GEOFISICA

INTERNACIONAL

REVISTA DE LA UNION GEOFISICA MEXICANA. AUSPICIADA POR EL INSTITUTO DE GEOFISICA DE LA UNIVERSIDAD NACIONAL AUTONOMA DE MEXICO

Vol. 28 México, D. F., 1o. de diciembre de 1989 Núm. 5

# *MID-TERTIARY SILICEOUS IGNEOUS ACTIVITY ABOVE CRATONIC AND ACCRETED BASEMENT IN NORTHERN MEXICO; COMPARISON OF TWO LOCALITIES*

A progress report

A. ALBRECHT*
D. G. BROOKINS*
*(Received: February 3, 1989)*
*(Accepted: July 10, 1989)*

## RESUMEN

El borde sur del craton de Norteamérica está situado en el norte de México, pero no puede ser localizado con exactitud por falta de afloramientos del basamento. Este trabajo investiga la química de la gruesa cubierta de 1 000 m de rocas ígneas del Terciario que predominan en la Sierra Madre Occidental mexicana, como un indicador de las variaciones de la composición del basamento. Con este fin se estudiaron dos localidades: San Buenaventura, situado en el noroeste de Chihuahua, representa la actividad ígnea sobre el basamento cratónico del Precámbrico; la sección del Cañón del Cobre en El Divisadero, al suroeste de Chihuahua, representa la actividad ígnea por encima de terrenos de acreción con basamento desconocido. En ambas áreas predominan flujos de lava silícea e ignimbritas. La sección de 600 m en Buenaventura se caracteriza por una estructura de caldera de 11 km de extensión asociada a una intrusión granítica resurgente. El área adyacente a la estructura de la caldera está formada por varias ignimbritas mayores y flujos intermedios de lava de composición basáltica, de andesítica a riolítica. Toda la secuencia está representada en el campo de rocas calcialcalinas con alto contenido de potasio. Las rocas silíceas se caracterizan por feldespato potásico, plagioclasa, biotita, clinopiroxeno, anfíbolas y fases opacas. La edad Rb/Sr es de 33.2 Ma con una tasa inicial de $^{87}Sr/^{86}Sr$ de $0.706577 \pm 0.000425$. Como todas las rocas silíceas están representadas sobre la capa isocrónica, se ha interpretado que se derivan de una fuente magmática común, probablemente un gran compuesto plutónico. La existencia de rocas acumulativas dentro del complejo granítico sugiere que la etapa final de diferenciación no ocurrió a una profundidad mayor. Existe un aumento lineal de abundancia de elemento LIL con $SiO_2$ y esto debe tomarse en cuenta al comparar la secuencia Buenaventura con otras secuencias.

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* *Department of Geology, The University of New Mexico, Albuquerque, NM 87131, U.S.A.*

La sección del Cañón del Cobre en El Divisadero se caracteriza enteramente por rocas silíceas de composición dacítica a riolítica. La sección completa de 1 400 m consiste en capas horizontales de flujos de lava silícea e ignimbritas. La sección se ha subdividido en unidad inferior y unidad superior. La superior tiene una edad Rb/Sr de 29.0 Ma con una tasa inicial de $^{87}Sr/^{86}Sr$ de 0.705644 ± 0.000335.

Mineralógicamente, las rocas silíceas son similares a las rocas Buenaventura, a excepción de una mayor abundancia de anfíbolas, que sugiere una evolución petrográfica similar. La comparación de los datos geoquímicos de El Divisadero con los de la secuencia Buenaventura muestra que además de la diferencia en composición isotópica Sr existe una diferencia significativa en los elementos de los grupos K, Ti y Th, en las abundancias de REE y en las tasas interelementales. Las rocas ígneas terciarias pueden, por lo tanto, utilizarse como indicadores de las variaciones del basamento.

## ABSTRACT

The southern edge of the North American craton is located in northern Mexico, but it cannot be exactly located due to lack of basement outcrops. This papers investigates the chemistry of the 1 000 m thick cover of Tertiary igneous rocks dominating the Mexican Sierra Madre Occidental as a tracer of variations in basement composition. For this purpose two localities have been studied. San Buenaventura, located in northwestern Chihuahua, represents igneous activity above Precambrian cratonic basement. The Copper Canyon section at El Divisadero in southwestern Chihuahua represents igneous activity above accreted terranes with unknown basement. Both areas are dominated by siliceous lava flows and ignimbrites. The 600 m section at Buenaventura is characterized by an 11 km large caldera structure associated with a resurgent granitic intrusion. The area adjacent to the caldera structure is formed by several major ignimbrites and intermediate lava flows of basaltic andesitic to rhyolitic composition. The entire suite plots in the field of high K calc-alkaline rocks. The siliceous rocks are characterized by K-feldspar, plagioclase, biotite, clinopyroxene, amphibole and opaque phases. The Rb/Sr age is 33.2 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.706577 ± 0.000425. As all siliceous rocks plot on the isochron they are interpreted as being derived from a common magmatic source, probably a large composite pluton. The existence of cumulative rocks within the granite complex suggest that the final stage of differenciation did not occur at greater depth. A linear increase of LIL element abundance with $SiO_2$ exists and has to be taken into account when comparing the Buenaventura suite with other suites.

The Copper Canyon section at El Divisadero is characterized entirely by siliceous rocks of dacitic to rhyolitic composition. The entire section of 1 400 m consists of horizontal layers of siliceous lava flows and ignimbrites. The section has been subdivided into a lower and upper unit. The upper unit has a Rb/Sr age of 29.0 Ma old with an initial $^{87}Sr/^{86}Sr$ ratio of 0.705644 ± 0.000335.

Mineralogically the siliceous rocks are similar to the Buenaventura rocks, with the exception of a larger amphibole abundance, suggesting similar petrographic evolution. Comparison of geochemical data from El Divisadero with the Buenaventura suite shows that besides the difference in Sr-isotopic composition a significant difference exists in the K-, Ti-, and Th-group elements, REE abundances, and interelement ratios. The Tertiary igneous rocks can therefore be used as indicators of basement variations.

## INTRODUCTION

The southern margin of the North American craton has been of interest to geoscientists of different backgrounds. Paleogeographic reconstructions (Almazán-Vázquez *et al.*, 1986; Stewart, 1988) point out the distinct facies change occurring in paleozoic rocks north and south of latitude 28° (Stewart, 1988) in northern Mexico. Based on known basement occurrences Campa and Coney (1983) constructed a tectonostratigraphic terrane map of the Mexican Republic. In northern Mexico they distinguished the Chihuahua terrane from terranes located farther south, and interpreted the Chihuahua terrane as part of the North American craton underlain by Precambrian basement. The southern terranes mostly lack basement outcrops and were described as suspect terranes accreted throughout Mesozoic time. They are characterized by Late Jurassic to Mid-Cretaceous submarine volcanic and sedimentary sequences (Campa and Coney, 1983). The boundary between the Chihuahua and the southern Guerrero terrane is situated within the Sierra Madre Occidental and covered by Tertiary volcanic rocks of at least 1 000 m thickness. Silver and Anderson (1974) and Anderson and Silver (1979) recognized a major tectonic structure in the Mojave and Sonoran deserts. Along this so called Mojave-Sonora megashear a left-lateral tectonic dislocation of 700 to 800 km was interpreted to have occurred. Several authors (*e.g.* Stewart, 1988) tended to draw this major tectonic boundary across the Sierra Madre Occidental eastward. If the Mojave-Sonora megashear extends eastward and if it represents the boundary between the cratonic Chihuahua terrane and the accreted Guerrero terrane cannot be studied directly due to the 1 000 m cover of Tertiary volcanic rocks. These Tertiary volcanic rocks have been investigated in various locations throughout the northern Sierra Madre Occidental (*e.g.* McDowell and Clabaugh, 1979; Cameron *et al.*, 1980, 1985; Bagby, 1979; Demant and Cocheme, 1983; Cocheme, 1981; Cocheme, 1985; Cocheme *et al.*, 1986; Guerra Peña, 1976, Piguet, 1987; Delpretty, 1987). McDowell and Clabaugh (1979), based on samples from the central part of the Sierra Madre and various localities in Chihuahua subdivided the entire Tertiary igneous activity in northern Mexico into three zones. The Sierra Madre forms "Zone I", characterized by calc-alkaline rocks of lower alkalinity, and the rocks east of the Sierra Madre are part of zone II, the higher alkalinity intermediate suite. Subduction and mantle diapirism have been used to explain these geochemical differences (McDowell and Clabaugh, 1979 and references therein). Comparison of additional data from the northern Sierra Madre (Albrecht *et al.*, 1987; 1988) shows a considerable increase in alkalinity northward. This northward increase in alkalinity of rocks of similar age and geotectonic setting will be discussed throughout this paper and will be put in relation to variations in the basement make-up, *i.e.* cratonic *vs* accreted. For this purpose two localities, one located in the north, above cratonic basement, and one located in the south, above accreted basement will be analyzed (Fig. 1).

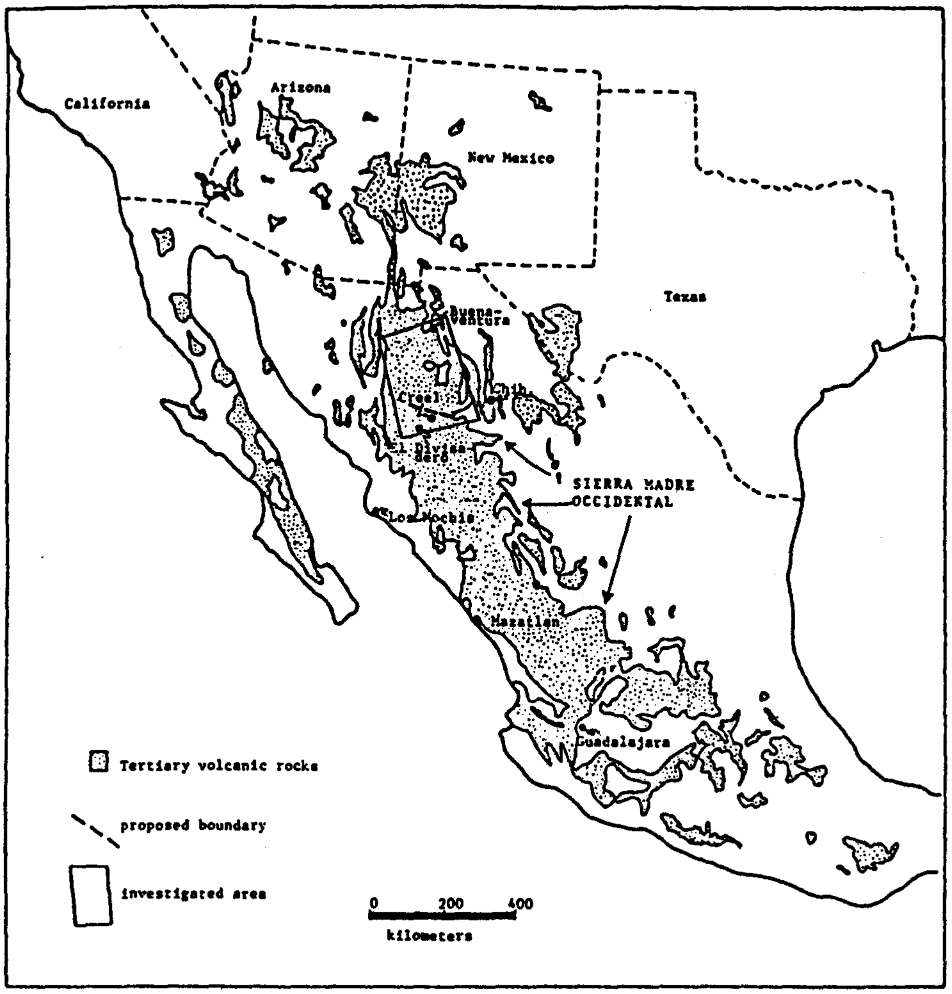

Fig. 1. Location map of the Sierra Madre Occidental and adjacent Tertiary volcanic fields (redrawn after Cameron and Cameron, 1986). Indicated are the two studied areas Buenaventura and El Divisadero. The line between these localities depicts the approximate boundary between cratonic and accreted basement (Albrecht *et al.*, 1988).

