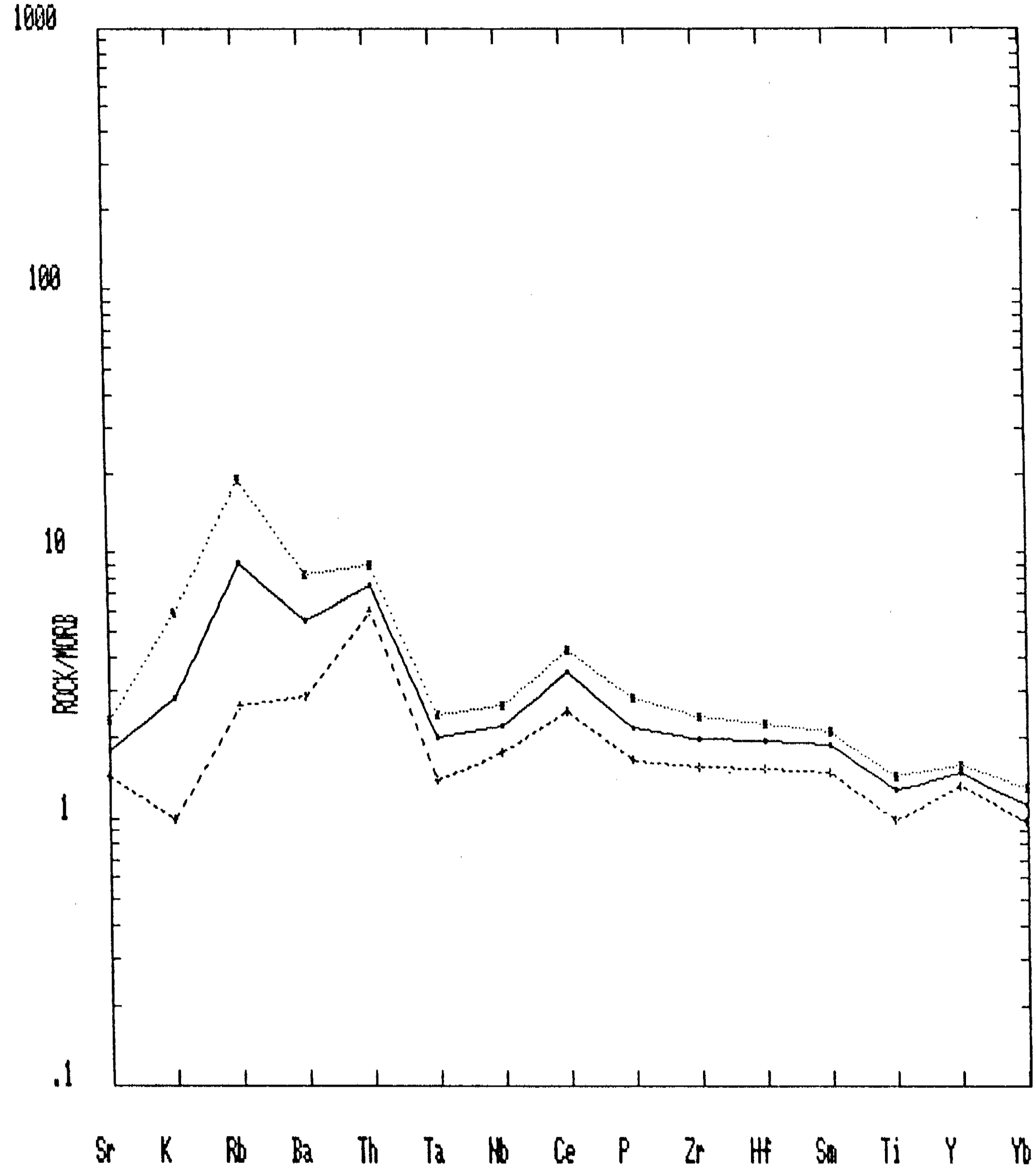

Figure 14a. MORB-normalized trace element distributions in least altered amphibolites. Shown are range of compositions (broken lines) and mean (solid line). Normalizing values from Pearce (1983).

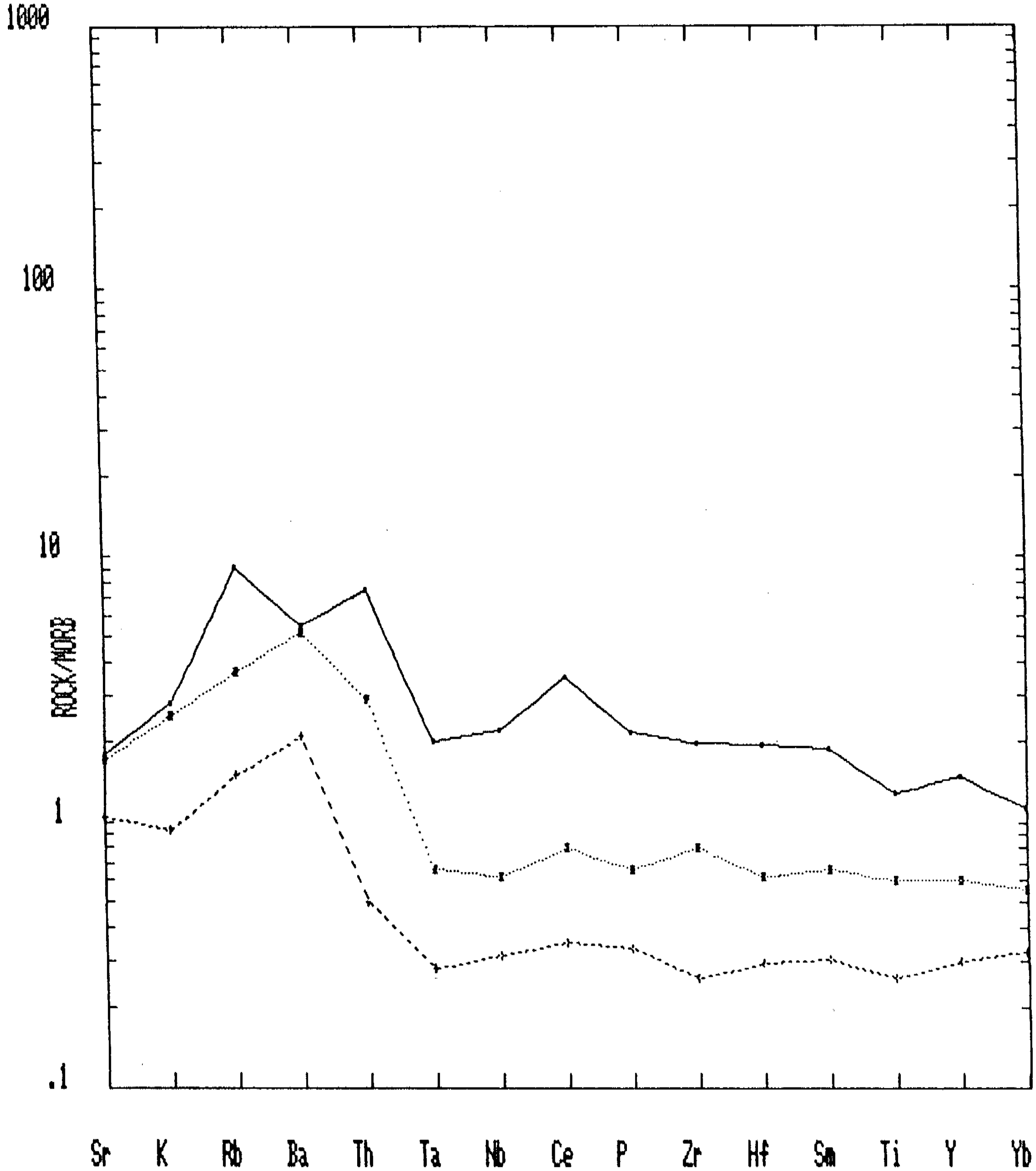

Figure 14b. MORB-normalized trace element distributions in island arc tholeiites (broken lines) and mean Dos Cabezas amphibolite (solid line). Normalizing values and island arc tholeiite data from Pearce (1983).

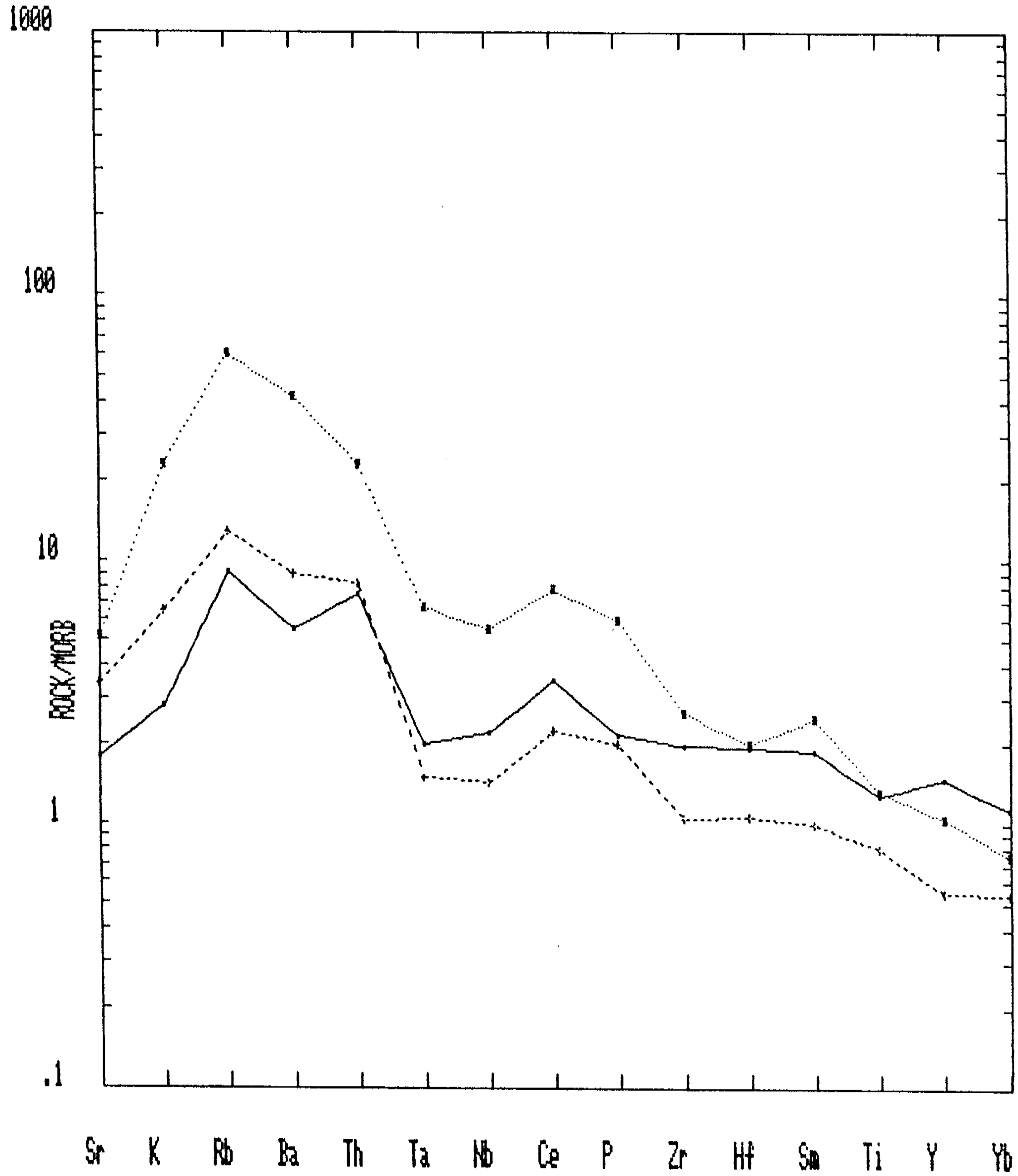

Figure 14c. MORB-normalized trace element distributions in continental margin arc basalts from Chile (broken lines) and mean Dos Cabezas amphibolite (solid line). Normalizing values and Chilean basalt data from Pearce (1983).

basalts such as those of central Chile (Fig. 14c). This type of basalt, which generally belongs to the calc-alkaline series, exhibits within-plate enrichment of HFSE from the sub-continental lithosphere with an additional selective enrichment in LILE superimposed on the pattern (Pearce, 1983). The enrichment of Y and Yb in the amphibolites relative to the Chilean basalts and MORB indicates that garnet was not an important phase in the petrogenesis of the Dos Cabezas mafic magmas. Also, the Ti depletion relative to Sm and Y in the amphibolites probably reflects fractionation of a Ti-bearing phase such as magnetite-ilmenite or spinel.

In order to further characterize the tectonic setting of the amphibolites, various tectonomagmatic discrimination diagrams involving immobile elements are used. While the fields on these plots are constructed from Phanerozoic examples, they still provide a useful reference for comparing similar rock types. The enrichment of HFSE in the Dos Cabezas amphibolites is reflected on many plots where they plot in the within-plate basalt or MORB fields but not in the island-arc basalt fields (Figs. 15, 16) . On the Ti-Zr-Y plot of Pearce and Cann (1973), the amphibolites plot in the ocean floor basalt field although calc-alkaline (continental margin or evolved oceanic arc) basalts can also plot in the same area (Fig. 17). The subduction zone characteristics of the amphibolites are evident on the Hf-

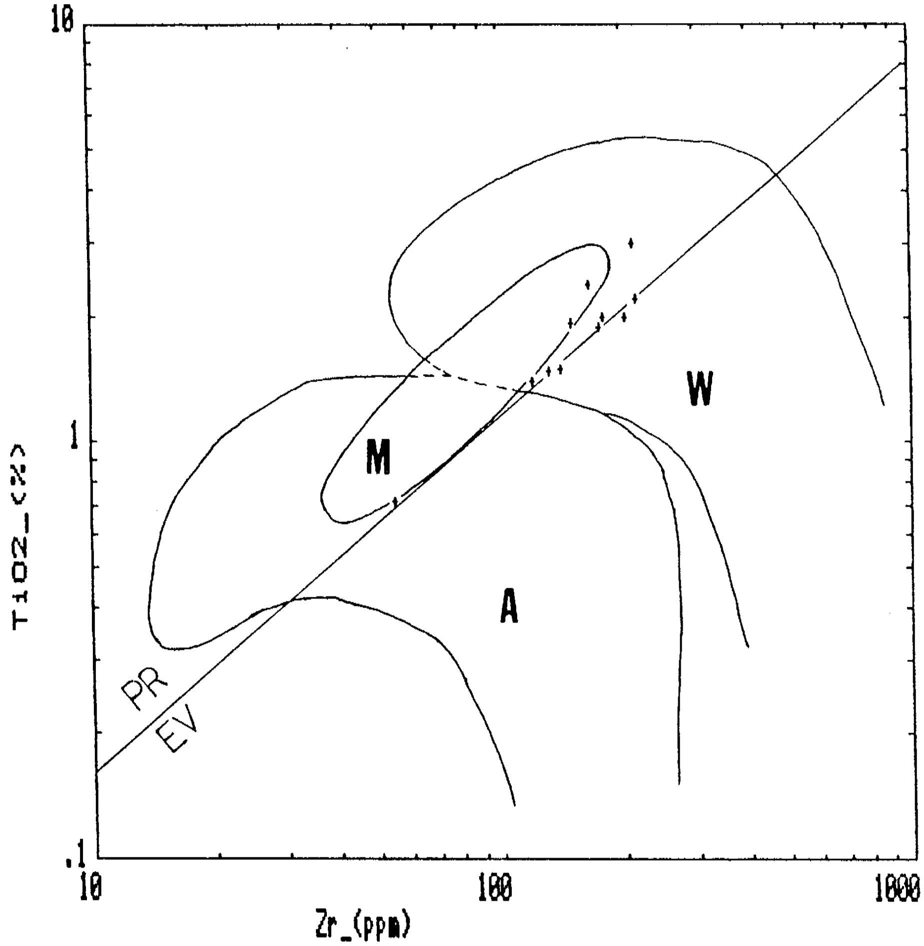

Figure 15. Distribution of Dos Cabezas mafic rocks on Zr-TiO2 diagram. Fields after Pharaoh and Pearce (1984). PR: primitive, EV: evolved, M: mid-ocean ridge basalts, W: within-plate basalts, A: arc basalts. Samples in evolved field have undergone significant magnetite fractionation.

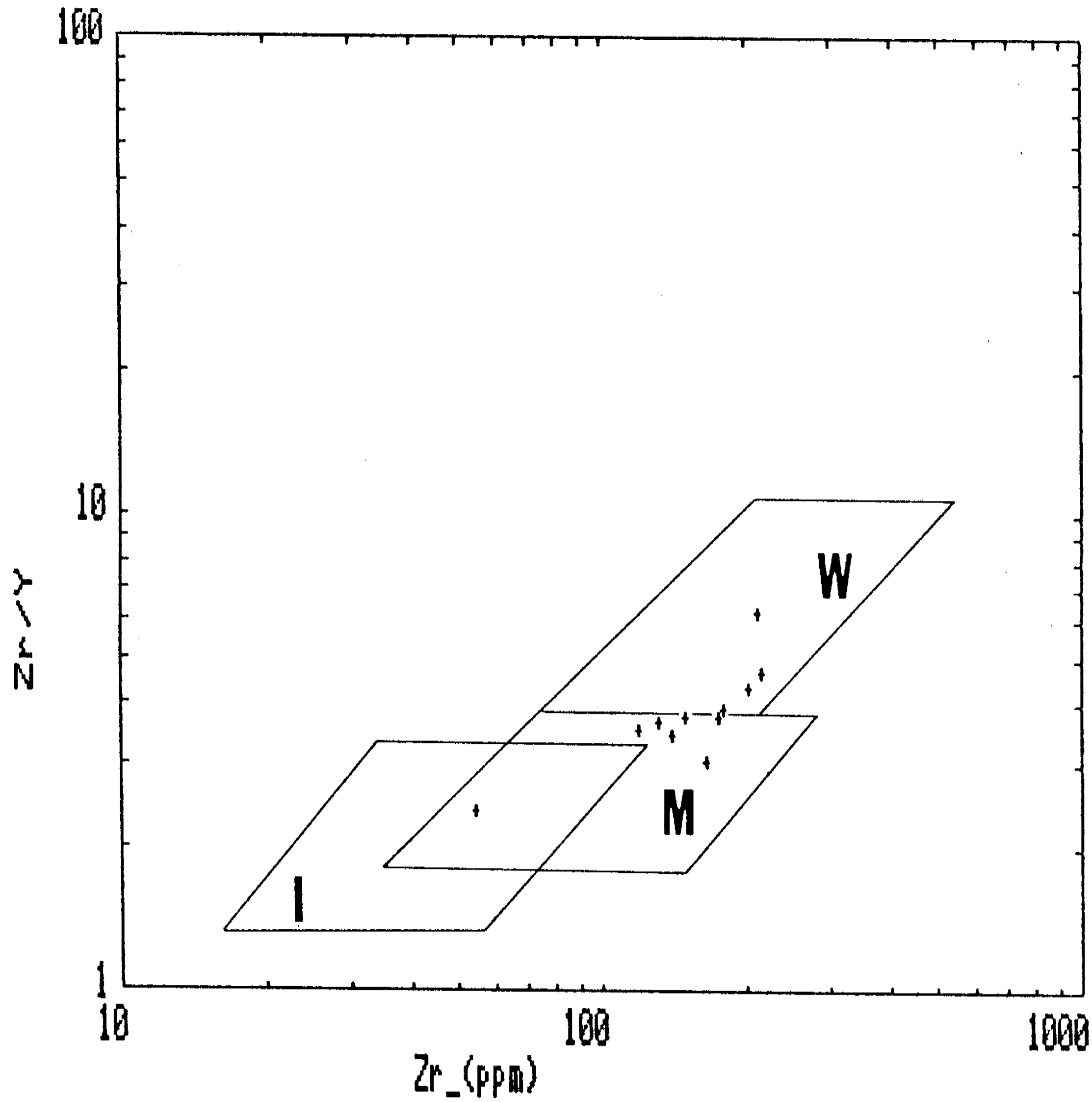

Figure 16. Distribution of amphibolites on Zr-Zr/Y diagram. Fields after Pearce and Norry (1979). W: within-plate basalts, M: mid-ocean ridge basalts, I: island arc basalts.

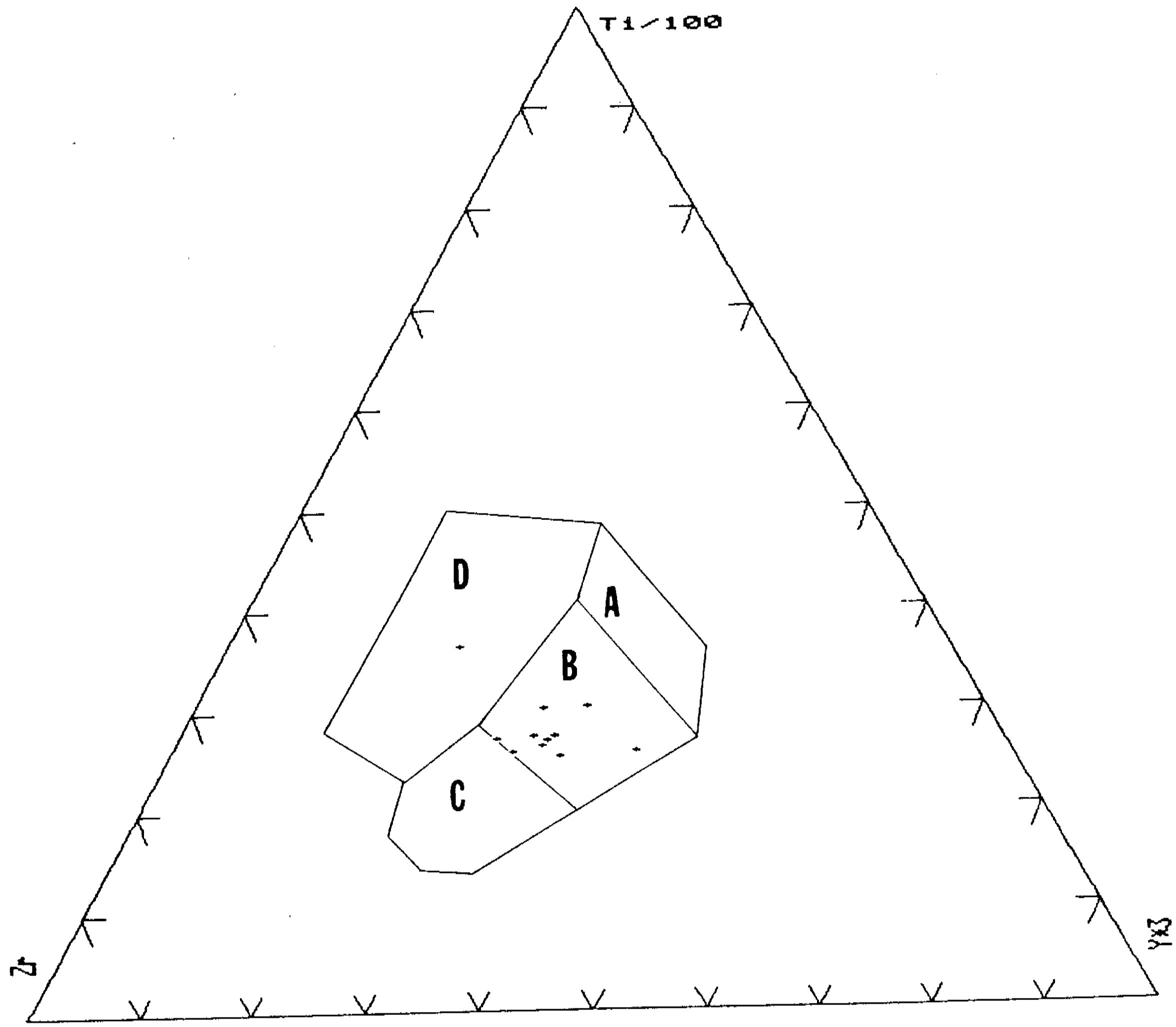

Figure 17. Distribution of amphibolites on Ti-Zr-Y diagram of Pearce and Cann (1973). A+B: low-K tholeiites, B: ocean floor basalts, B+C: calc-alkaline basalts, D: within-plate basalts.