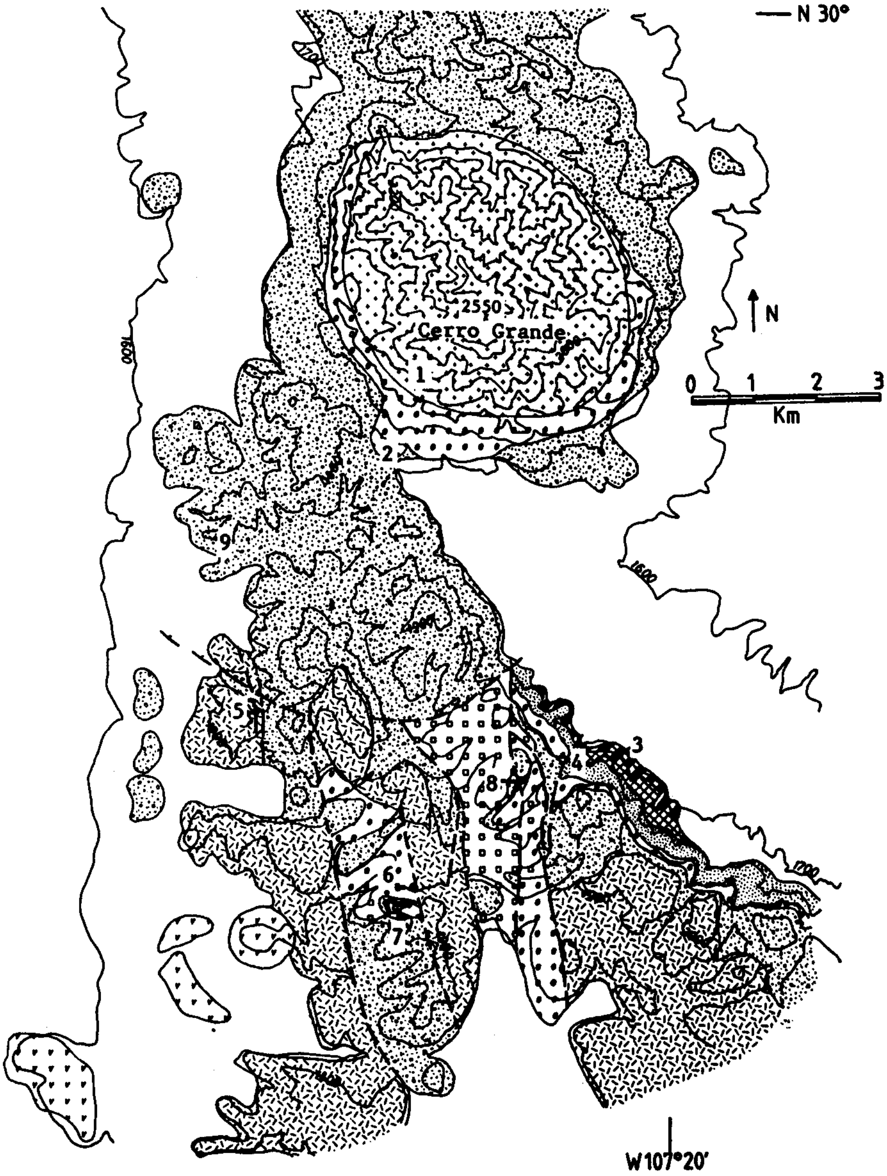

Fig. 2. Generalized geologic map of the Cerro Grande region, San Buenaventura.
Contour lines drawn every 100 m, numbers indicate sample location (Table 1) (for legend, see Fig. 3).

## *Geology of the two localities*

### San Buenaventura

East and north-east of San Buenaventura an area of 240 km$^2$ was mapped in detail. The area is characterized by strong relief ranging from 1 500 to 2 600 meters, dominated by the Cerro Grande, mountain ranges extending south and northward, and basin structures to the east and west. The area was chosen because: 1. known Precambrian outcrops in the vicinity (Dyer, 1987), 2. good exposures, and 3. the occurrence of volcanic and plutonic rocks of various composition. Fig. 2 shows the generalized geologic map of the Buenaventura area and Fig. 3 the stratigraphic column. Within the 600 m thick section 4 major ignimbrite sheets, several siliceous lava flows and 3 mafic lava flows occur. The hypabyssal granite complex forming the

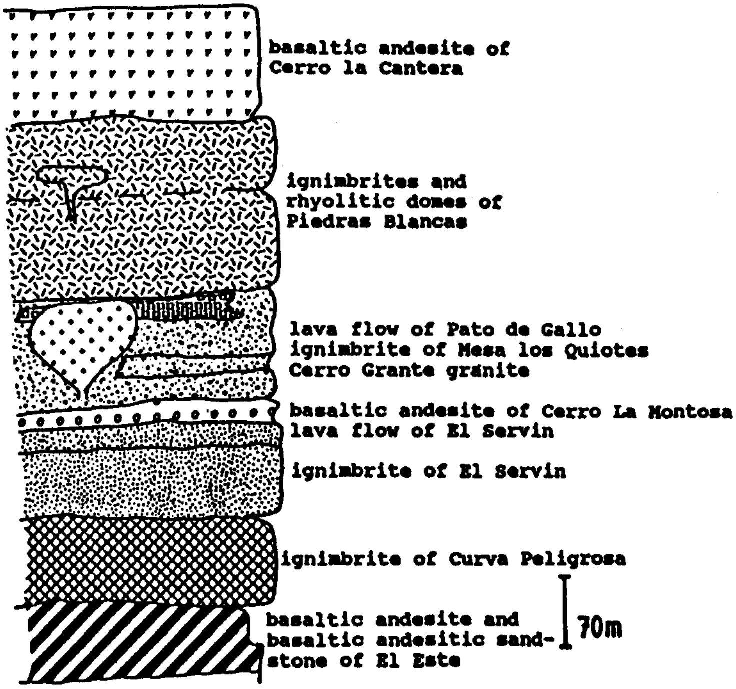

Fig. 3. Stratigraphic column and description of map units for the Cerro Grande region, San Buenaventura.

Cerro Grande is surrounded by thick ignimbrites, interpreted as caldera-fill, interfingering with lava flows and different volcanic breccias. The boundary between the caldera fill facies and the much thinner outflow sheet sequence is also characterized by a larger occurrence of volcanic breccias, and smaller areas of hydrothermal alteration. This zone is interpreted as the structural caldera wall. Field geologic information led to the following conclusions. The area was part of an early basaltic andesitic volcanism during which the basaltic andesite of El Este erupted (see Fig. 3 for stratigraphic nomenclature). A volcanic center for this lava flow was not encountered in the field area. Subsequently two major ignimbrite outflow sheets reached the area, the Tuff of la Curva Peligrosa and the Tuff of El Servín. These ignimbrites are overlain by the basaltic andesite of Cerro La Montosa. For these eruptive rocks no volcanic centers were located. The volcanic activity hereafter is related to the emplacement of a siliceous magma chamber (Fig. 4). The first products are local outpourings of rhyolitic lavas, represented by the Puerta de Buenaventura lava

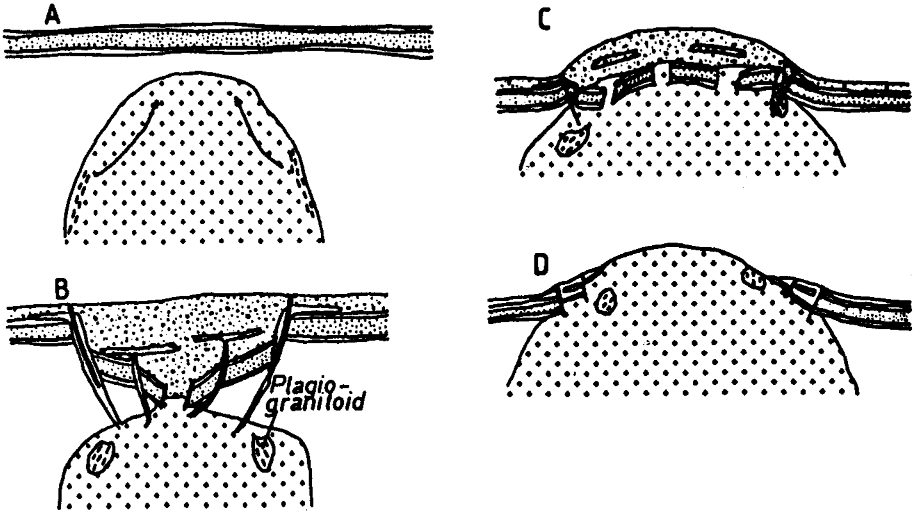

Fig. 4. Cartoon representing different stages of igneous activity in the Cerro Grande region.

A. Differentiating granitoid magma chamber of dacitic composition with formation of plagio-granitoid fractionation assemblage. Arrows represent movement of lighter, residual rhyolitic liquid.

B. Eruption, deposition of Mesa los Quiotes ignimbrites, emplacement of rhyolitic dykes and collapse of caldera.

C. Resurgence and intrusion of granitic magma. D. Uplift and erosion of granite body (for legend, see Fig. 3).

flow. Deposition of the Mesa los Quiotes tuff, collapse of a caldera structure and filling of the caldera occurred simultaneously. Emplacement of rhyolitic dikes and local rhyolitic flows continued as shown by the Pata de Gallo flow. Resurgence of the caldera structure followed and a resurgent granite intruded the caldera-fill tuff and the basaltic andesite of Cerro La Montosa. The basaltic andesite of Cerro La Montosa shows contact metamorphism in the contact zone to the Cerro Grande granite. At the southern edge of the granite complex, a plutonic rock composed of plagioclase, clinopyroxene, and pockets of amphibole/biotite and K-feldspar/quartz forms a large megablock. The meaning of this rock-type will be discussed in more detail in the next sections. It is interpreted as a mineral assemblage which crystallized at the edge of the granite body and was brought up during resurgence. Subsequent to the resurgent activity, the ignimbrite of Las Piedras Blancas was deposited, before the final deposition of the Cerro La Cantera basaltic andesite. Volcanic centers for these two final igneous events are not known.

### El Divisadero

The section of the Barranca del Cobre close to the railway station of El Divisadero was mapped. It comprises an area of 25 km$^2$ and a change in altitude from 900 meters at the Río Urique to 2 300 meters on the Mesa de la Barranca. Fig. 5 shows the generalized geological map. The entire 1 400 meters of rocks exposed are intermediate to siliceous volcanics, both ignimbrites and lava flows. The section was subdivided into a lower unit composed of intermediate volcanics and an upper unit of siliceous volcanics. No volcanic centers were discovered in the entire area. Because the volcanic layers are virtually undisturbed, the stratigraphic relationship was established easily for most units (Fig. 6). The oldest units cropping out in the vicinity of the Río Urique river are intermediate lava flows characterized by a high amount of basaltic andesitic xenocrysts. This basal formation is overlain by a second formation consisting of intermediate lava flows and ignimbrites. The upper unit consists of 3 major ignimbrite units of rhyolitic composition.

## MINERALOGICAL AND GEOCHEMICAL ASPECTS OF IGNEOUS EVOLUTION

### Mineralogical changes and igneous evolution

Throughout the following sections the data relating both the Buenaventura and the El Divisadero localities will be compared. Rock classification is strictly based on

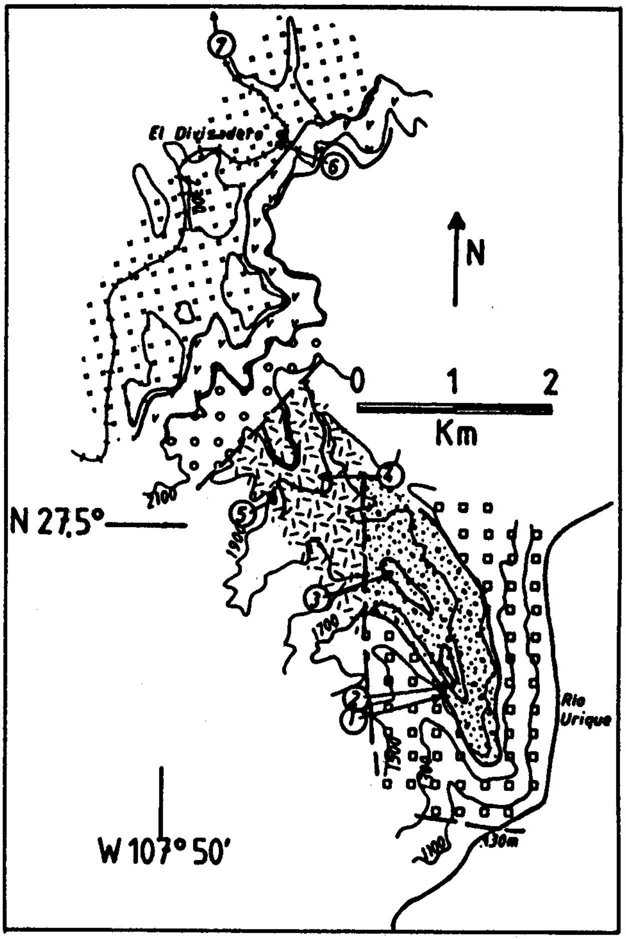

Fig. 5. Generalized geologic map of the Barranca del Cobre section at El Divisadero. Contour lines drawn every 100 m, numbers indicate sample location (Table 1) (for legend, see Fig. 6).