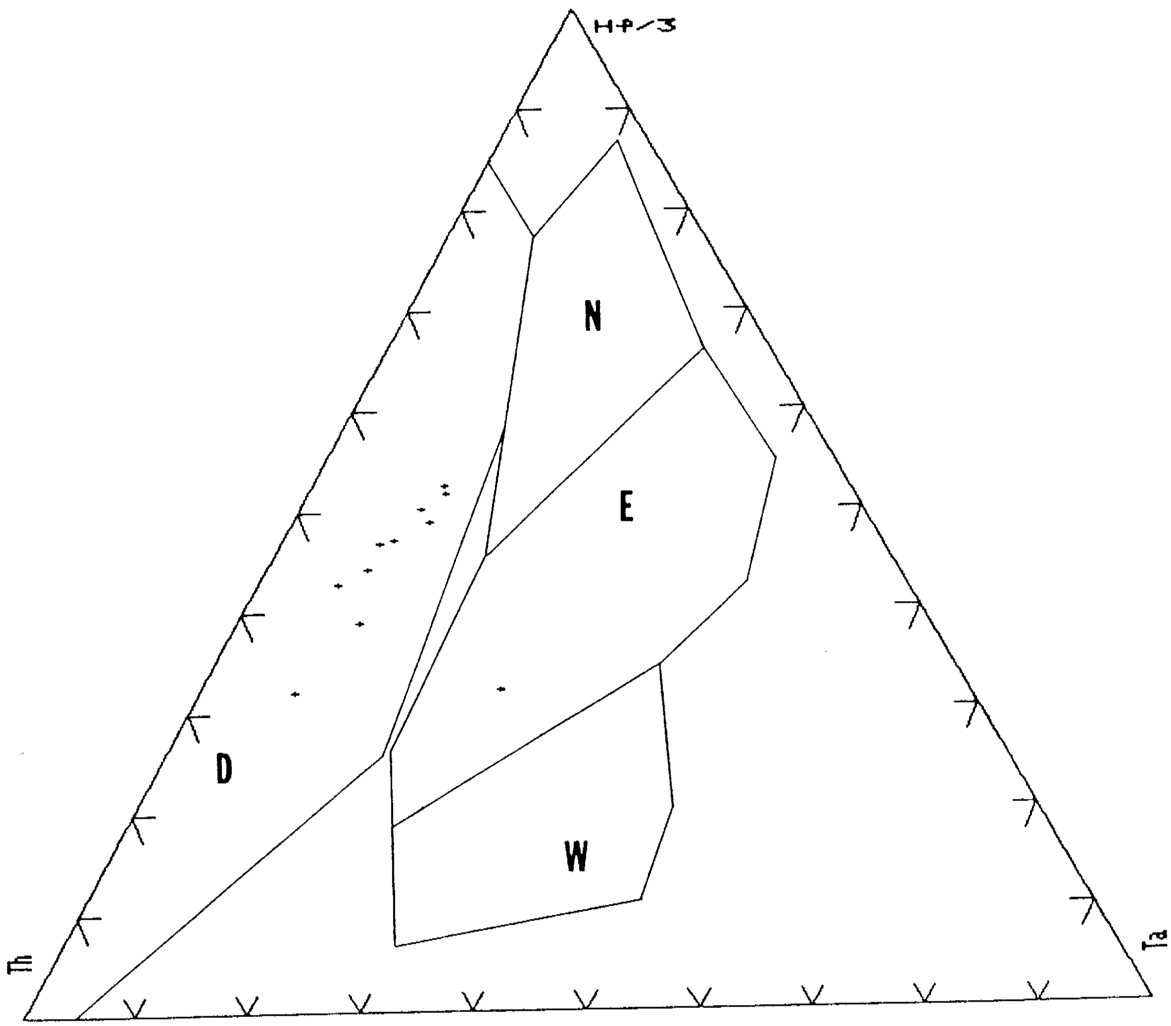

Figure 18. Distribution of amphibolites on Hf-Ta-Th diagram of Wood (1980). N: N-MORB, E: E-MORB and tholeiitic within-plate basalts, D: destructive plate-margin basalts, W: alkalic within-plate basalts.

Ta-Th plot of Wood (1980) where they fall in the destructive plate-margin field (Fig. 18).

In terms of overall geochemical characteristics, the Dos Cabezas mafic rocks are the least similar to island-arc basalts or MORB. They are somewhat more similar to incompatible element enriched mafic rocks from continental margin or within-plate (continental rift or oceanic island) tectonic settings.

FELSIC VOLCANIC ROCKS

The three populations of felsic volcanics from the Dos Cabezas are calc-alkaline (Fig. 12) and have rather distinctive major and trace element characteristics (Tables 1, 2). The rhyodacite porphyries from WT and ET are compositionally indistinguishable and define a coherent group. One sample from WT, 29-DC, a volcaniclastic variety from map unit ts, also displays essentially the same geochemical characteristics as the intrusive counterparts. The rhyodacites are characterized by silica contents between 66-68 % SiO_2, K_2O/Na_2O generally greater than 1 and relatively high concentrations of HFSE. REE patterns are light-REE enriched (~150 x chondrites) with small negative Eu anomalies and slightly depleted to flat heavy-REE (Fig. 19). The most acceptable model for the production of the rhyodacites is a 20 % partial melt of an undepleted felsic granulite possibly at mid-crustal levels (Appendix B).

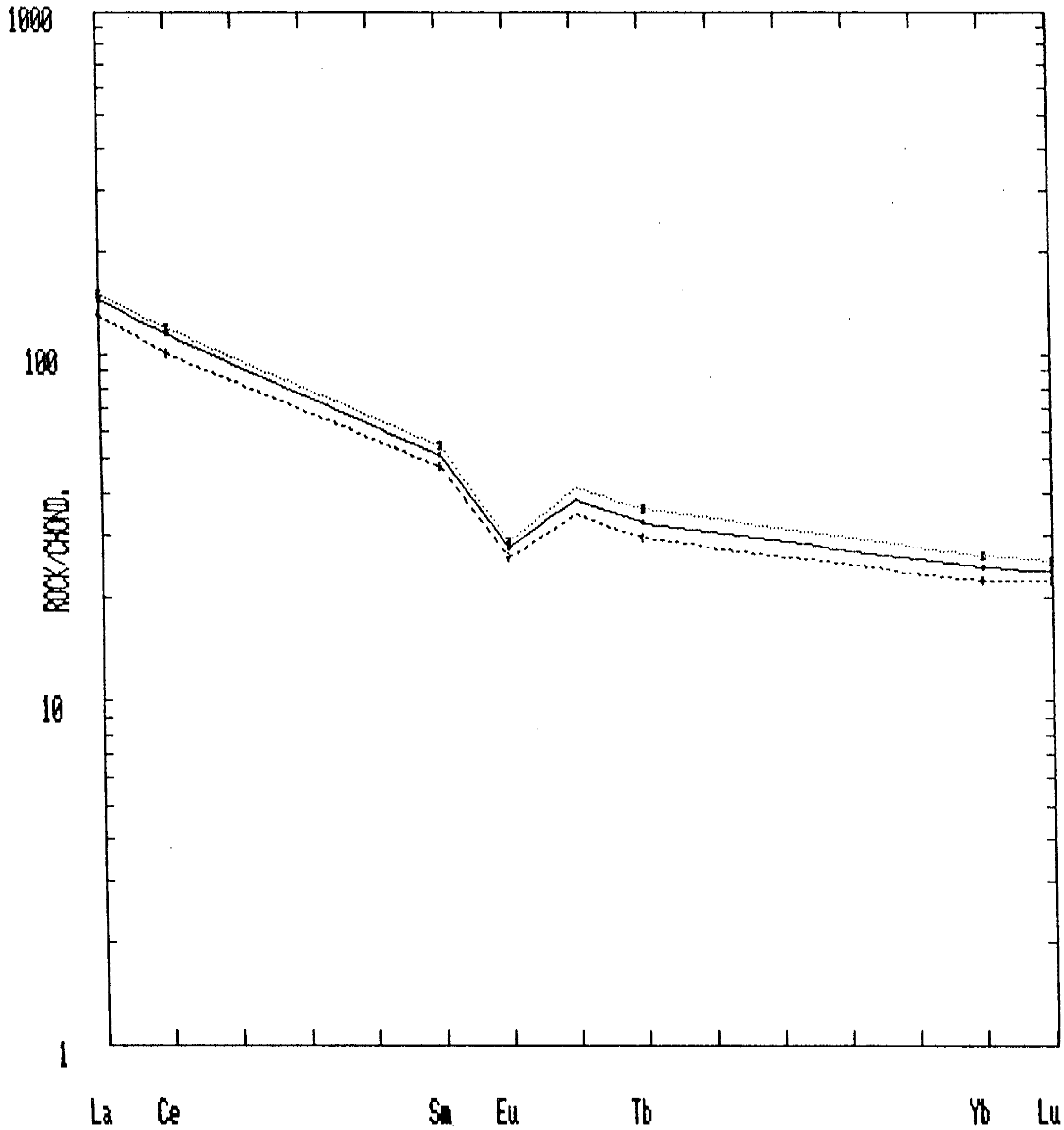

Figure 19. Chondrite-normalized REE pattern envelope of variation (broken lines) and mean (solid line) for rhyodacites.

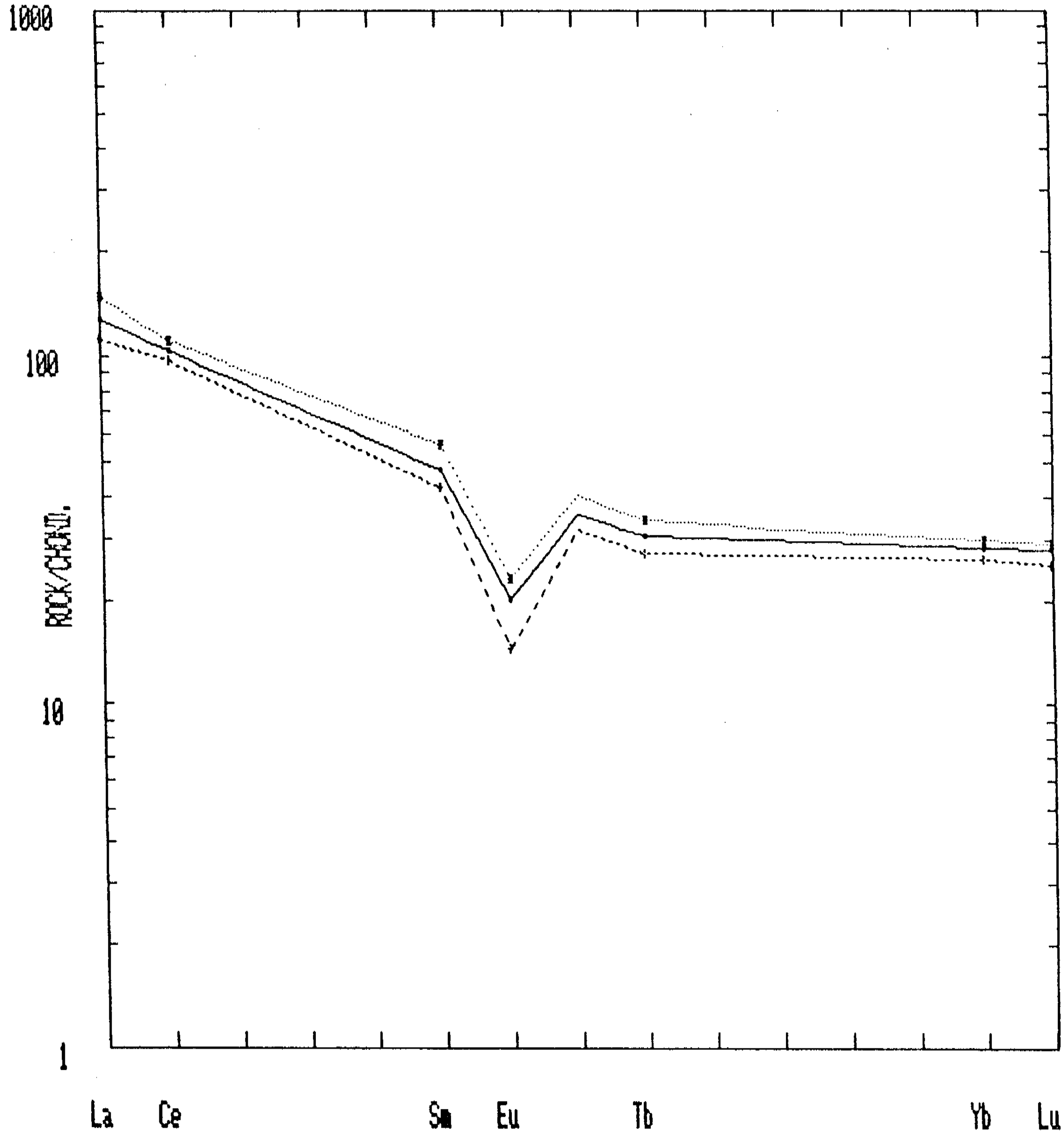

Figure 20. Chondrite-normalized REE pattern envelope of variation (broken lines) and mean (solid line) for quartz latites.

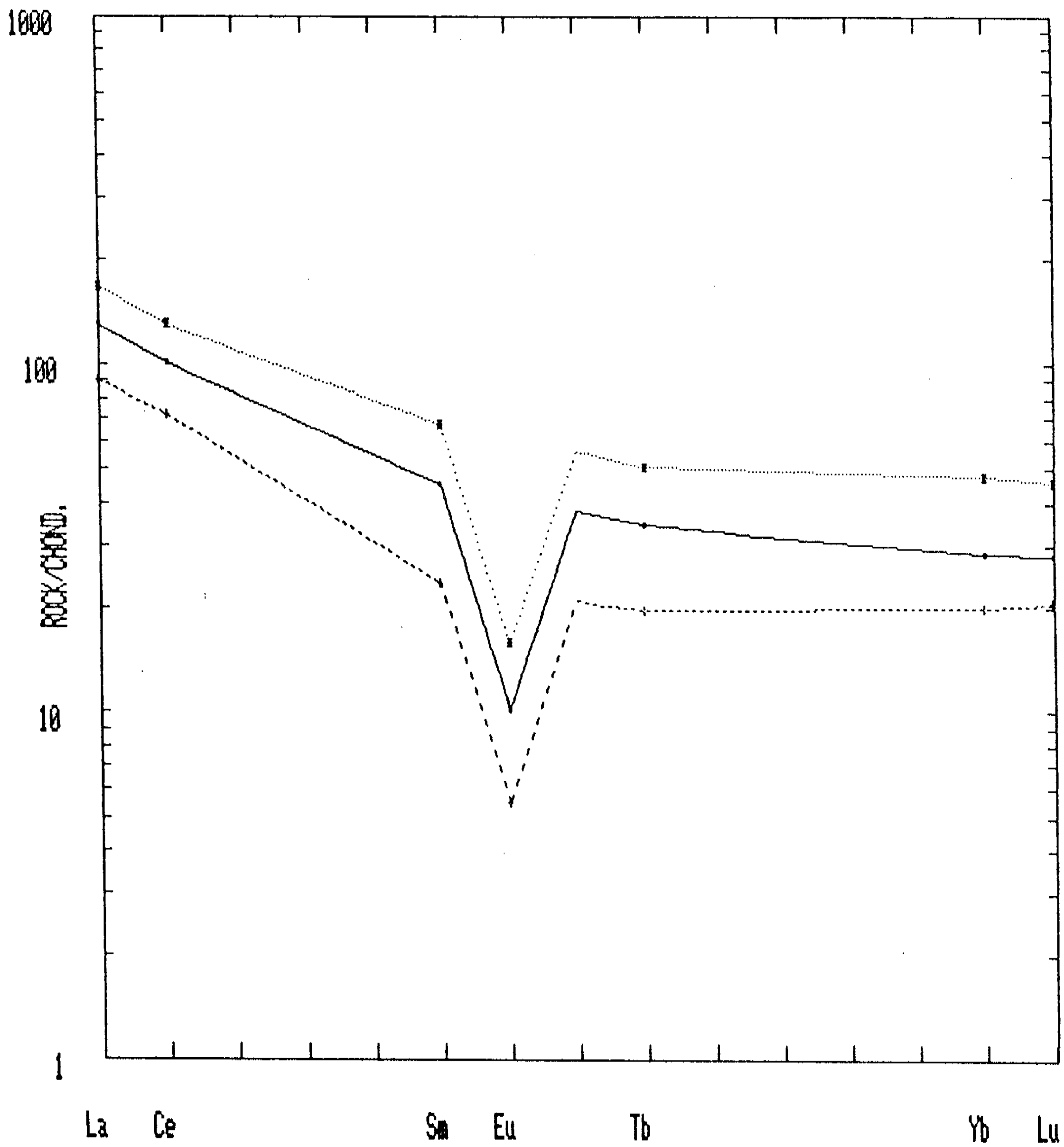

Figure 21. Chondrite-normalized REE pattern envelope of variation (broken lines) and mean (solid line) for rhyolites.

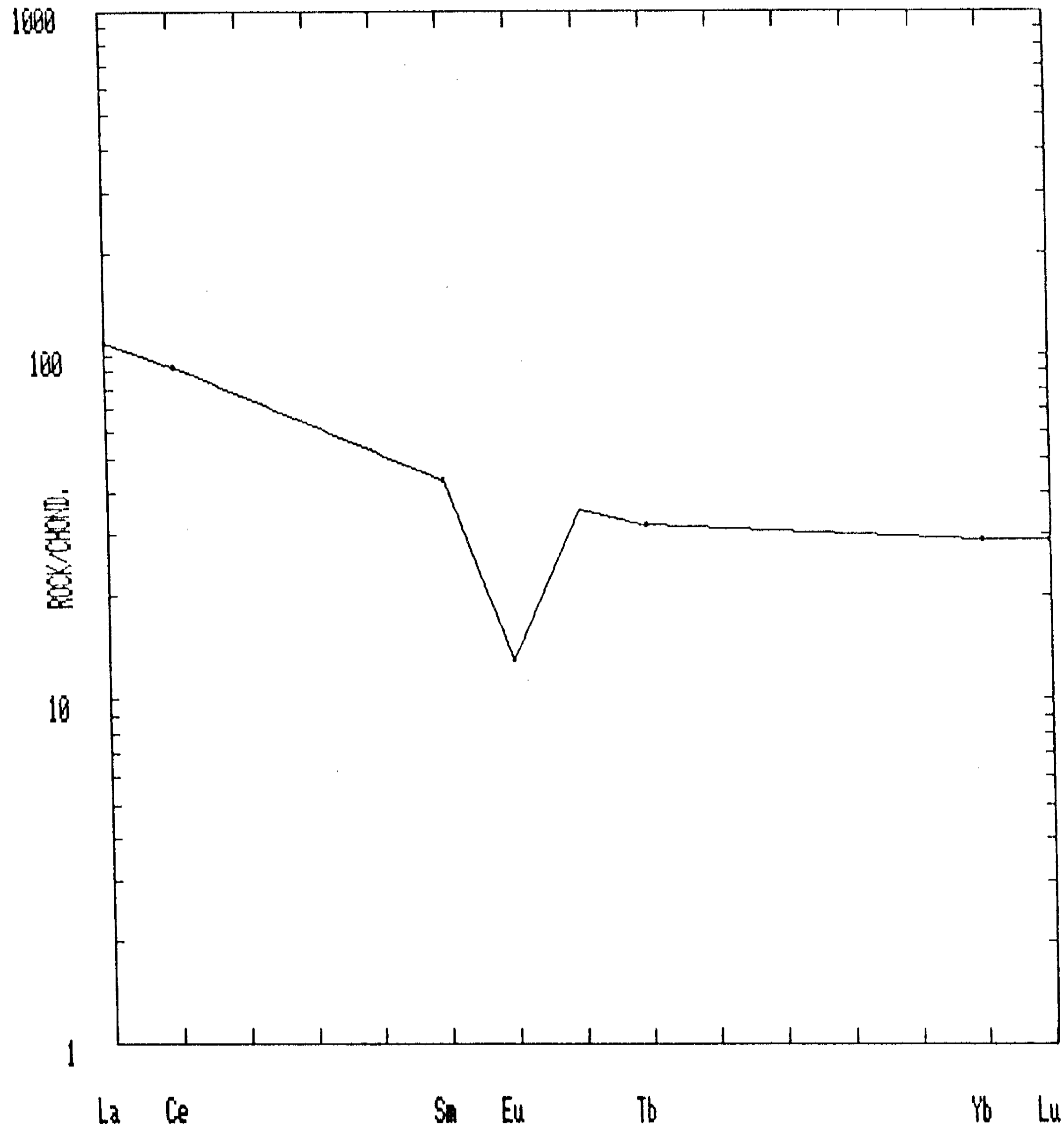

Figure 22. Chondrite-normalized REE pattern for Sommer gneiss, sample SG-313.

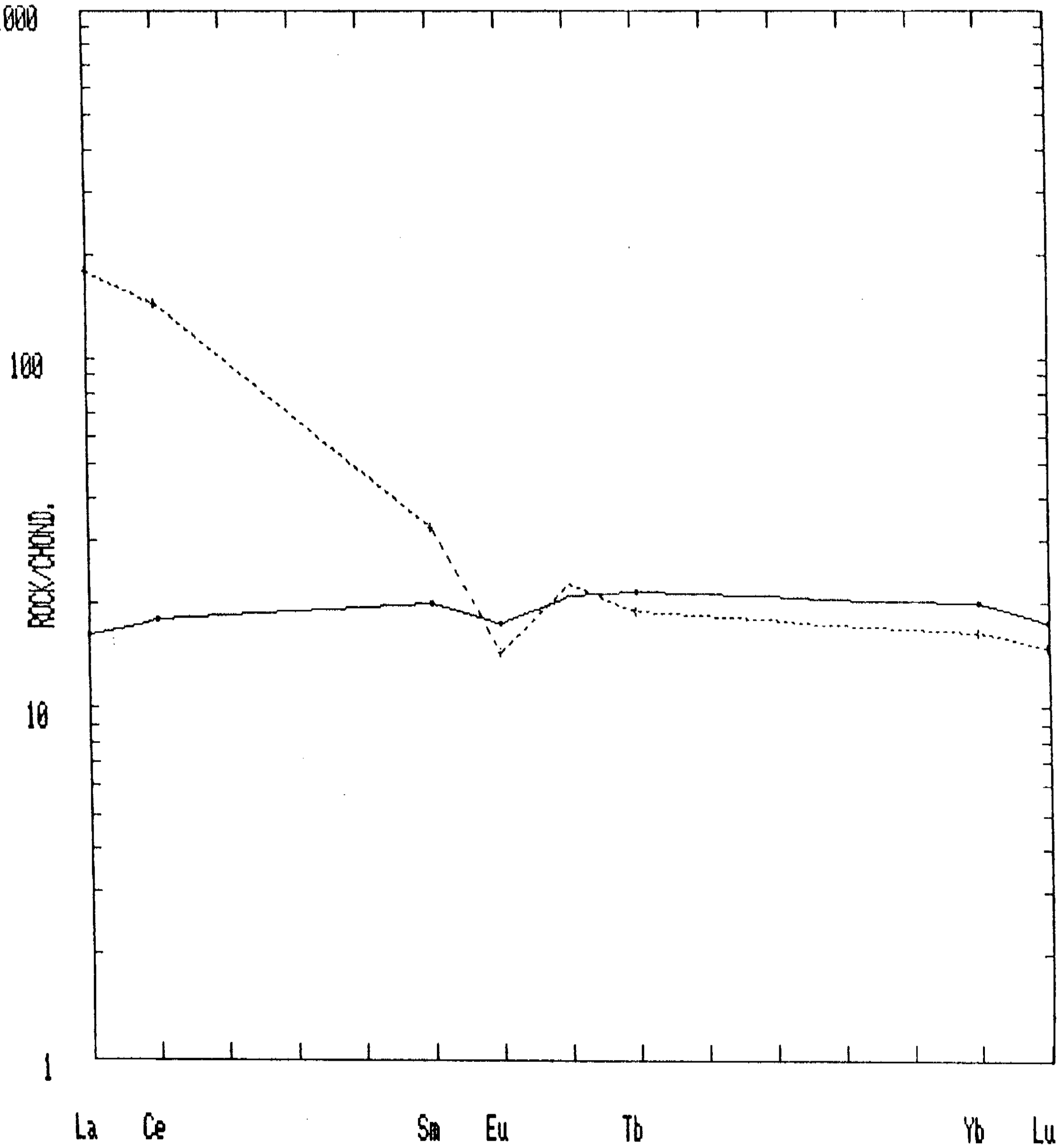

Figure 23. Chondrite-normalized REE patterns for typical oceanic island arc rhyolite (solid line) and typical continental-margin arc rhyolite (broken line). Data from Ewart (1979) and references therein.