$SiO_2$ content following the work of Cameron *et al.* (1980). Basalts have less than 53 wt.-%, basaltic andesites 53 to 56 wt.-% $SiO_2$, andesites 56 to 63 wt.-% $SiO_2$, dacites 63 to 70 wt.-% $SiO_2$, and rhyolites 70 wt.-% $SiO_2$ and more. Mineral assemblages support this classification. Mafic rocks are characterized by plagioclase, Fe-Ti-oxides, clinopyroxene and olivine as phenocrysts. The abundance of olivine decreases from basaltic to andesitic rocks and is not encountered in dacites. Clinopyroxene, which is an abundant phase in mafic rocks is joined by amphibole in all siliceous rocks. Biotite, which is subordinate in the intermediate rocks becomes the most abundant mafic phenocryst in the rhyolitic samples. Plagioclase, which is dominant for all mafic and intermediate rocks, becomes much rarer in rhyolites and disappears completely in high-silica rhyolites. K-feldspar is the most abundant phenocryst in all rhyolites. Quartz phenocrysts appear in the dacitic samples and become more abundant in the rhyolites. Apatite and zircon are common trace minerals. The abundance of zircon increases from dacites to rhyolites; however, apatite abundance stays rather constant. These mineralogical changes characterize dacitic and rhyolitic rocks from both type localities. The only difference is the higher abundance of amphibole in all siliceous rocks from the El Divisadero section. Comparison for more basic rocks cannot be done due to lack of mafic rocks in the El Divisadero section. For this reason mafic rocks will not be considered further. The megablock of cumulative rocks found at the southern edge of the granitic intrusion can be used to specify the kind and abundance of minerals involved in the fractionation process. This block is interpreted as part of a mineral assemblage, which crystallized at the edge of the granitoid body during an early stage of magma evolution. Rhyolitic rocks can be visualized as the residual, lighter liquid of the crystallization process, which migrated into higher levels of the intrusion (McBirney and Noyes, 1979; McBirney, 1980). As remnants of this early crystallizing assemblage (called plagiogranitoid) do crop out, it is interpreted that this differentiation did not take place at great depth. Fig. 7 shows photomicrographs of the plagiogranitoid. Plagioclase, clinopyroxene, amphibole and Fe-Ti-oxides form the dominant minerals. These are interpreted as early phases, while biotite and myrmekitic intergrowth of quartz and K-feldspar are found interstitially, therefore representing the trapped residual liquid. This observation is of great importance, because it can be used to trace the fractionation path from dacitic to rhyolitic composition. For the Buenaventura sequence it can be stated, solely based on petrographic and mineralogical grounds, that the evolution from intermediate to siliceous rocks is based on fractional crystallization of a plagioclase-clinopyroxene-, amphibole- and Fe-Ti-oxide assemblage. Such cumulative assemblages were not encountered in the El Divisadero section. It is assumed however, based on the similar mineralogical make-up of intermediate and siliceous rocks that a similar fractionation path occurred. The larger abundance of amphibole in El Divisadero rocks might be used to include larger amounts of amphibole for the differentiation assemblage for this location. This will be discussed further in the geochemistry section.

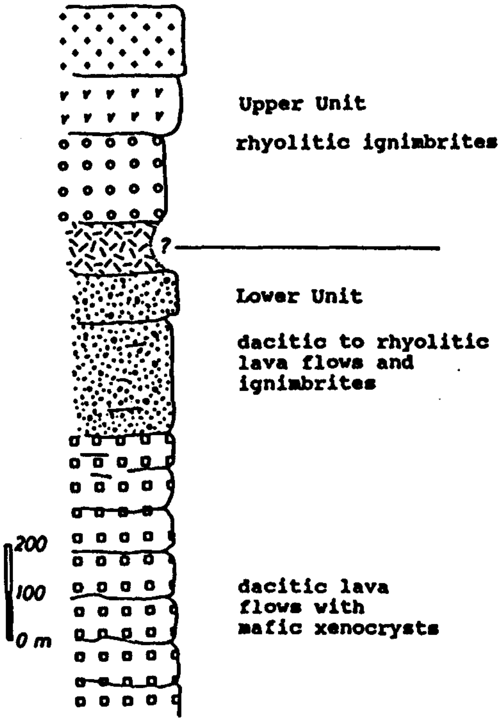

Fig. 6. Stratigraphic column and description of map units for the Barranca del Cobre section at El Divisadero.

## Geochemical aspects

### *Major and trace elements*

Any geochemical characterization of siliceous volcanic rocks, in particular ignimbrites, must consider the following processes that may affect the final composition of the sample studied: (1) Modification due to differentiation, (2) reaction with late-stage residual fluids, (3) flow differentiation and degree of welding and (4) low temperature alteration (Magonthier, 1984, and references therein). The effects of low temperature alteration has been minimized by careful selection of rocks in the field, and petrography before chemical analysis. Flow differentiation and degree of welding may change the composition of ignimbrites, but cannot be quantified. The same holds for reaction with late-stage residual fluids. The possibility of samples showing unexpected elemental variations therefore exists. Modification due to differentiation is of primary concern. As both type localities exhibit samples of a wide range of chemical composition (Table 1) the general trend of differentiation can be worked out for each suite. Throughout this article the amount of $SiO_2$ is being used as a differentiation index. It has been pointed out in the previous section that the Buenaventura suite contains basalts and basaltic andesites which are not encountered in El Divisadero. Inspection of silica content of both suites shows that in addition to this difference the Buenaventura suite includes high-silica rhyolites (>76 wt.-% $SiO_2$), also not present in El Divisadero. This will produce a larger variation in elemental abundances solely based on the amount of fractionation. Using Harker-type variation diagrams this type of enrichment can be quantified. Figure 8 shows such a variation diagram for $K_2O$. This diagram in addition to an AFM diagram (not shown) can be used to characterize the volcanic suites as high-K calc-alkaline rocks (Gill, 1981). The scatter of K abundance is due to reaction with late-stage residual fluids and/or flow differentiation. This phenomenon is particularly obvious for ignimbrites. We have chosen not to reject these analyses to point out this general problem related to ignimbrites. The relative enrichment of the Buenaventura suite in $K_2O$ is diagnostic and will be discussed later. Figure 9 shows a Harker variation diagram for $TiO_2$. In both suites the abundance of Ti is controlled by Fe-Ti oxides, and the decrease of Ti with increasing $SiO_2$ can be explained by Fe-Ti-oxide removal throughout the fractionation path. The overlap in Ti abundance for both suites can be used to exclude differences in the fractionation history, at least regarding the involvement of Fe-Ti-oxides. The variation of Zr with increasing $SiO_2$ is shown in Figure 10. For each suite two general trends can be seen: Zr enrichment with increasing silica for intermediate rocks and enrichment and/or depletion for siliceous rocks. Such trends can be explained only by the involvement of a Zr-rich phase such as zircon in the fractionation assemblage, apparently when the differentiating magma reached a rhyolitic composition. As zircon fractionation played a more significant role in the El Divisadero suite, caution must be applied when comparing elemental abundances that can be affected by zircon fractionation. The dominance of amphibole in the El Divisadero samples might be reflected in trace element abundances. Figures 11 a, b shows variation diagrams for Y and Yb. For the Buenaventura suite both trace elements show enrichment with increasing differentiation therefore excluding amphibole as an important fractionating mineral phase. This is different for the El Divisadero suite. Both Y and Yb show no enrichment with increasing silica. This can be explained by the participation of amphibole in the fractionation process. Figure 12

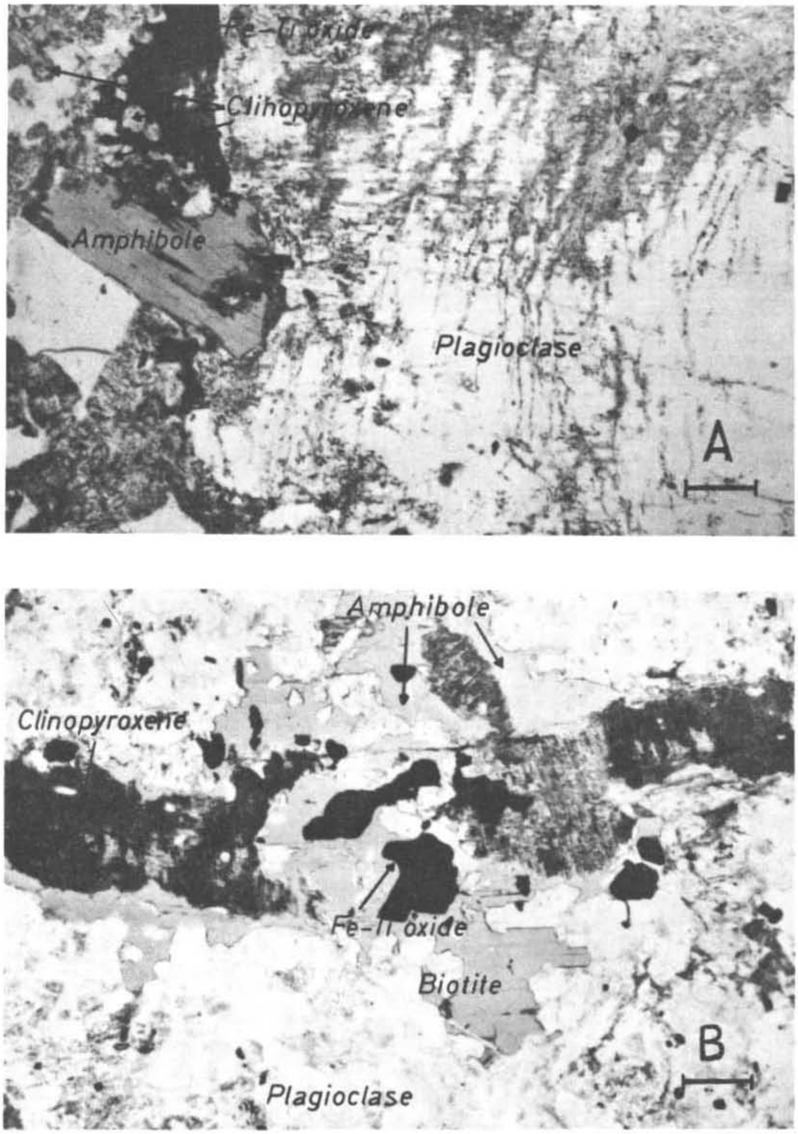

Fig. 7. Photomicrographs of plagio-granitoid sample 87/3-1; scale bar is 2.5 mm.
A. Plagioclase macro-phenocryst with amphibole, clinopyroxene and Fe-Ti oxide.
B. Clinopyroxene relict overgrown by amphibole, with biotite, Fe-Ti oxides and plagioclase.

Table 1

Representative analytical data from the San Buenaventura and El Divisadero localities

SAN BUENAVENTURA

| Sample # | 87/3-1 | 87/1-4 | PM3E | 86/6-1 | 86/6-42 | 86/6-39 | 86/6-31 | 86/8-5 | 86/7-17 |
|---|---|---|---|---|---|---|---|---|---|
| Rocktype | plag.-granitoid | granite | dacite | dacite | dacite | dacite | rhyolite | rhyolite | rhyolite |
| I.D.-# | 1 | 2 | 4 | 3 | 7 | 6 * | 8 | 9 | 5 |
| XRF-data | | | | | | | | | |
| % SiO2 | 57.3 | 70.3 | 66.3 | 69.1 | 69.3 | 69.3 | 70.2 | 73.4 | 76.9 |
| K2O | 2.5 | 5.2 | 8.9 | 8.6 | 5.7 | 5.9 | 5.6 | 4.3 | 4.8 |
| TiO2 | 1.05 | 0.42 | 0.43 | 0.16 | 0.52 | 0.69 | 0.56 | 0.41 | 0.09 |
| P2O5 | 0.43 | 0.14 | 0.1 | 0.03 | 0.11 | 0.09 | 0.1 | 0.03 | 0.03 |
| ppm Rb | 104 | 278 | 624 | 536 | 190 | n.d. | 192 | 129 | 321 |
| Sr | 707 | 188 | 89 | 74 | 19 | n.d. | 27 | 170 | 18 |
| Y | 29 | 62 | 92 | 81 | 63 | n.d. | 65 | 48 | 82 |
| Zr | 227 | 259 | 343 | 116 | 402 | n.d. | 444 | 362 | 76 |
| Nb | 13 | 26 | 18 | 24 | 32 | n.d. | 32 | 27 | 37 |
| Ba | 1494 | 2017 | 2647 | 150 | 166 | 160 | 269 | 2527 | 2049 |
| INAA-data | | | | | | | | | |
| ppm Hf | 5.82 | 9.18 | 10 | 5.5 | 11.4 | 10.6 | 13.8 | 10.1 | 5.44 |
| La | 32.6 | 48.4 | 46 | 42 | 120 | 136 | 91.6 | 56.2 | 31.4 |
| Ce | 78.9 | 112 | 100 | 63 | 242 | 195 | 202 | 130 | 86.9 |
| Nd | 26 | 48 | 35 | 21 | n.d. | 108 | n.d. | n.d. | 28 |
| Sm | 7 | 8.35 | 5.8 | 7.1 | 15.6 | 14.6 | 14.1 | 10.4 | 7.56 |
| Eu | 2.18 | 0.833 | 1.53 | 0.32 | 3.17 | 3.16 | 2.65 | 2.52 | 0.219 |
| Tb | 1.02 | 1.01 | 0.76 | 0.66 | 2.37 | 1.57 | 1.46 | 1.42 | 1.73 |
| Dy | 3.47 | 6.15 | 4.2 | 4.9 | 8.85 | 8.8 | 8.33 | 6.78 | 8.41 |
| Yb | 2.29 | 4.42 | 2.55 | 2.9 | 5.62 | 4.4 | 5.13 | 4.26 | 7.43 |
| Lu | 0.31 | 0.63 | 0.39 | 0.38 | n.d. | 0.63 | n.d. | n.d. | 1 |
| Th | 11 | 32.3 | 21.4 | 41.2 | 26.1 | 25.1 | 28.9 | 10.9 | 45 |
| U | 2.72 | 4.3 | 5.7 | 8.2 | n.d. | 5.3 | n.d. | n.d. | 7.6 |