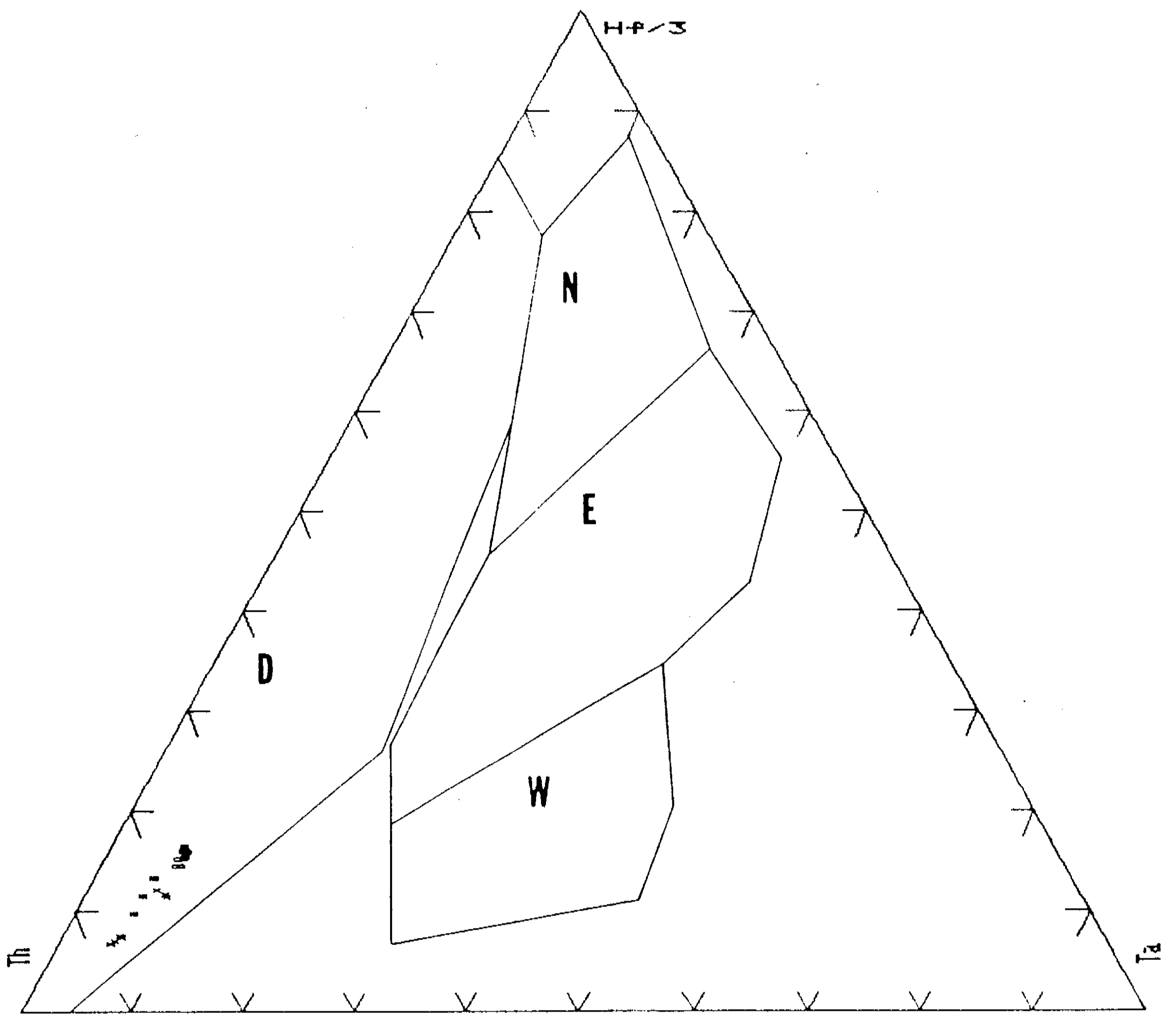

Figure 24. Distribution of Dos Cabezas felsic volcanics on Hf-Ta-Th diagram of Wood (1980). N: N-MORB, E: E-MORB and tholeiitic within-plate differentiates, W: alkalic within-plate differentiates, D: destructive plate-margin settings. Symbols as in Fig. 10.

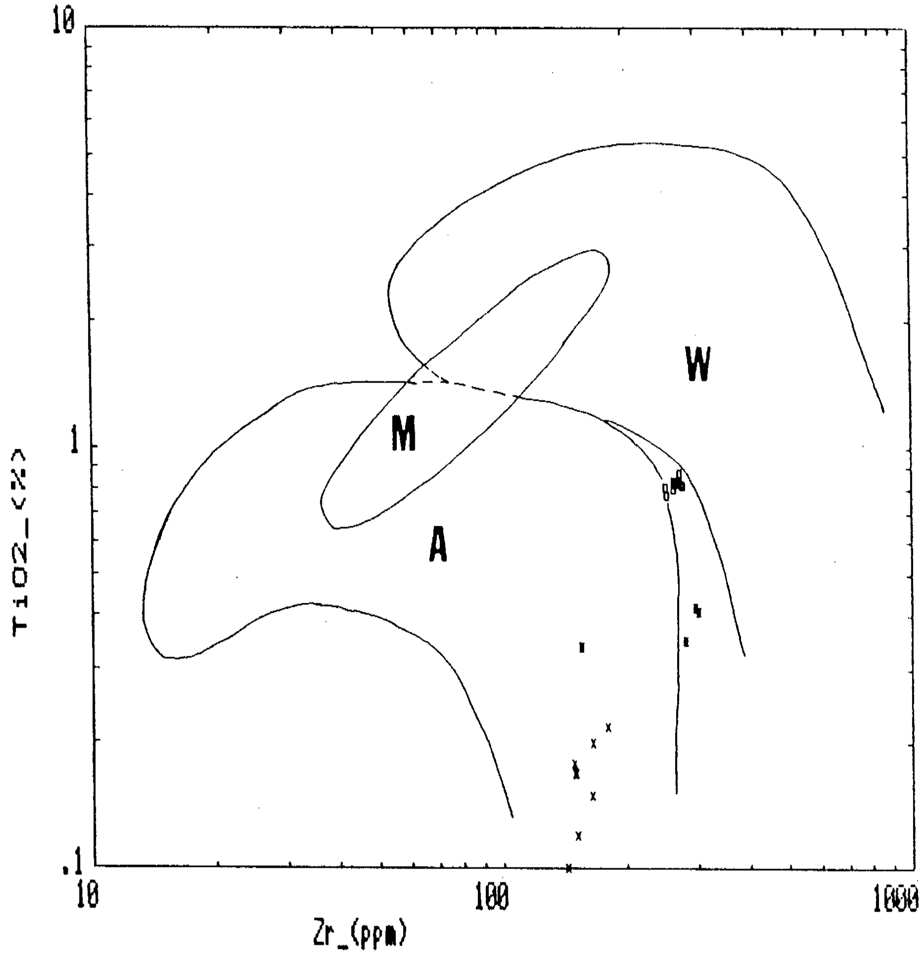

Figure 25. Distribution of felsic volcanics on Zr-TiO2 diagram. Fields after Pharaoh and Pearce (1984). M: mid-ocean ridge setting, W: within-plate settings, A: arc settings. Symbols as in Fig. 10.

The quartz latites are typified by 71-74 % SiO_2, K_2O > 4 % and also by high contents of HFSE. REE patterns of these rocks are similar to to the rhyodacites except for slightly larger negative Eu anomalies (Fig. 20). Geochemical modeling allows the production of these rocks by 30 % fractional crystallization of plagioclase, orthopyroxene, magnetite-ilmenite and traces of minor phases from the rhyodacite magma (Appendix B). The only quartz latite analyzed from WT, sample X18, has chemical characteristics similar to both the quartz latites and the rhyolites (lower Y, Zr and Hf; Table 1). This could be a result of more zircon fractionation during the production of the WT quartz latites. Alternatively, since this sample is a tuff, it may be a rhyolite that was not silicified.

The rhyolites are characterized by high silica, lower Zr and Hf than the other felsic rocks and variable contents of REE, Y and Pb. All the rhyolites from WT appear to be tuffs but the intrusive varieties in ET (QP samples, Table 2) are compositionally indistinguishable from the extrusive types (GT samples, Table 2) suggesting a comon petrogenesis for the two groups. The rhyolites from WT and ET are chemically similar except for Th and Sr which are lower in the WT samples. Exactly why this is so is not clear but it could reflect alteration effects. REE patterns are light-REE enriched with variable abundances but similar slopes, variable large negative Eu anomalies and flat heavy-REE contents (Fig. 21). Geochemical modeling indicates that the rhyolites can be produced from the quartz latites by 20 % fractional crystallization of chiefly plagioclase plus minor amounts of orthopyroxene, magnetite-ilmenite, zircon and trace amounts of apatite and allanite (Appendix B). Although only one sample of syntectonic Sommer gneiss was analyzed, it is interesting to note that it is compositionally similar to the rhyolites (Tables 1, 2) and has a REE pattern like the rhyolites (Fig. 22). It is possible that the Sommer gneiss is a plutonic equivalent of the Dos Cabezas felsic volcanics.

The overall geochemical features of the Dos Cabezas felsic volcanics, like the associated mafic rocks, are similar to those of Proterozoic felsic volcanics in central and southern New Mexico and southeastern Arizona (Condie and Budding, 1979; Copeland, 1986). When compared to modern rhyolites, the Dos Cabezas felsic volcanics are most similar to continental margin arc types (Figs. 19, 20, 21, 23) although the high contents of heavy-REE and Y, the large negative Eu anomalies and the low concentrations of Sr in the Dos Cabezas rhyolites are also similar to felsic rocks from intracratonic rifts. On most tectonomagmatic discrimination diagrams, the Dos Cabezas felsic volcanics generally lie in the destructive plate-margin field (Figs. 24, 25).

FERRUGINOUS CHERTS

Two specimens of oolitic ferruginous chert from WT are reported in Table 1. Although the composition of iron formations is quite variable (Davy, 1983; Fryer, 1983) and the Dos Cabezas oolitic rocks do not contain the minimum amount of iron (15 % Fe or 21.4 % Fe_2O_3) to be considered an ironstone, they are similar to Proterozoic chemical sedimentary rocks of the Gunflint Iron Formation in the Lake Superior region which are cherty, oolitic and contain less than 15 % Fe (Kimberley, 1978). However, when compared to "pseudo-oolitic" rocks from South Africa (Reimer, 1983b), the Dos Cabezas rocks contain less SiO_2 and more Fe_2O_3 and Na_2O.

The most striking chemical feature of the Dos Cabezas oolitic rocks is the high amounts of HFSE and REE (Table 1). The REE pattern of sample OI-1 is depicted in Fig. 26 and displays extreme light-REE enrichment (~350 x chondrites) with a small negative Eu anomaly and high abundances of heavy-REE (~60 x chondrites). The extreme enrichment of these elements may be due to the presence of sphene which can concentrate REE, Zr, Y and Nb up to several thousand parts per million (Staatz et al., 1977). Erickson (1969) tentatively identified garnet in one sample, which can concentrate heavy-REE and Y. In addition, REE-bearing phases such as apatite, monazite and xenotime have been reported from iron formations (Fryer, 1983). X-ray

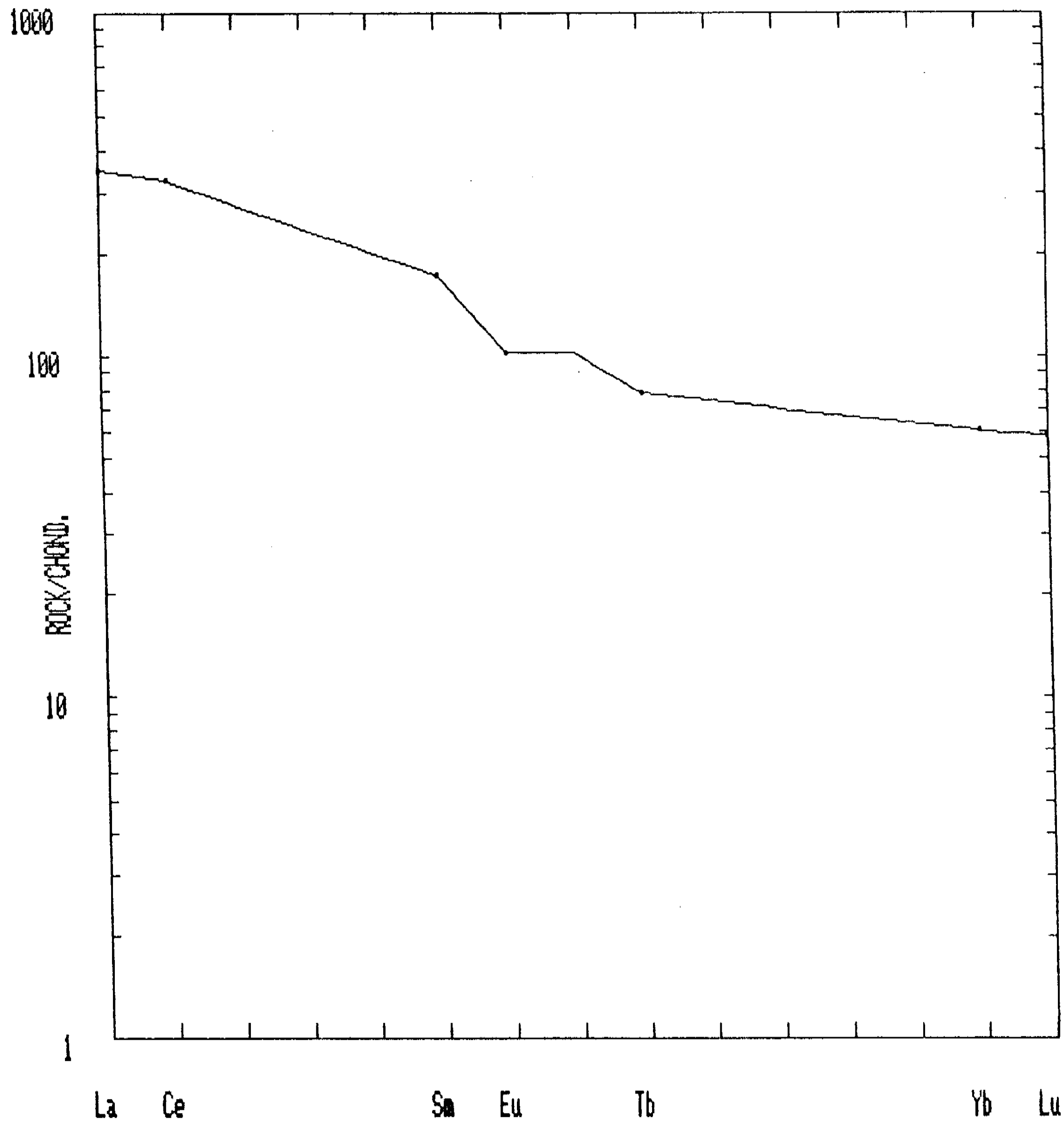

Figure 26. Chondrite-normalized REE pattern for oolitic ferruginous chert, sample OI-1.

diffraction scans of the ferruginous cherts unfortunately yielded confident identification of only quartz, plagioclase, illite and magnetite. Part of the Proterozoic Sokoman Iron Formation in Canada is strongly enriched in REE, Zr, Nb and Y possibly due to carbonate complexing during modification by fluids associated with a nearby volcanic complex (Fryer, 1983). The unusual trace element composition of the Dos Cabezas oolitic rocks may be related to the presence of minor phases that concentrate trace elements or fluid modification or a combination of both.

TECTONIC SETTING

One of the objectives of this study is to delineate a possible tectonic setting for the Proterozoic supracrustal rocks in the Dos Cabezas Mountains by comparison to modern tectonic environments. Although the Precambrian appears to have had higher heat flow and thinner lithosphere than today, it is likely that by the Proterozoic some form of plate tectonics similar to modern-style plate tectonics was in operation (Fyfe, 1981; Kroner, 1981; Windley, 1983). Therefore, it is reasonable to reconstruct Proterozoic tectonic settings based on Phanerozoic analogs.

Although WT and ET are separated by ~10 km due to intrusion of granitic plutons (Fig. 2), they are believed to be related. This is supported by similar structural style and the presence of volcanic rocks with similar composition in both terranes. The relationship between ET and WT to ST cannot be stated unequivocally but ST may represent a younger cratonic succession (Erickson, 1969; Condie et al., 1985).

The WT-ET succession is comprised of felsic volcanic and hypabyssal rocks; various clastic, mostly coarse-grained, sedimentary rocks; some basaltic rocks and minor amounts of chemical sedimentary rocks. Like other early Proterozoic sequences in southeastern Arizona, the base of the succession has not been recognized nor is it exposed.

Provenance studies of the coarse clastic sediments in ET indicate the importance of granitic and felsic volcanic rocks (Condie et al., 1985) and implies the presence of nearby uplifted continental material. Using modal sandstone composition tectonic setting diagrams (such as the QFL plot of Dickinson and Suczek, 1979), the feldspathic quartzites and arkoses predominantly lie in the recycled orogen field which includes collisional zones, rapidly elevated continental margin arcs and subsiding continental rifts or back-arc basins (Condie et al., 1985). The presence of conglomerates, oolitic rocks and carbonates suggests depositional environments ranging from terrestrial to tidal to possibly shallow-water marine or lacustrine (Pettijohn, 1975). These environments can also be found at continental margins or in subsiding rift or back-arc basins. The absence of graywackes and large amounts of marine volcaniclastics suggests that the WT-ET succession does not represent an island-arc setting. At the present level of erosion, felsic volcanic and subvolcanic rocks predominate over mafic varieties. If this distribution is representative, a continental margin setting is suggested (Basaltic Volcanism Study Project, 1981). The presence of numerous granitic plutons also supports such a setting. Also, the deformational style of WT and ET (broad folds) indicates compressive regimes at least during metamorphism of these rocks. Overall, the lithologic assemblage in the

WT-ET sequence is similar to Proterozoic supracrustal rocks in central and southern New Mexico (Condie and Budding, 1979).

Tectonic reconstruction of the WT-ET succession must also take into account geochemical constraints. The apparent bimodality of the Dos Cabezas volcanic suite (Fig. 10) suggests a continental rift setting (Ewart, 1979) although some arc systems exhibit bimodal volcanism (Donnelly and Rogers, 1980). The bimodal nature of the Dos Cabezas suite could be due to sampling bias or as discussed by Condie (1986), some form of differential preservation. The implied existence of an enriched mantle source for the amphibolites (Appendix B) seems to rule out MORB or island-arc settings. While the amphibolites are tholeiitic based on major elements (Figs. 11, 12), they have trace element characteristics similar to calc-alkaline basalts from continental-margin arcs (Fig. 14c). The trace element composition of the amphibolites also appears to have both subduction zone and within-plate signatures (Figs. 14, 15, 18). Geochemical modeling of the felsic volcanics (Appendix B) suggests the importance of continental crust in their petrogenesis, even though convergent plate settings are indicated on tectonomagmatic discrimination plots (Figs. 24, 25). This can be explained by a continental-margin arc setting.

The spectrum of available data for the WT-ET succession seems to be most consistent with a continental-margin arc system. Modern continental-margin arcs are characterized by high relief, mainly andesitic to felsic volcanism (generally believed to be related to the underlying continental crust), enriched sub-continental mantle, granitic batholiths in their roots and compressional tectonic style (Dickinson, 1973; Dewey, 1980; Basaltic Volcanism Study Project, 1981; Pearce, 1983). The chemical composition of the Dos Cabezas volcanics, the apparent superimposition of tectonic settings (within-plate and subduction zone) for the amphibolites, the inferred existence of enriched mantle, continental crust for the production of voluminous felsic volcanics, the provenance of arkosic sediments in ET, the compressive deformational features and abundant granitic plutons can all be accommodated by an active continental margin setting.

Problems associated with delineation of a tectonic setting for the WT-ET succession include the unknown nature of the basement to the Dos Cabezas Proterozoic rocks, the lack of geochronologic control and the uncertain relationship to other early Proterozoic rocks in nearby ranges.

As stated previously, the large amounts of felsic volcanics and coarse-grained clastic sedimentary rocks in WT and ET are unique compared to the quartz wacke sequences (Pinal Schist) that dominate the early Proterozoic in southeastern Arizona. The quartz wackes are believed to be turbidites deposited in submarine fans (Copeland, 1986). Perhaps the WT-ET succession, as first suggested by Copeland (1986), represents remnants of an arc proper whereas the turbidites represent distal material being shed into a marginal basin. The recent discovery of melange deformation zones in the Pinal Schist of the Johnny Lyon Hills and Little Dragoon Mountains (Swift, 1986) might indicate that old structural complexities are obscuring relationships between early Proterozoic areas in southeastern Arizona. Since little is known about the early Proterozoic rocks of Sonora (Mexico), it may be a key area in providing missing information about Proterozoic crustal evolution in this part of North America.

Early Proterozoic crustal evolution in the southwestern United States seems to have been by accretion of various island arcs, continental-margin arcs and associated back-arc basins to the Wyoming Archean province during the period 1800 to 1650 Ma ago (Condie, 1986).

SUMMARY AND CONCLUSIONS

Early Proterozoic supracrustal rocks in WT consist of a sequence of felsic tuffs, associated volcaniclastics, basaltic rocks and minor amounts of epiclastic and chemical sedimentary rocks intruded by a large hypabyssal rhyodacite porphyry. Mafic dikes (amphibolites) also occur within the sequence. ET is comprised predominantly of feldspathic quartzites, arkoses and conglomerates derived from granitic and felsic volcanic sources but also contains volcanic rocks similar to those in WT. These rocks have been slightly metamorphosed (greenschist facies) but primary features are generally preserved. In addition, various, mostly post-tectonic, granitic plutons intrude both areas. By inference to similar rocks in nearby ranges, the supracrustal rocks in the WT-ET succession are ~1690 Ma old and were deformed during an orogenic event 1625 to 1680 Ma ago (Silver, 1978).

The Dos Cabezas volcanics define a bimodal suite with calc-alkaline felsic volcanics subdivided into rhyodacites, quartz latites and rhyolites. Tholeiitic amphibolites can be produced by partial melting of an enriched lherzolite source followed by chiefly olivine fractionation. Geochemical modeling suggests the felsic rocks cannot be readily produced from the mafic rocks by fractional crystallization but the rhyodacites may be produced by anatexis of undepleted granulite and the quartz latites and rhyolites by differentiation of rhyodacite magma. In general, the Dos Cabezas volcanics are compositionally similar to modern volcanics from continental-margin arcs rather than oceanic island-arcs.

The available geologic and geochemical data are consistent with formation of the WT-ET succession in an active continental-margin arc system that was part of new crust accreted to the Archean proto-North America craton during the early Proterozoic.

While this study is by no means the final word on the early Proterozoic geology of the Dos Cabezas Mountains, it is hoped that this work can be the starting point for further research such as detailed structural analysis of the WT-ET and/or ST successions, geochronologic and associated isotopic investigations, and more trace element geochemistry to characterize the plutonic rocks and to determine if the analyses presented here are representative.

APPENDIX A - SAMPLE LOCATIONS

Geographic localities of WT samples used for chemical analyses and/or petrographic examination. RRP=Railroad Pass 7.5' quad, WX=Willcox 15' quad.

1. DC-2, amphibolite, SE1/4 SE1/4 sec. 29, T13S, R26E, RRP; chemistry, map unit: a, (collected by K.C.C.)

2. DC-3, amphibolite, NE1/4 SE1/4 sec. 29, T13S, R26E, RRP; chem., map unit: a, (coll. by K.C.C.)

3. AZ-2, amphibolite, NE1/4 NW1/4 sec. 17, T13S, R26E, RRP; chem. and petrography, map unit: a, (coll. by K.C.C.)

4. AZ-6, amphibolite, SW1/4 NW1/4 sec. 17, T13S, R26E, RRP; chem. and pet., map unit: a, (coll. by K.C.C.)

5. 5A-DC, amphibolite, SW1/4 NW1/4 sec. 18, T13S, R26E, RRP; chem. and pet., map unit: a

6. Y7, amphibolite, SW1/4 SE1/4 sec. 7, T13S, R26E, RRP; chem., map unit: a

7. 18A, amphibolite, SE1/4 NW1/4 sec. 18, T13S, R26E, RRP; chem., map unit: a

8. 12-DC, amphibolite, SW1/4 NW1/4 sec. 15, T13S, R25E, WX; chem. and pet., map unit: a

9. WB-1, amphibolite breccia, SW1/4 NW1/4 sec. 15, T13S, R25E, WX; pet., map unit: a

10. 17L, lapilli tuff, SW1/4 SE1/4 sec. 17, T13S, R26E, RRP; chem. and pet., map unit: ts

11. DC-8, chlorite schist, SE1/4 NW1/4 sec. 15, T13S, R25E, WX, chem. and pet., map unit: ts

12. OI-1, oolitic ferruginous chert, SW1/4 SE1/4 sec. 17, T13S, R26E, RRP; chem., map unit: ts

13. DC-10A, oolitic ferruginous chert, SW1/4 SE1/4 sec. 17, T13S, R26E, RRP; chem. and pet., map unit: ts (coll. by K.C.C.)