* XRF data Trier

EL DIVISADERO

| Sample # | 88/1-4 | 88/1-3 | 88/1-7 | 88/1-10 | 87/11-4 | 87/11-1 | 88/3-7 |
|---|---|---|---|---|---|---|---|
| Rocktype | dacite | dacite | rhyolite | rhyolite | rhyolite | rhyolite | rhyolite |
| XRF-data | | | | | | | |
| I.D. # | 2 | 1 | 3 | 4 | 6 | 7 * | 5 |
| % SiO2 | 66.3 | 68.2 | n.d. | n.d. | 71.8 | 73.5 | 75.8 |
| K2O | 3.6 | 4.2 | 1.5 | 3.1 | 3.9 | 4.1 | 4.3 |
| TiO2 | 0.54 | 0.55 | 0.5 | 0.39 | 0.37 | 0.29 | 0.2 |
| P2O5 | 0.13 | 0.13 | n.d. | n.d. | 0.06 | 0.04 | 0.03 |
| ppm Rb | 136 | 176 | n.d. | n.d. | 119 | 147 | 120 |
| Sr | 281 | 269 | n.d. | n.d. | 234 | 60 | 88 |
| Y | 36 | 40 | n.d. | n.d. | 23 | 43 | 33 |
| Zr | 222 | 214 | n.d. | 260 | 164 | 165 | 119 |
| Nb | 18 | 14 | n.d. | n.d. | 20 | 20 | 20 |
| Ba | 1430 | 1766 | 800 | 1310 | 1400 | 1865 | 1999 |
| INAA-data | | | | | | | |
| ppm Hf | 6.7 | 7.1 | 5.3 | 7.2 | 5.49 | 6.6 | 4.92 |
| La | 25.5 | 25.4 | 27.5 | 34.2 | 38.2 | 30.9 | 33.4 |
| Ce | 47 | 57 | 49 | 72 | 70.4 | 71 | 69.3 |
| Nd | 24 | 28 | b.13 | 43 | 24 | 46 | n.d. |
| Sm | 4.7 | 4.9 | 6.6 | 7 | 4.23 | 6.2 | 5.38 |
| Eu | 1.31 | 1.46 | 1.61 | 1.78 | 1.01 | 1.33 | 1.05 |
| Tb | 0.7 | 0.8 | 0.72 | 1.23 | 0.773 | 0.91 | 1.09 |
| Dy | 4.8 | 4.6 | 6.2 | 6.2 | 2.09 | 5.8 | 3.66 |
| Yb | 3.2 | 3 | 3.1 | 4.2 | 2.55 | 4.1 | 3.14 |
| Lu | 0.5 | 0.53 | 0.45 | 0.64 | 0.39 | 0.58 | n.d. |
| Th | 8 | 9.1 | 6.2 | 12 | 12.4 | 19.1 | 10.9 |
| U | 3.17 | 3.24 | 2.26 | 4.4 | 2.78 | 6.7 | n.d. |

* XRF data Trier

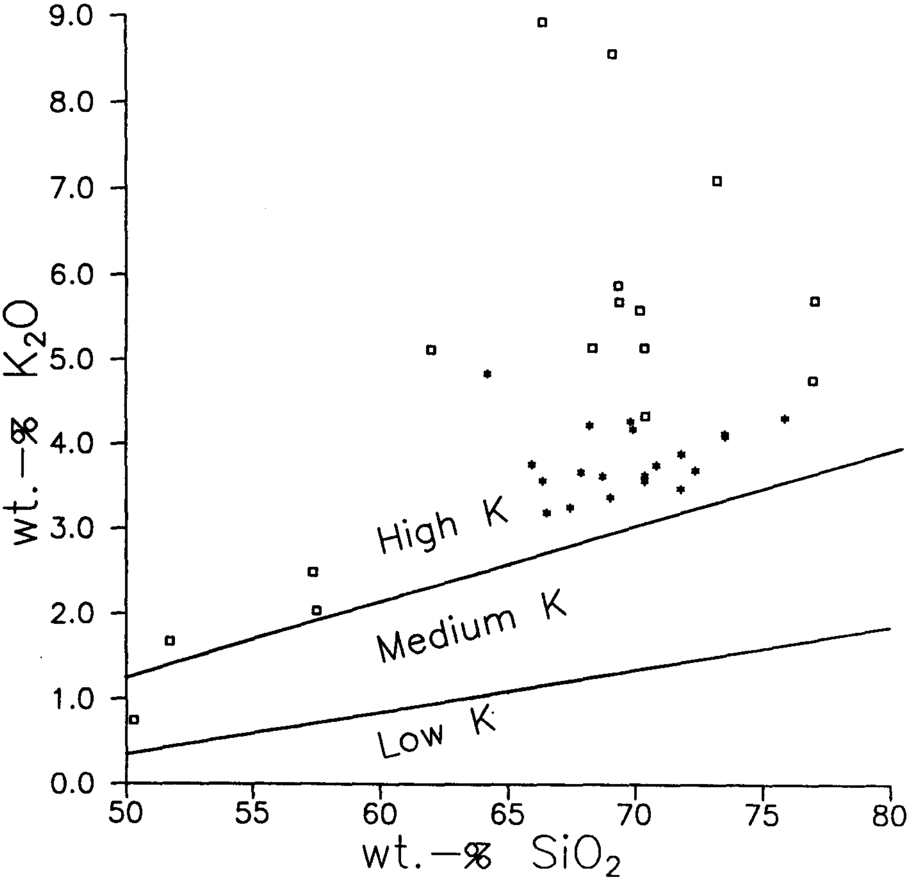

Fig. 8. Harker-type variation diagram for $K_2O$; boundary lines between low-, medium and high K after Gill (1981); open squares depict Buenaventura samples, stars El Divisadero samples.

represents variation diagrams for Rb, Nb, Ce, Th and U. They are representative for the K-group, the high-field-strength elements, the light REE and the U-group elements respectively. In all cases a general increase in trace element abundances can be recorded. It should be mentioned already that the Buenaventura suite has higher abundances for the elements represented in these diagrams. Chondrite-normalized REE abundance diagrams for the Buenaventura and El Divisadero suites are repre-

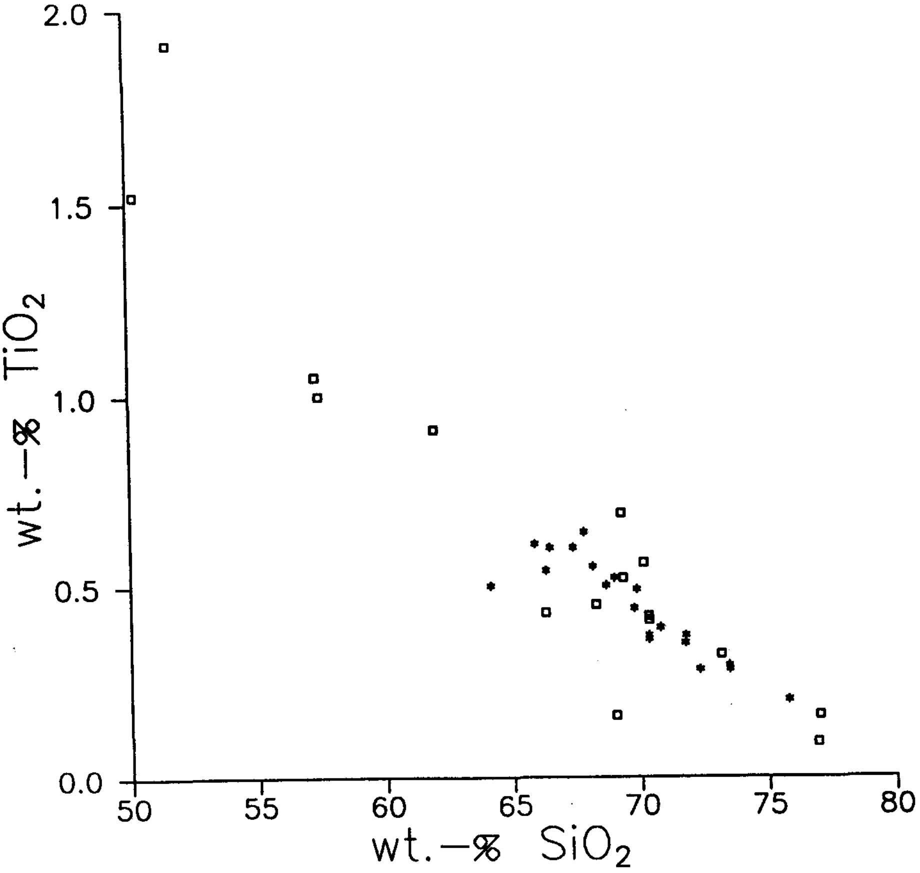

Fig. 9. Harker-type variation diagram for Ti; symbols as in Fig. 8.

sented in Figures 13 a, b, respectively. For the Buenaventura suite 7 representative samples have been depicted. They span the compositional range from dacites to high-silica rhyolites and include both ignimbrites as well as lava flows. The variation in both light and heavy REE is due to enrichment processes caused by fractionation of minerals with low distribution coefficients ($K_D$) for the REE (Henderson, 1984). These minerals are clinopyroxene, Fe-Ti oxides, plagioclase (except for Eu), amphibole (except for the heavy REE). Interelement fractionation of the REE is achieved by removal of minerals with relatively high distribution coefficients (Henderson,

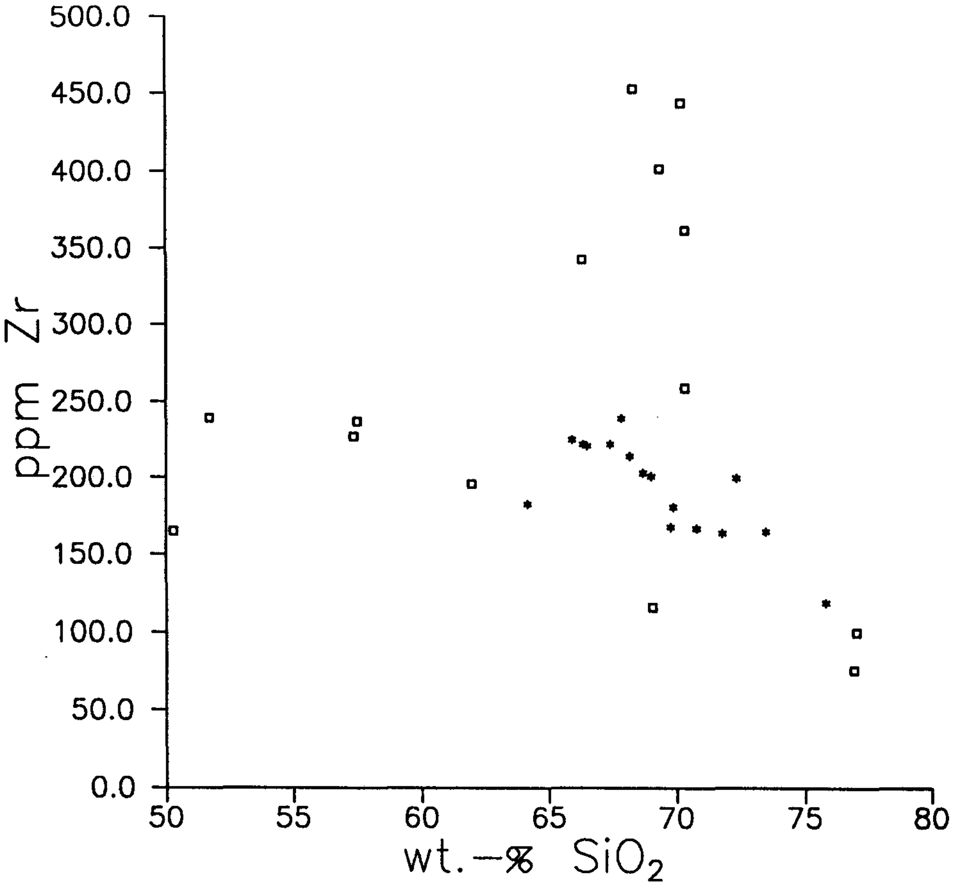

Fig. 10. Harker-type variation diagram for Zr; symbols as in Fig. 8.

1984). Such phases are plagioclase, alkalifeldspar (Eu), amphibole (HREE), apatite (middle REE), sphene (all REE) and zircon (HREE). To what extent trace minerals have participated in fractionation processes has to be further investigated. Petrographic analysis shows the existence of apatite in fractionated plagioclase. Zircon fractionation seems likely for some samples. Comparison of high-silica rhyolites (*e.g.* 86/7-17) with rhyolitic lava flows (*e.g.* 86/6-31) indicates that the REE abundances have been altered considerably by removal of high $K_D$ phases. Possible involvement of alkali-feldspar during the last phase of differentiation is required for the high silica rhyolites to explain the negative Eu anomaly. REE abundance pattern for the El Divisadero suite shows less variation, due to the non existence of high silica rhyolites. Inter-element fractionation processes (removal of trace minerals) must have played a certain role, as can be seen in variations of the middle REE. In spite of variations occurring within each suite, comparison shows the enrichment of all samples from the Buenaventura region in REE relative to the El Divisadero suite.

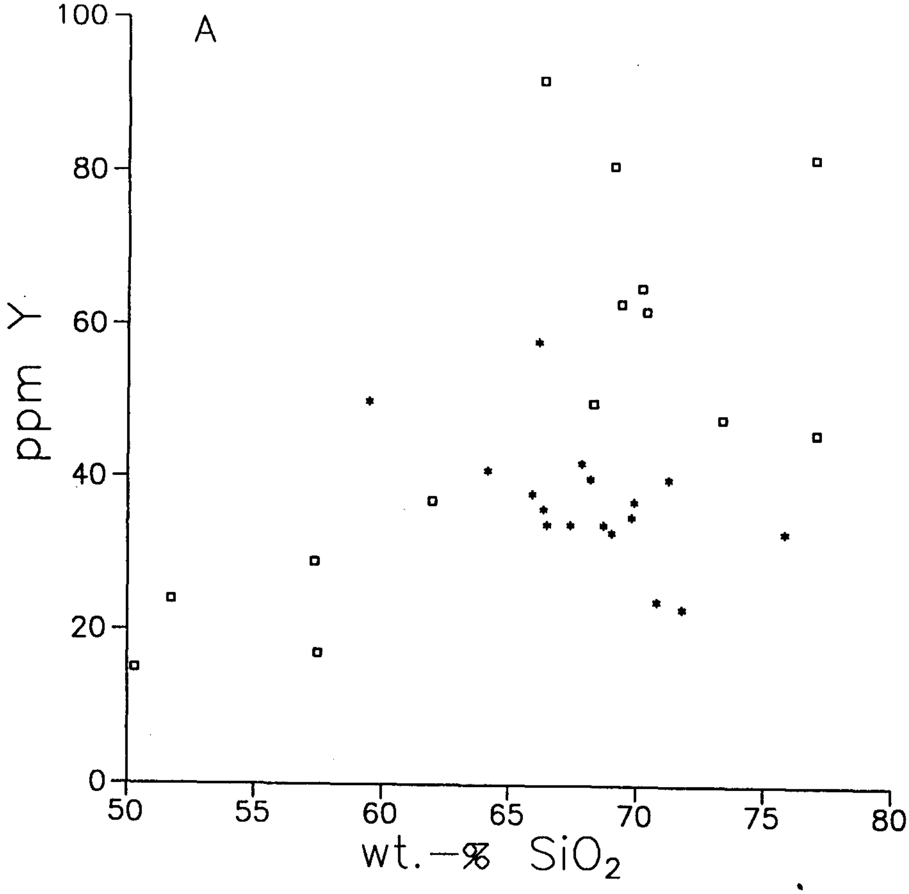

Fig. 11 (A). Harker-type variation diagrams for Y; symbols as in Fig. 8.

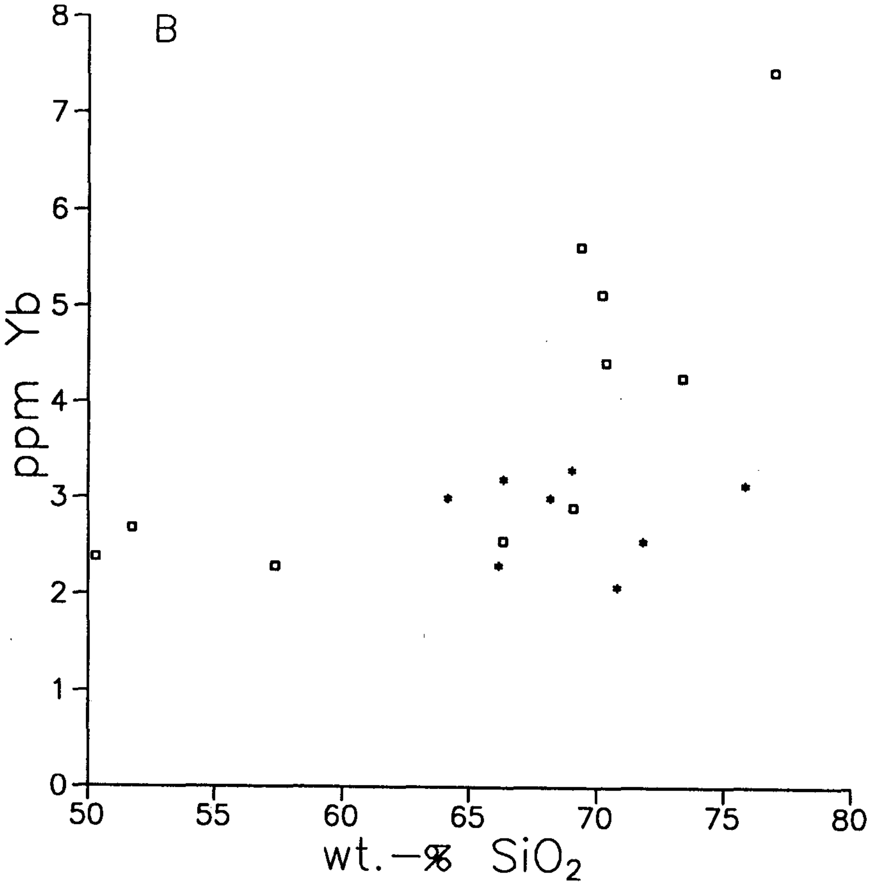

Fig. 11 (B). Harker-type variation diagrams for Yb; symbols as in Fig. 8.

Elemental ratios further reflect the differences between the magmatic suites. Figures 14 a-d represent variations of elemental ratios with increasing $SiO_2$. These ratios can be used to evaluate contributions of different sources. Northward increase of Rb/Cs (Fig. 14a) excludes larger incorporation of subducted material. The stronger enrichment of LIL elements relative to HFS elements, as shown by the Rb/Zr (Fig. 14b) can be used to reduce a possible increase of OIB mantle component northward. These plots in addition to Th/U and Th/Ta (Fig. 14c, d) indicate the effective northward enrichment of hygromagmatophile elements (Joron and Treuil, 1977).

## *Sr isotopic composition and Rb/Sr age dating*

Strontium isotope data have been collected on whole rock samples and mineral separates of both localities. Details on individual data, analytical procedures and errors will be published elsewhere (Albrecht *et al.*, in press). The $^{87}Sr/^{86}Sr$ ratios and Sr- and Rb concentrations were determined by isotope dilution. Whole rock and mineral separate data have been plotted on a conventional isochron plot for the Buenaventura suite (Fig. 15) and the upper suite from El Divisadero (Fig. 16). The fact that samples from individual suites form isochrons undermines the hypothesis that they are indeed cogenetic. For the Buenaventura suite an age of 33.2 Ma and an initial Sr-ratio of 0.706577 ± 0.000425 were determined. For the El Divisadero upper sequence an age of 28.9 Ma and an initial of 0.705644 ± 0.000335 has been determined.

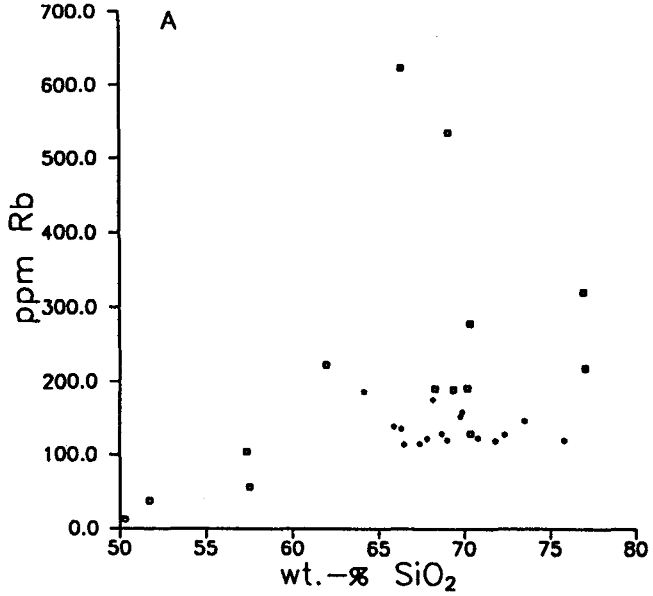

Fig. 12 (A). Harker-type variations diagrams for Rb; symbols as in Fig. 8.

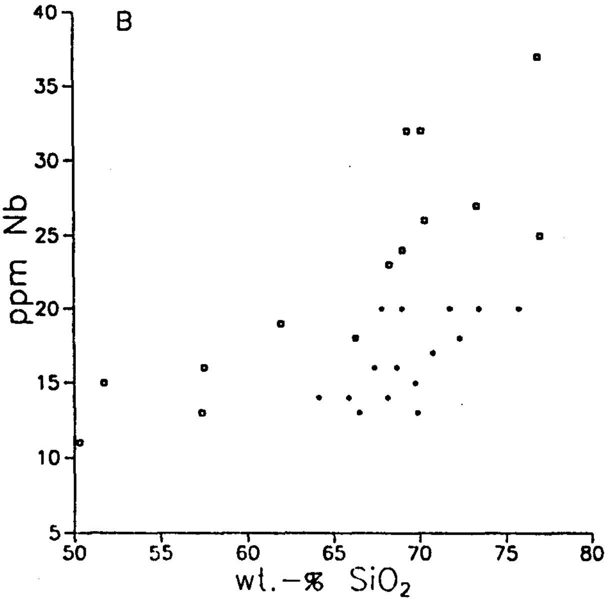

Fig. 12 (B). Harker-type variations diagrams for Nb; symbols as in Fig. 8.

## *Discussion and comparison with other suites*

Spidergrams have shown their use in particular for comparison of different suites. In Figure 17 dacitic and rhyolitic samples from both the Buenaventura and the El Divisadero suite are depicted. It illustrates several points made earlier. The negative relative abundances of Sr, P, and Ti show the involvement of plagioclase, Fe-Ti-oxides and apatite in the fractionation assemblage. The most significant point is the difference in abundance of trace elements not significantly affected by fractional crystallization. Trace element variations in granitic rocks have been investigated by Pearce *et al.* (1984), and empirically assigned to tectonic settings. Rock samples from both localities are plotted in the Y+Nb *vs.* Rb diagram (Fig. 18), which according to Pearce *et al.* (1984) can be used to distinguish tectonic settings as per their trace element composition. The Buenaventura suite plots in the field of within-plate-granites (WPG) which is characterized by enriched/or non-depleted source regions. The samples from El Divisadero plot in the field of volcanic arc granites (VAG) characterized by more depleted source regions. It can therefore be

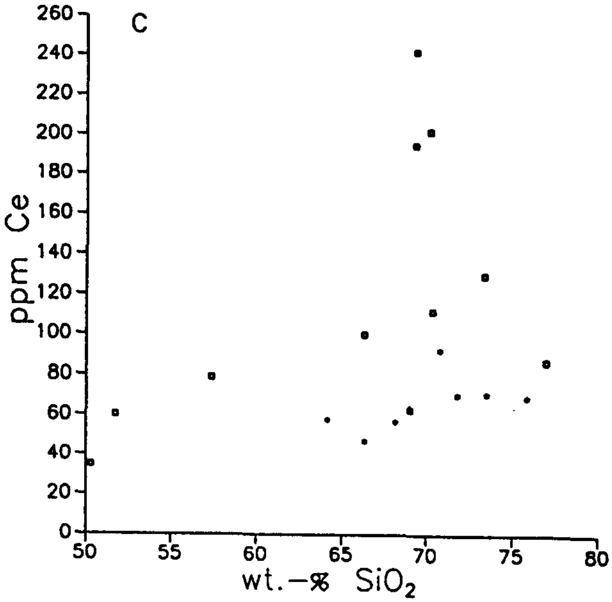

Fig. 12 (C). Härker-type variations diagrams for Ce; Symbols as in Fig. 8.