14. S1-DC, arkose, SW1/4 NW1/4 sec. 18, T13S, R26E, RRP; pet., map unit: rt

15. V341, coarse volcaniclastic, NE1/4 SW1/4 sec. 34, T13S, R26E, RRP; pet., map unit: c

16. V351, coarse volcaniclastic, SW1/4 SW1/4 sec. 35, T13S, R26E, RRP; pet., map unit: c

17. V395, felsic tuff (with eutaxitic texture), SE1/4 SW1/4 sec. 35, T13S, R26E, RRP; hand spec. (Fig. 7), map unit: ft

18. X18, felsic tuff, SE1/4 SW1/4 sec. 18, T13S, R26E, RRP; chem. and pet., map unit: ts

19. 29-DC, volcaniclastic rhyodacite, SW1/4 NW1/4 sec. 18, T13S, R26E, RRP; chem. and pet., map unit: ts

20. DC-5, rhyodacite porphyry, N1/2 NW1/4 sec. 29, T13S, R26E, RRP; chem., map unit: rp, (coll. by K.C.C.)

21. DC-6, rhyodacite porphyry, SE1/4 NW1/4 sec. 29, T13S, R26E, RRP; chem., map unit: rp, (coll. by K.C.C.)

22. 6A-DC, rhyodacite porphyry, NE1/4 NW1/4 sec. 19, T13S, R26E, RRP; chem. and pet., map unit: rp

23. 23-DC, rhyodacite porphyry, SE1/4 NE1/4 sec. 30, T13S, R26E, RRP; chem. and pet., map unit: rp

24. 8A-DC, rhyolite tuff, SW1/4 NW1/4 sec. 18, T13S, R26E, RRP; chem. and pet., map unit: rt

25. 10-DC, rhyolite tuff, NW1/4 NW1/4 sec. 18, T13S, R26E, RRP; chem., map unit: rt

26. X7, rhyolite tuff, SW1/4 SE1/4 sec. 7, T13S, R26E, RRP; chem., map unit: rt

27. SG-313, Sommer gneiss, NE1/4 NE1/4 sec. 13, T13S, R25E, RRP; chem., map unit: grl

APPENDIX B - GEOCHEMICAL MODELING

The petrogenesis of the Dos Cabezas volcanics has been investigated using well established geochemical modeling relationships (Allegre and Minster, 1978). Major element calculations are made using computer programs modified after Wright and Doherty (1970) with mineral compositions taken from the literature (Deer et al., 1966; Frey and Prinz, 1978; Coolen, 1982; Janardhan et al., 1982; Ramsay et al., 1984). Mineral modes and melt proprtions are also estimated from published sources (Schilling, 1975; Wyllie et al., 1976; Weaver, 1980; Condie and Allen, 1984). Table 3 contains the equations used for Rayleigh fractional crystallization and non-modal equilibrium (batch) partial melting. Distribution coefficients are similar to those in Condie et al., (1985, Appendix 2). Computerized spreadsheet programs are used in the trace element modeling.

Mafic Rocks

The low Mg numbers and relatively low Ni content of the amphibolites indicate that they do not represent melts that were in equilibrium with mantle material. Using the simplest scenario of only olivine fractionation, a parent basaltic magma is calculated using the average of samples DC-2, DC-3, 5ADC, A-1, A-2 and A-3 as the derivative liquid. The results of this calculation and some magnesian

TABLE 3. EQUATIONS USED IN GEOCHEMICAL MODELING OF TRACE ELEMENTS

Fractional Crystallization

$$\frac{C_l}{C_o} = F^{(D-1)}$$

Batch Melting

$$\frac{C_l}{C_o} = \frac{1}{D+F(1-P)}$$

$$D = \sum m_i \, K_d$$

$$P = \sum p_i \, K_d$$

where

C_o = initial concentration of an element

C_l = instantaneous concentration of an element in the liquid

F = fraction of melt

D = bulk distribution coefficient

P = bulk distribution coefficient for melting

K_d = distribution coefficient for an element (mineral/liquid)

m_i = mass fraction of a mineral in source rock or solid cumulate

p_i = mass fraction of a mineral entering the melt rich rocks for comparison are presented in Table 4. In terms of major elements, the calculated parent magma has a high MgO content but is similar to the average olivine basalt from Baffin Island which is considered by some to be a primary magma (Clarke, 1970; Basaltic Volcanism Study Project, 1981). With respect to trace elements, the calculated parent is similar to the calculated Kilauea parent magma (Ramsay et al., 1984) and a MgO-rich Proterozoic amphibolite from the Dragoon Mountains (Copeland, 1986). Employing a more realistic fractionation assemblage of olivine, clinopyroxene and plagioclase +/- ilmenite, it is possible to calculate a parent magma that has major element contents similar to the calculated Kilauea parent or Baffin Island olivine basalt but the trace element contents are practically the same as those of the simple olivine fractionation model except Ni which requires a somewhat higher Kd for olivine (~8) to remain at the same level. However, it is not possible to calculate a parent magma similar to the Dragoon amphibolite based on major elements using olivine, clinopyroxene and plagioclase +/- ilmenite fractionation. This could be due to major element mobilization or the Dragoon sample could be a cumulate similar to other MgO-rich rocks in southern Arizona although petrographic data is not reported for this sample (Copeland, 1986). If the rock is a cumulate, the trace elements indicate that it could not be a residue for any of the

TABLE 4. CALCULATED PARENT BASALT COMPARED TO SOME MgO-RICH ROCKS

Ref.		1	2	3
	Calc. Parent Magma	Avg. Ol. Basalt, Baffin Isl.	Dragoon Amphib. 84-162	Proposed Kilauea Parent
SiO_2	44.8	46.0	49.0	46.4
TiO_2	1.08	0.77	0.75	1.96
Al_2O_3	8.83	11.0	10.6	10.8
Fe_2O_3-T	13.8	11.6	12.4	12.7
MgO	25.1	20.1	14.3	17.5
CaO	4.98	9.34	11.1	8.61
Na_2O	1.09	1.06	0.96	1.63
K_2O	0.24	0.08	0.87	0.40
TOTAL	99.9	100.0	100.0	100.0
Ni	607	950	518	700
Rb	10	2	61	-
Ba	61	55	51	-
Sr	119	186	116	265
Th	0.8	-	2	-
Y	24	18	21	18
Zr	98	52	89	127
Nb	4	-	8	-
La	7.7	-	10	13
Ce	19	-	25	32
Sm	3.4	-	3.7	5.2
Eu	1.1	-	1.0	-
Tb	0.7	-	0.5	-
Yb	2.1	-	2.0	1.7
Lu	0.4	-	0.3	-
Phase	1-F=0.45			
Olv	1.0			

References:
1.) Clarke (1970)
2.) Copeland (1986)
3.) Ramsay et al. (1984)

Note: Parent basalt calculated using average of six least altered amphibolites as derivative liquid. 1-F=amount of fractional crystallization, olv=olivine.

models tested.

The important point drawn from this aspect of the modeling is that regardless of the reasonable fractionating phases involved, the enriched nature of the Dos Cabezas amphibolites (high Zr etc.) cannot be accounted for by simple fractional crystallization and this indicates that the enrichment may be a feature ultimately inherited from the mantle source.

Using the calculated parent magma from Table 4 as the derivative liquid, a lherzolite source was calculated for 10 and 20 % melting. The model parameters and analyses of other lherzolites are given in Table 5a. For both degrees of melting, the calculated compositions fall within one standard deviation for each oxide in average lherzolite (LeMaitre, 1976) although the calculated MgO values are low when compared to lherzolites from specific localities. The calculated Ni content is similar to that in published analyses of lherzolites. The computed trace element abundances and trace element contents of lherzolites, primordial mantle and chondrites are presented in Table 5b. The model trace element concentrations indicate that it is possible for enriched upper mantle to produce the Dos Cabezas mafic rocks and it is interesting to note that for 10 % melting, the calculated source abundances are similar to calculated primordial mantle (Wood, 1979).

TABLE 5a. CALCULATED MAJOR ELEMENT COMPOSITION OF LHERZOLITE SOURCE COMPARED TO AVERAGE LHERZOLITES

Ref.			1	2	3	3
	Calc. Lherz. F=0.1	Calc. Lherz. F=0.2	Avg. Lherz.	Avg. Lanzo Lherz.	Avg. Matsoku Lherz.	Avg. Kil.Hole Lherz.
SiO2	48.1	47.7	45.1	48.3	47.9	44.8
TiO2	0.43	0.50	0.44	0.30	0.04	0.12
Al2O3	5.50	5.87	4.33	2.80	1.70	3.36
Fe2O3-T	7.95	8.60	13.5	7.55	6.96	8.78
MgO	26.9	26.7	30.2	36.9	42.1	39.5
CaO	10.2	9.65	5.56	3.96	0.94	3.16
Na2O	0.90	0.92	0.58	0.15	0.18	0.27
K2O	0.02	0.05	0.27	-	0.12	0.03
TOTAL	100.0	100.0	100.0	100.0	99.9	100.0
Ni	1830	1790	-	1650	2030	2060

Phase	Mode	Melt
Olv	0.60	0.25
Cpx	0.25	0.20
Opx	0.15	0.55

References:
1.) LeMaitre (1976)
2.) Ernst (1981)
3.) Basaltic Volcanism Study Project (1981)

Note: Lherzolite source calculated using parent basalt from Table 4 as derivative liquid. F=fraction melted, olv=olivine, cpx=clinopyroxene, opx=orthopyroxene.

TABLE 5b. CALCULATED TRACE ELEMENT CONTENT OF LHERZOLITE SOURCE COMPARED TO AVERAGE LHERZOLITES, PRIMORDIAL MANTLE AND CHONDRITES

Ref.			1	1	2	3
	Calc. Lherz. F=0.1	Calc. Lherz. F=0.2	Avg. Matsoku Lherz.	Avg. Kil.Hole Lherz.	Wood's Prim. Mantle	C1 Chond.
Rb	1	2	–	–	0.9	3.5
Ba	7	13	–	–	7.6	3.6
Sr	15	26	–	–	23	11
Th	0.1	0.2	0.3	0.2	0.1	0.05
Y	5	6	–	–	1.9	1.6
Zr	12	21	–	–	11	3.9
Nb	0.6	1	–	–	0.6	0.25
La	0.8	1.6	2.1	0.2	0.7	0.37
Ce	2.1	3.9	5.3	0.4	1.9	0.96
Sm	0.5	0.8	0.4	0.3	0.4	0.23
Eu	0.2	0.2	0.1	0.1	–	0.09
Tb	0.1	0.2	–	–	0.1	0.06
Yb	0.4	0.6	–	0.3	–	0.25
Lu	0.1	0.1	0.01	0.06	–	0.04

References:
1.) Basaltic Volcanism Study Project (1981)
2.) Wood (1979)
3.) Taylor (1982) except Nb, Y, Zr which are from Jochum et al. (1986)

Note: Model parameters given in Table 5a.

Felsic Rocks

In terms of petrogenesis, felsic rocks can be enigmatic due to the variety of sources and processes that can produce silicic magmas. Several models involving partial melting of amphibolite or mafic granulite and fractional crystallization of Dos Cabezas mafic rocks were tested and rejected. These models yield results that are unsatisfactory for both major and trace element compositions. For example, major element distributions allow the production of the rhyodacites from the Dos Cabezas mafic rocks by fractionating plagioclase, olivine, clinopyroxene and magnetite, but such a model requires a large amount of fractional crystallization (~80 %) and the same assemblage yields poor agreement with observed trace element contents. Conversely, ad hoc mineral assemblages involving the proper proportions of minor minerals can balance the trace element contents but they produce unsatisfactory results for major elements. Also, the absence of geochemical trends between mafic and felsic rocks suggests that the felsic rocks are not produced by progressive fractional crystallization of a mafic parent.

The most acceptable model for the production of the felsic rocks involves partial melting of a felsic granulite source to generate the rhyodacite magma followed by two stages of fractional crystallization to produce the quartz latites and the rhyolites. Table 6a illustrates the

TABLE 6a. CALCULATED MAJOR ELEMENT COMPOSITION OF RHYODACITE SOURCE COMPARED TO SOME GRANITIC ROCKS

Ref.		1	2
	Calc. Rhyodacite Source	Avg. Madras Charnockite	Avg. Granite
SiO2	71.9	72.6	71.9
TiO2	0.34	0.37	0.30
Al2O3	14.6	13.5	14.4
Fe2O3-T	2.67	3.62	3.08
MgO	0.69	1.16	0.71
CaO	1.75	1.67	1.82
Na2O	3.52	2.88	3.68
K2O	4.23	4.08	4.11
P2O5	0.04	0.07	-
TOTAL	99.7	100.0	100.0
		F=0.2	
Phase	Mode	Melt	Residue
Opx	0.15	-	0.19
Kfel	0.11	0.34	0.05
Mgt	0.01	0.01	0.01
Plag	0.34	0.31	0.3475
Biot	0.08	0.04	0.09
Qtz	0.3094	0.30	0.3118
Zir	0.0005	-	0.0006
All	0.0001	-	0.0001

References:
1.) Weaver (1980)
2.) LeMaitre (1976)

Note: Rhyodacite source calculated using average rhyodacite as derivative liquid. F=fraction melted, opx=orthopyroxene, Kfel=K-feldspar, mgt=magnetite, plag=plagioclase, biot= biotite, qtz=quartz, zir=zircon, all=allanite.