argued that the rocks from both suites have different source regions. Cameron *et al.* (1985) and Ruiz *et al.* (1988) developed opposite models, one interpreting the Tertiary volcanic rocks as mantle derived with subsequent fractional crystallization (Cameron *et al.*, 1985), and the other as lower crustal partial melts (Ruiz *et al.*, 1988). Neither of these models seems to explain satisfactorily petrological data from both the Buenaventura and El Divisadero suites. A model explaining the origin of the Buenaventura and El Divisadero suites needs to involve both crustal and subcrustal (mantle) components. Such a model was presented by Hildreth and Moorbath (1988) for arc magmatism in Central Chile. They used melting, assimilation, storage and homogenization (MASH) to establish the base-level geochemical variations present in the igneous suites of Central Chile. Such processes occur preferentially at the mantle-crust boundary, and the rocks will show both mantle and crustal signatures. Cameron *et al.* (1989) have analyzed basaltic andesites throughout northern Mexico and the southwestern U. S. Their data do not indicate significant variations in the mantle component in northern Mexico. We therefore come to the conclusion that the geochemical differences that exist between the Buenaventura

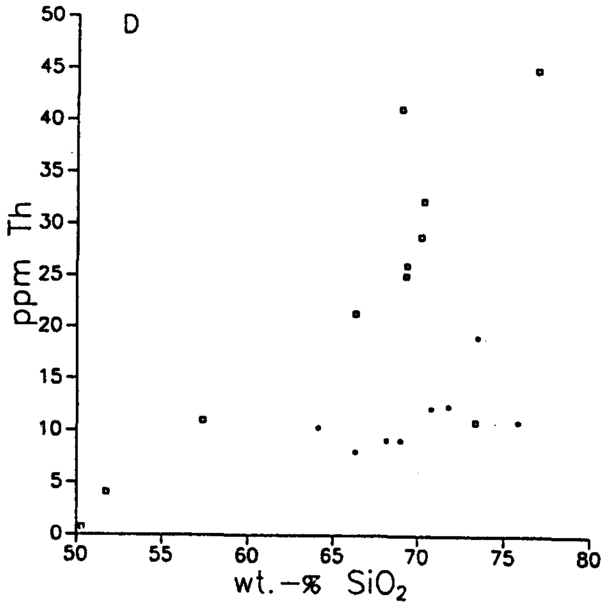

Fig. 12 (D). Harker-type variations diagrams for Th; symbols as in Fig. 8.

and El Divisadero suites are due to variations in composition of crustal rocks inforporated in the primary mantle-derived magma.

Similar geochemical variations in calc-alkaline rocks along volcanic arcs have been described elsewhere (Gill, 1981, and references therein). They are either due to differences in crustal thickness and/or crustal composition. The central Andes can be used for comparison with the northern Sierra Madre Occidental because siliceous endmembers form part of the igneous suites (Thorpe *et al.*, 1984). Extensive geochemical work has been carried out by several research groups (Dupuy *et al.*, 1976; Zentilli and Dostal, 1977; Hawkesworth *et al.*, 1982; Thorpe *et al.*, 1982; Thorpe *et al.*, 1984; Hildreth and Moorbath, 1988). In the central Andes well established geochemical differences exist between different zones. These zones are characterized by continental crust of different thickness, age and composition. Volcanic rocks above older and thicker continental crust are enriched in Rb, Ba, Th, K, Ce, Sr, and initial $^{87}Sr/^{86}Sr$ (Thorpe *et al.*, 1984). These variations are very similar to those described for the northern Sierra Madre Occidental. For the northern Sierra

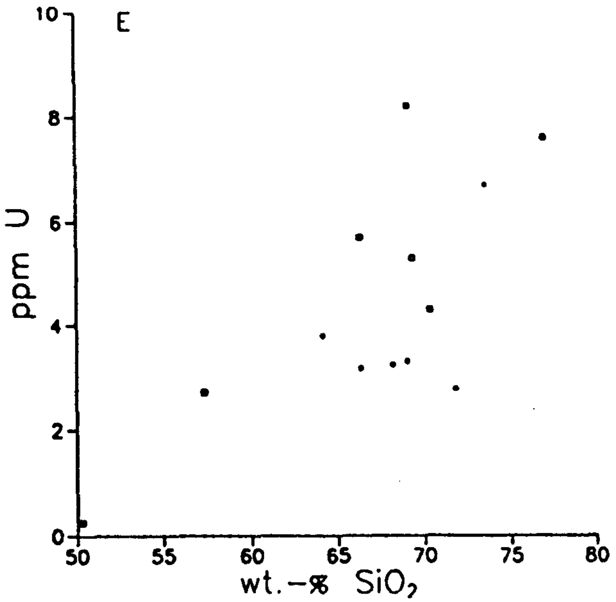

Fig. 12 (E). Harker-type variations diagrams for U; symbols as in Fig. 8.

Madre Occidental a simple increase in crustal thickness, and therefore larger amount of crustal input could explain the observed geochemical differences. Ruiz (1989) reported that "seismic and gravity data indicate that the crust under is not very different in thickness (*ca.* 35 km) anywhere under the SMO". We therefore conclude that not crustal thickness but crustal composition is responsible for the observed geochemical composition. Sr isotope data represent an additional indication for distinct crustal differences. The edge of the North American craton has been determined more accurately in the southwest of the USA (Kistler and Peterman, 1973, 1978; Burchfiel, 1979; Hill *et al.*, 1988). Here the limit of known Precambrian basement correlates well with the $^{87}Sr/^{86}Sr$ contour of 0.706 for Mesozoic igneous rocks. Additional data (Albrecht *et al.*, 1987, 1988) indicate the existence of a similar boundary for the northern Sierra Madre Occidental.

## SUMMARY

The two localities studied in the northern Sierra Madre Occidental are both charac-

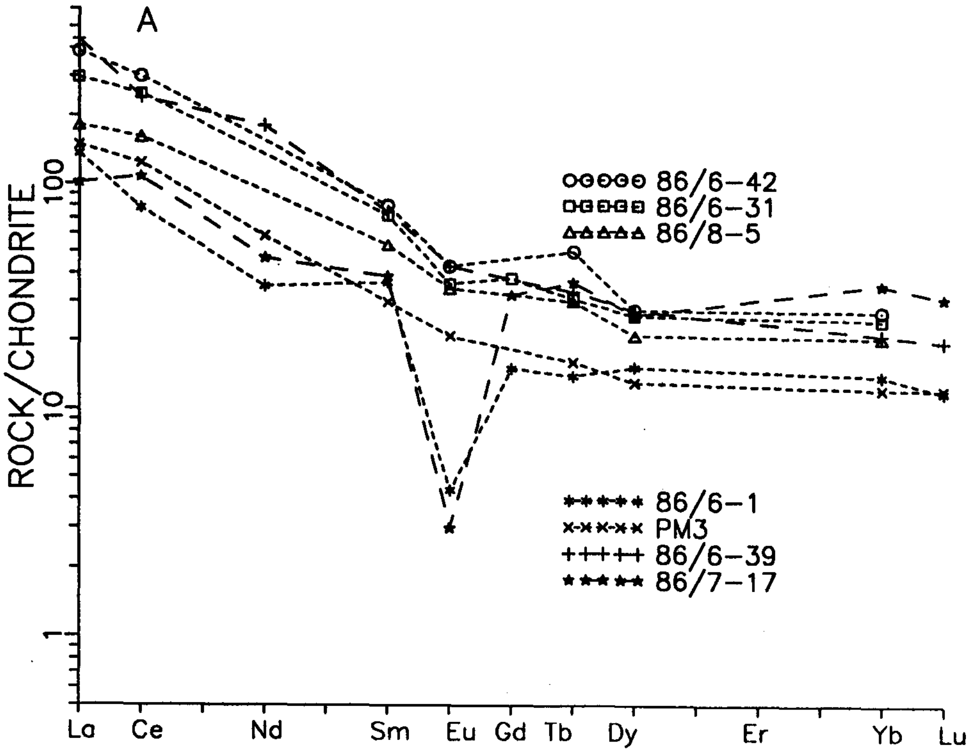

**Fig.13 (A).** Chondrite-normalized (Boynton, 1984) REE patterns for representative samples: San Buenaventura. For samples with significant negative Eu-anomalies Gd was interpolated.

terized by calc-alkaline rocks of dacitic to rhyolitic composition. Petrographically similar, they have distinct differences in Sr-isotopic and trace element abundances. In particular, Nb, Rb, LREE, Th and U can be used to distinguish the two suites. Lack of geochemical breaks in the 1 400 m section at El Divisadero excludes time changes. As the mantle component beneath the Sierra Madre does not vary significantly, and as the low Sr isotopic ratios exclude upper crustal evolvement, we come to the conclusion that the geochemical differences between San Buenaventura and El Divisadero reflect variations in the lower crustal component. The older, more evolved lower crustal lithologies (Precambrian craton) beneath Buenaventura in comparison to the younger lower crustal rocks of the accreted terranes show the following differences. (1) higher abundances of incompatible elements (*e.g.* Rb, Nb,

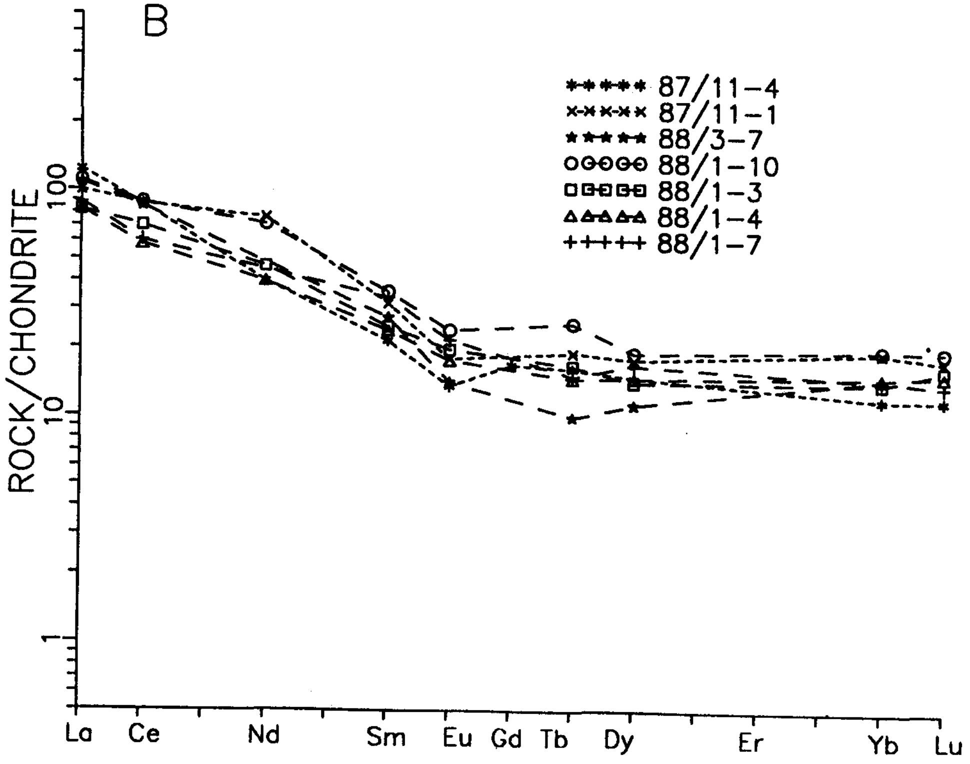

Fig. 13 (B). Chondrite-normalized (Boynton, 1984) REE patterns for representative samples: El Divisadero. For samples with significant negative Eu-anomalies Gd was interpolated.

Ce, Th, U; (2) higher relative abundances of highly magmatophile elements relative to high field strength elements; (3) enrichment of Th relative to U; (4) higher $^{87}Sr/^{86}Sr$ ratios.

The Tertiary volcanic rocks therefore reflect variations in basement composition and can be used to trace the southern limit of the north American craton. To answer questions on the exact position and nature of the boundary between terranes and craton needs further studies within the transition zone. But existing Sr isotope data (Albrecht *et al.*, in press) indicate that not a sharp boundary (as represented by a mega-shear), but a large zone characterizes the transition.

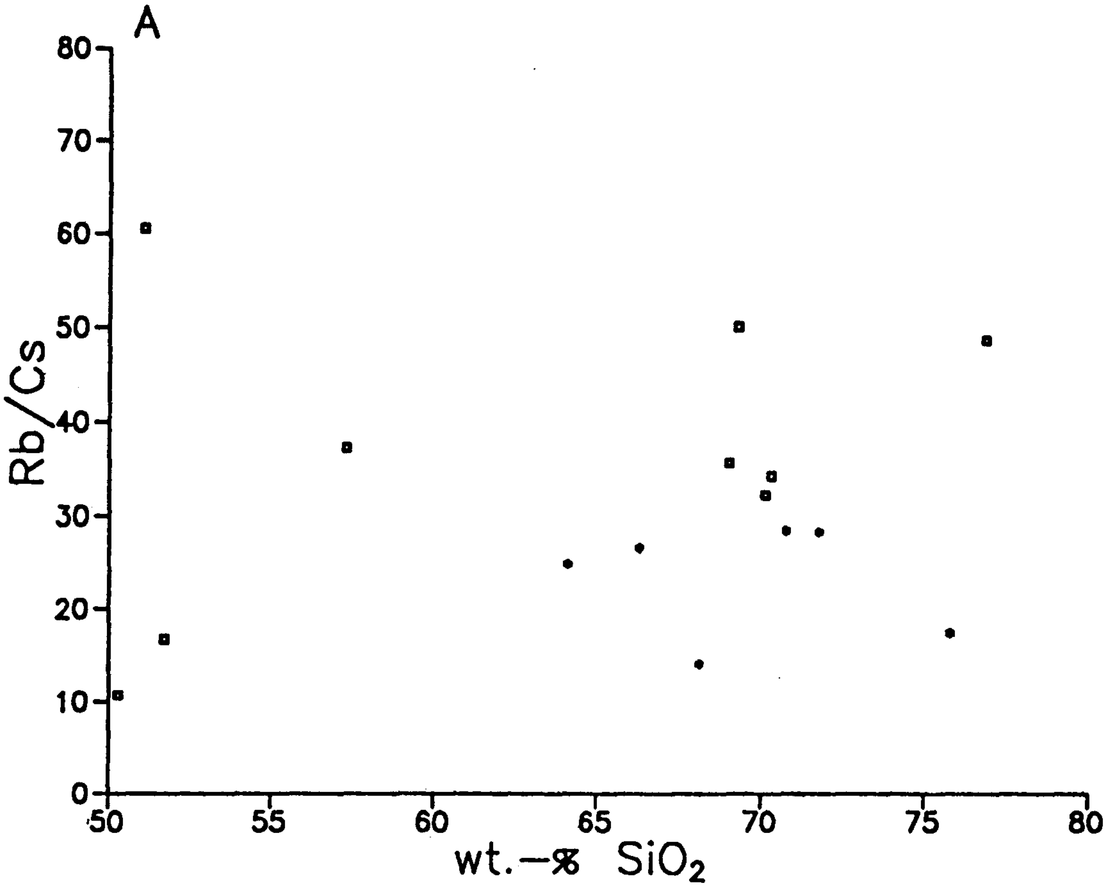

Fig. 14 (A). Comparison of variations of selected elemental ratios with silica between San Buenaventura and El Divisadero: Rb/Cs (see C for legend).

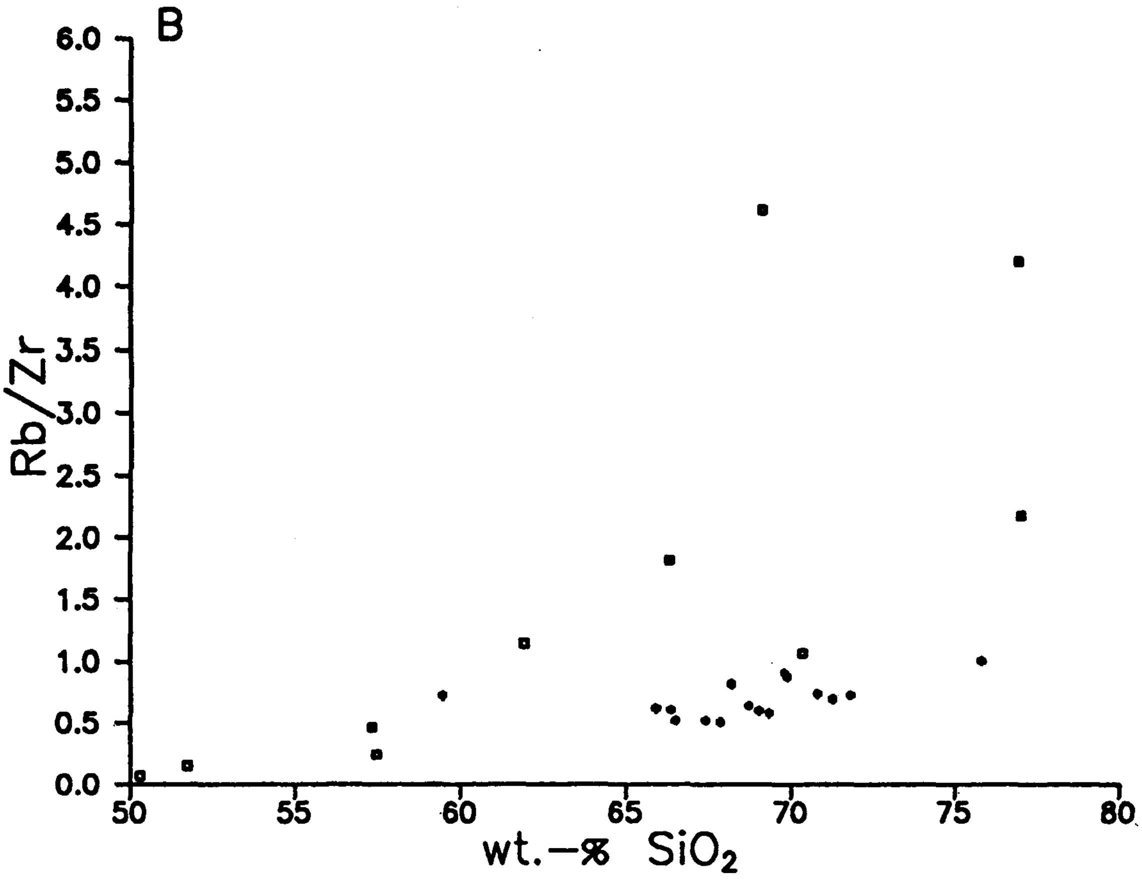

Fig. 14 (B). Comparison of variations of selected elemental ratios with silica between San Buenaventura and El Divisadero: Rb/Zr (see C for legend).

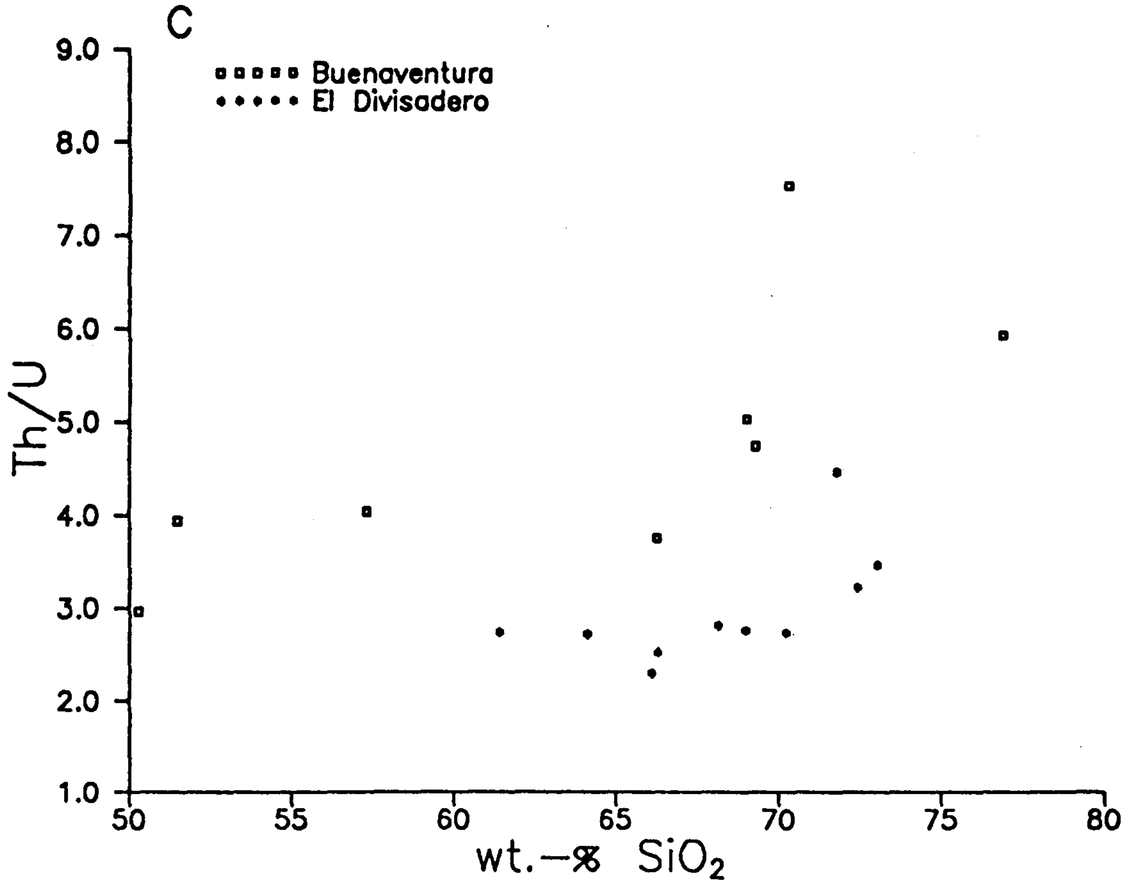

Fig. 14 (C). Comparison of variations of selected elemental ratios with silica between San Buenaventura and El Divisadero: Th/U.

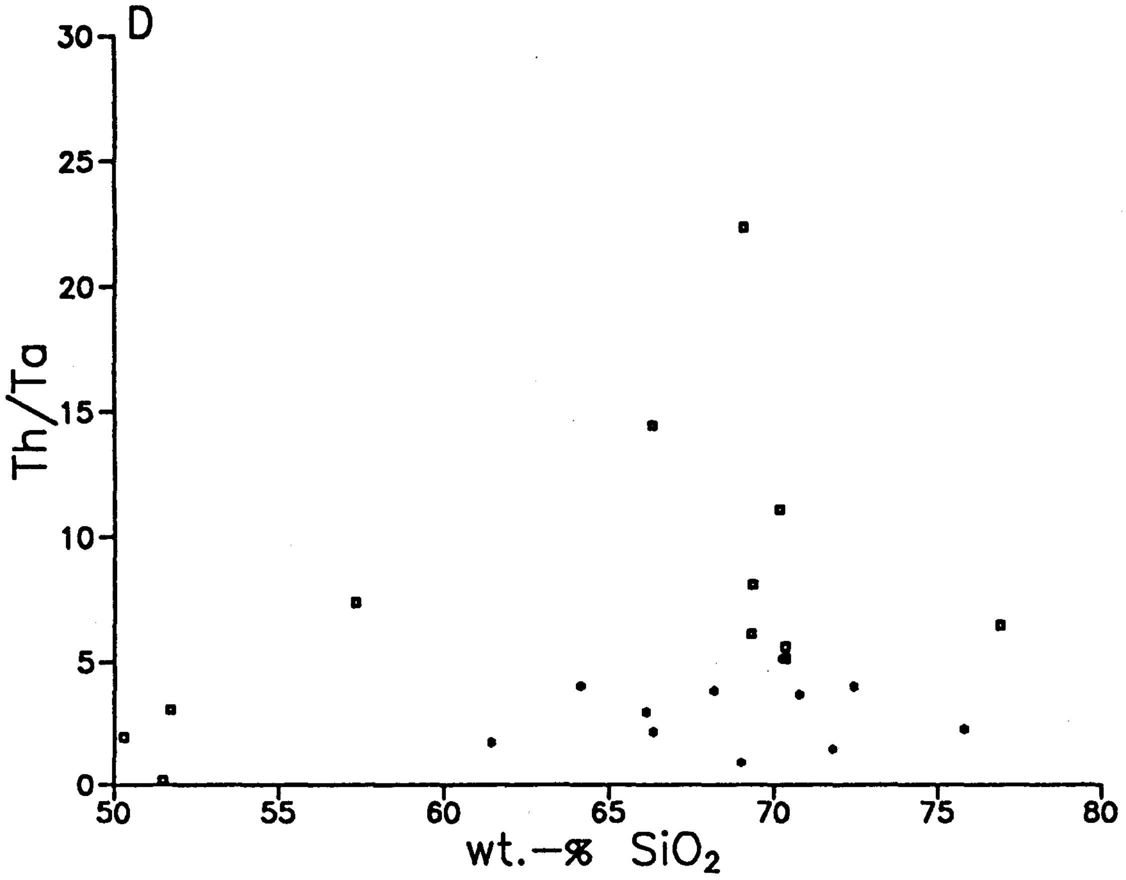

Fig. 14 (D). Comparison of variations of selected elemental ratios with silica between San Buenaventura and El Divisadero: Th/Ta (see C for legend).