TABLE 6b. CALCULATED TRACE ELEMENT CONTENT OF RHYODACITE SOURCE COMPARED TO SOME FELSIC GRANULITES AND CONTINENTAL CRUST ESTIMATES

Ref.		1	2	3	3	4
	Calc. Rhyodac. Source	Avg. Madras Charn.	Upper Cont. Crust	India Middle Crust	India Lower Crust	Lewisian Lower Crust
Rb	57	100	112	62	13	11
Ba	735	879	550	937	499	757
Sr	221	166	350	602	509	569
Th	7	19	11	8	1.4	0.4
Y	24	23	22	15	13	7
Zr	243	277	190	179	134	202
Nb	11	9	25	8	5	5
La	27	36	30	43	31	22
Ce	52	67	64	79	60	44
Sm	4	4	4.5	5	5	3
Eu	1.5	1.5	0.9	1.5	1.3	1.2
Tb	0.9	0.5	0.6	0.5	0.5	0.4
Yb	2.4	1.4	2.2	1.3	1.1	1.2
Lu	0.4	0.4	0.3	0.2	0.2	0.2

References:
1.) Weaver (1980)
2.) Taylor and McLennan (1985)
3.) Allen (1985)
4.) Weaver and Tarney (1984)

Note: Model parameters given in Table 6a.

similarity among major element compositions for the calculated rhyodacite source, average Madras charnockite (Weaver, 1980) and average granite (LeMaitre, 1976). Residual zircon and allanite are required in the granulite source to bring the light-REE and Zr into agreement (Table 6b). When compared to average granulites, the calculated granulite source does not display the depletion in Rb and Th which is characteristic of high-pressure crustal granulites (Table 6b) but it has trace element abundances similar to Madras charnockites (Weaver, 1980), upper continental crust (Taylor and McLennan, 1985) and India middle crust (Allen, 1985). This suggests that the rhyodacite magma may have been generated from undepleted granulite possibly at mid-crustal levels but probably not from lower crustal sources which are depleted in Rb and Th along with Cs and U (Condie and Allen, 1984).

Using the average rhyodacite composition as the original liquid and employing the model parameters in Table 7, it is possible to produce a rock very similar to the observed quartz latite in both major and trace element compositions. Then, by using the average quartz latite composition, it is feasible to produce the rhyolites by fractional crystallization of chiefly plagioclase based on trace elements (Table 8). This stage of the fractional crystallization requires somewhat more zircon removal than the previous step to explain the lower Zr content in the

TABLE 7. CALCULATED QUARTZ LATITE COMPARED TO AVERAGE OBSERVED QUARTZ LATITE

	Calc. Quartz Latite	Observed Quartz Latite
SiO2	73.5	74.3
TiO2	0.41	0.39
Al2O3	13.7	13.4
Fe2O3-T	2.95	2.73
MgO	0.57	0.39
CaO	2.25	1.52
Na2O	1.89	2.53
K2O	4.82	4.74
TOTAL	100.1	100.0
Rb	208	185
Ba	1000	883
Sr	76	95
Th	15	18
Y	63	62
Zr	297	259
Nb	18	15
La	44	42
Ce	98	91
Sm	10	8.6
Eu	1.6	1.4
Tb	1.6	1.5
Yb	6.0	5.7
Lu	1.0	0.96
Phase	1-F=0.3	
Opx	0.22	
Plag	0.6971	
Mgt-Ilm	0.08	
Ap	0.002	
Zir	0.0005	
All	0.0004	

Note: Average rhyodacite used as C_0 in this model. 1-F=amount of fractional crystallization, opx=orthopyroxene, plag=plagioclase, mgt-ilm=magnetite-ilmenite, ap=apatite, zir=zircon, all=allanite.

TABLE 8. CALCULATED RHYOLITE COMPARED TO AVERAGE OBSERVED RHYOLITE

	Calc. Rhyolite	Observed Rhyolite
Rb	229	172
Ba	1037	612
Sr	51	49
Th	19	20
Y	70	59
Zr	161	157
Nb	18	14
La	44	40
Ce	97	89
Sm	9.6	8.3
Eu	0.7	0.7
Tb	1.5	1.6
Yb	6.0	5.7
Lu	1.0	0.96
Phase	1-F=0.2	
Opx	0.03	
Plag	0.9348	
Mgt-Ilm	0.03	
Ap	0.002	
Zir	0.003	
All	0.0002	

Note: Average quartz latite used as C_0 in this model. Abbreviations as in Table 7.

rhyolites. The lower Rb and Ba contents observed in the rhyolites may be due to secondary loss of these elements. The low Eu concentrations of the rhyolites necessitate that the Eu Kd for plagioclase be near the high end of the range of estimated values (~4). No attempt was made to model the major elements in the rhyolites since they are altered and silicified.

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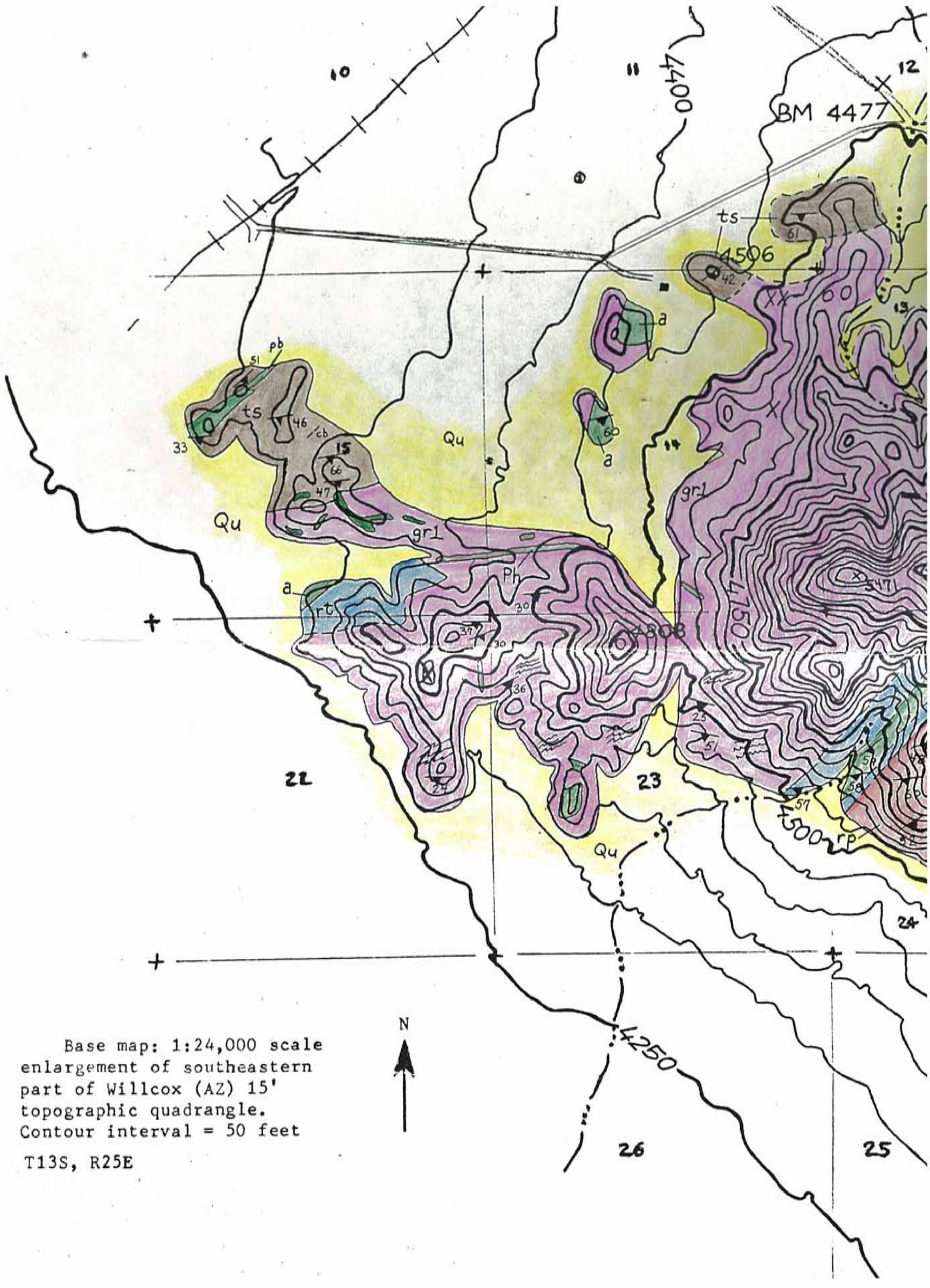

Base map: 1:24,000 scale enlargement of southeastern part of Willcox (AZ) 15' topographic quadrangle. Contour interval = 50 feet

T13S, R25E

--- PLATE 1 ---

GEOLOGIC MAP OF THE WESTERN
DOS CABEZAS MOUNTAINS, ARIZONA

Geologic mapping by G. P. Bowling, Cooper (1960) and Erickson (1969)

EXPLANATION

Description of Map Units

Qu — Unconsolidated Surficial Deposits (Quaternary) - soil and locally derived alluvial and colluvial gravel, sand, silt and clay deposited on flood plains, alluvial fans and pediments

UNCONFORMITY

Ph — Phanerozoic Rocks, Undivided - quartz veins and dikes, sills or stocks of basalt, andesite porphyry, dacite porphyry, rhyolite and quartz diorite (Tertiary); volcanic breccia, conglomerates, sandstones and siltstones (Cretaceous)

UNCONFORMITY

Plutonic Rocks

gr2 — Post-tectonic Granite (Middle Proterozoic) - coarse-grained, non-foliated, porphyritic, gray granitic rock; weathers buff, reddish-brown and green-gray; composed of K-feldspar megacrysts in a coarse groundmass of quartz, plagioclase and biotite (Polecat quartz monzonite of Erickson, 1969)

gr1 — Syntectonic Granite - variably foliated, slightly porphyritic, gray granitic rock; weathers reddish-brown and orange; composed of medium-grained plagioclase, quartz and K-feldspar in a grayish, aphanitic groundmass with some elongated clots of chlorite and biotite; also includes aplitic zones; this unit is sheared in many places resulting in a cataclastic rock composed of subhedral quartz and plagioclase grains in a fine-grained, sheared matrix with a pronounced internal foliation (Sommer gneiss of Erickson, 1969)

Supracrustal Rocks

E A R L Y

a — Amphibolites - variably foliated, fine to medium grained, dark green, mafic sills, dikes and fragmental pillow breccia (pb); composed mostly of epidotized plagioclase and actinolite with minor chlorite and magnetite; infrequently contains weathered pseudomorphs of plagioclase (up to ~1 cm long) or displays relict diabasic texture; most bodies represent mafic intrusives; also includes a few various mafic bodies within the granitic plutons

Rhyodacite Porphyry - large, hypabyssal, porphyritic body of rhyodacitic composition,

Z
O
I
C

c — conglomeratic rock; composed of variably stretched subangular to rounded clasts ranging from a few mm to 3 cm in size, clasts are comprised chiefly of fine-grained quartzite; also includes some volcaniclastic rocks

ts — Tuffs and Sediments Undivided - variably foliated, thinly interbedded volcanic and subordinate sedimentary rocks; volcanic rocks - various gray to brown, porphyritic, layered, felsic volcaniclastic tuffs containing up to 25% phenocrysts of plagioclase, quartz and K-feldspar in a fine-grained groundmass and minor amounts of more mafic, layered volcaniclastics; sediments - green-gray to tan arkoses, siltstones and phyllites (shales) and very minor amounts of carbonate (cb) and purple to gray, oolitic ferruginous chert (fc)

rt — Rhyolite Tuff - white to gray, foliated tuff of rhyolitic composition, weathers grayish-green to buff-brown; composed of 10-30% phenocrysts of quartz and plagioclase in a sericitic groundmass; subordinate amounts of intercalated fine to medium-grained clastic sediments and fine-grained, dark green, thin amphibolite layers are included in this unit

fc - ferruginous chert

NOTE: Early Proterozoic rocks are metamorphosed to greenschist facies. As age relations for the supracrustal rocks are not well established, Precambrian units shown on this map are intended to be rock-stratigraphic. Correlations shown or implied are rock correlations and may transgress time boundaries. Peripheral portions are from Cooper (1960) and/or Erickson (1969).

Symbols


Geologic contact, dashed where approximate or inferred

Strike and dip of foliation


Strike of vertical foliation


Fault, type of movement uncertain, dashed where approximate or inferred, dotted where covered


Normal fault, ball on downthrown side


Shear zones


Axis and plunge of anticlinal fold