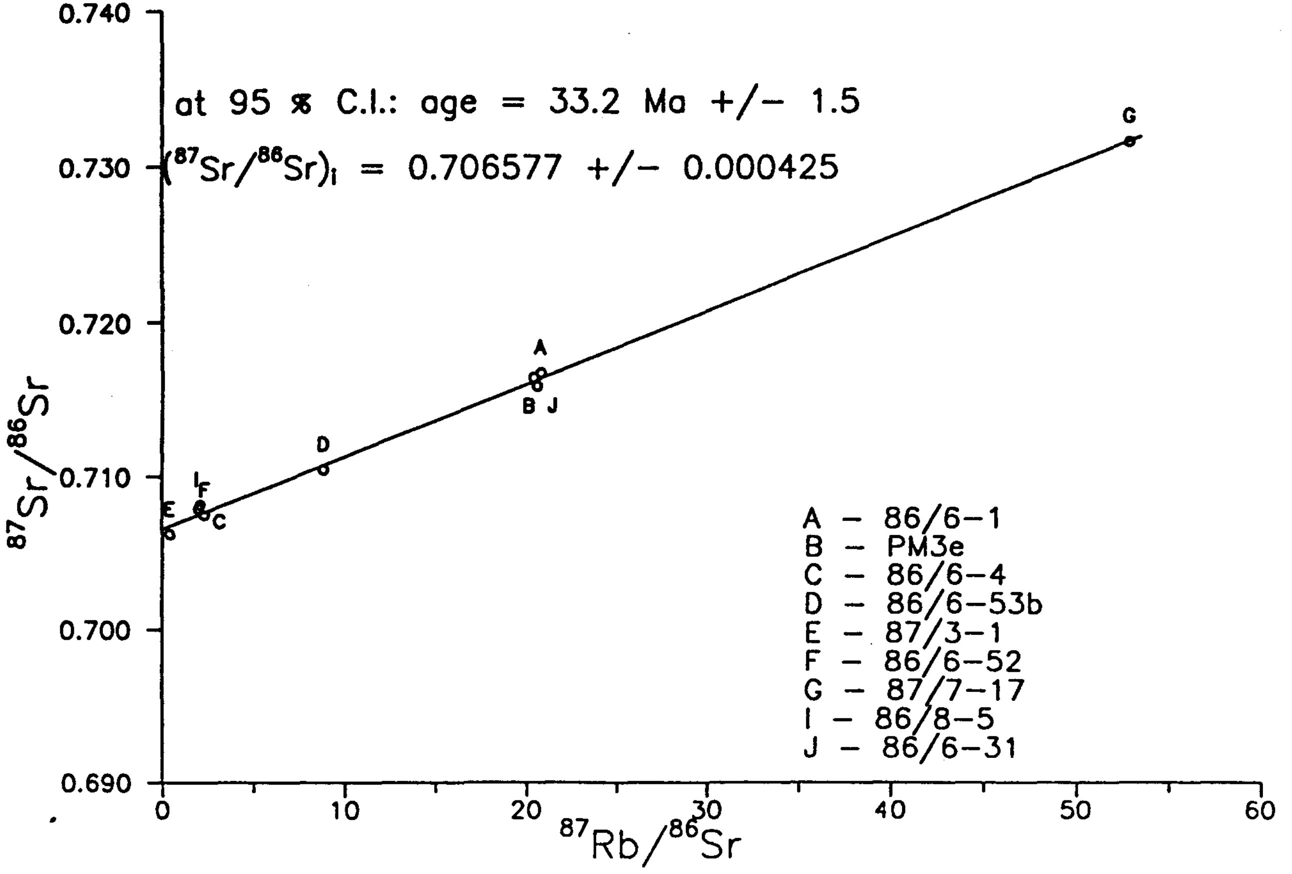

Fig. 15. Conventional isochron plot for whole rock samples from San Buenaventura.

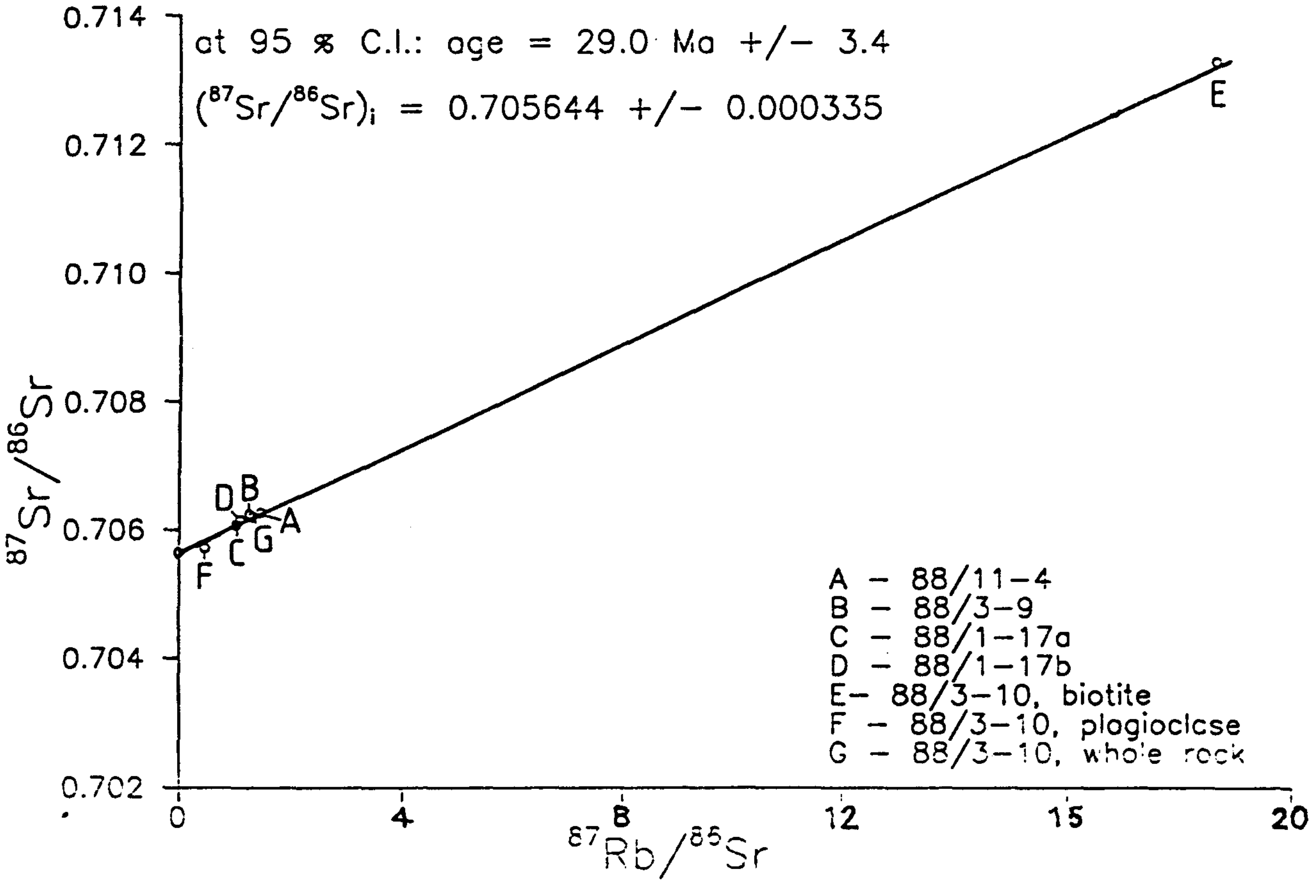

Fig. 16. Conventional isochron plot for whole rock samples and mineral separates from the upper unit at El Divisadero.

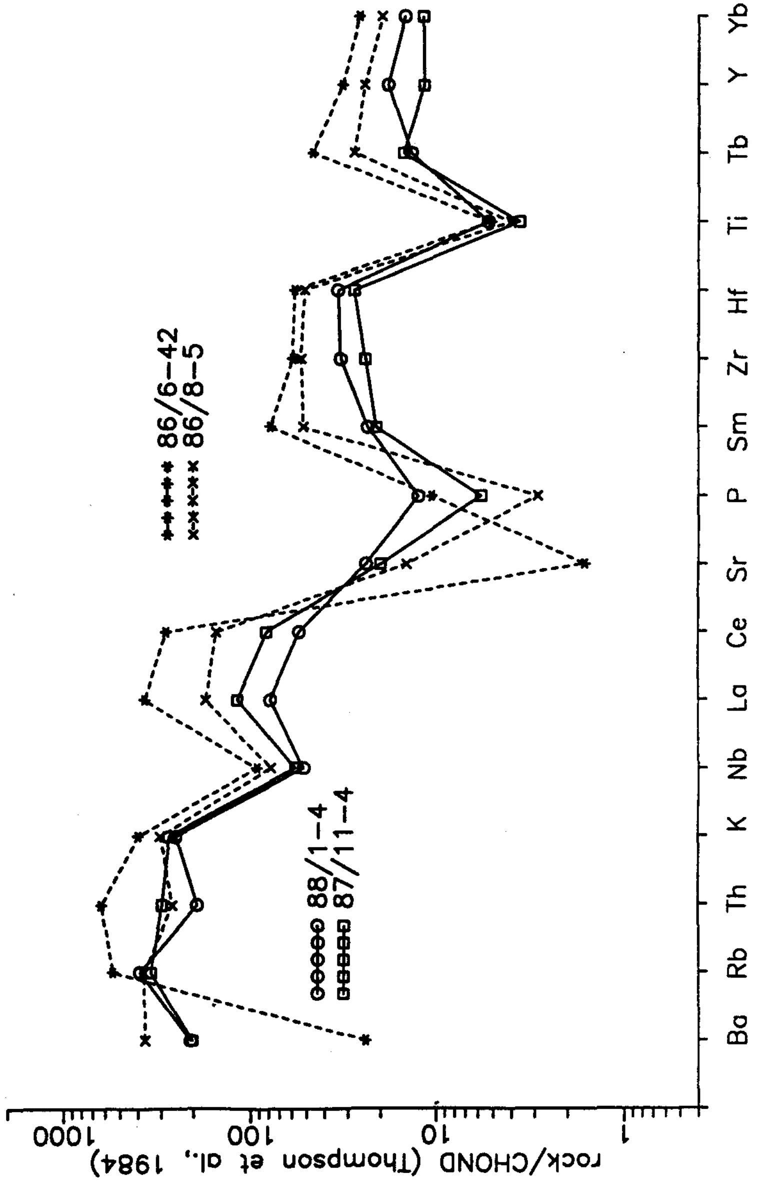

Fig. 17. Thompson-type spider-gram for two representative samples from Buenaventura (star and cross) and El Divisadero (open symbols).

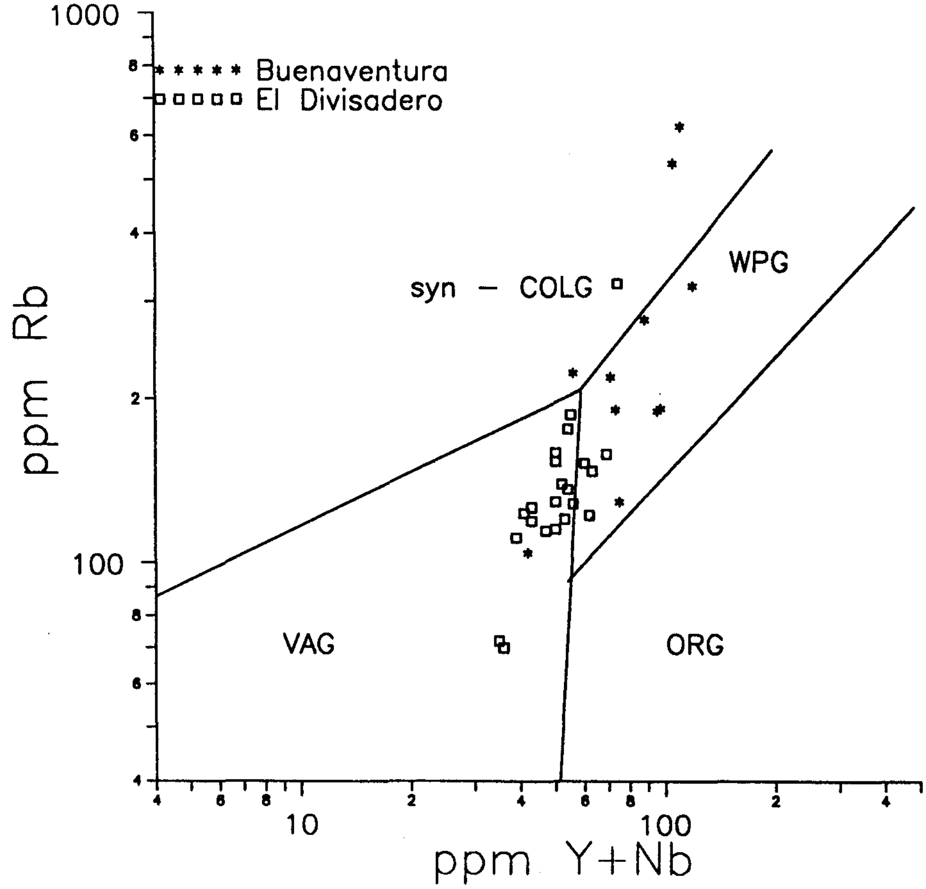

Fig. 18. Pearce type (Pearce *et al.*, 1984) discriminate diagram for granitic rocks. Represented are all samples from both localities.

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