

# Assimilation of sialic crustal material by volcanics of the easternmost extension of the Trans-Mexican Volcanic Belt- Evidence from Sr and Nd isotopes

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## RESUMEN

Las rocas volcánicas basálticas hasta riolíticas, de edad Plioceno al Cuaternario, provenientes de la parte extrema oriental de la Faja Volcánica Trans-Mexicana (FVTM), se caracterizan por  $^{87}\text{Sr}/^{86}\text{Sr}$  de 0.70342 a 0.70511 y  $^{143}\text{Nd}/^{144}\text{Nd}$  de 0.51250 a 0.51287. Dado que las rocas volcánicas son muy jóvenes (de edad Plioceno al Cuaternario), se pueden considerar estas relaciones isotópicas medidas como las iniciales. Estos isótopos se correlacionan negativamente y, con una excepción, caen en el campo del 'arreglo del manto'. La variación isotópica no se puede explicar por modelos binarios sencillos, ni por modelos de tipo AFC. Nuestra interpretación sugiere un modelo complejo involucrando las heterogeneidades en el manto y la asimilación del material cortical.

**PALABRAS CLAVE:** Rocas volcánicas, Plioceno, Cuaternario, FVTM, estroncio, neodimio, manto, corteza, asimilación.

## ABSTRACT

Pliocene to Quaternary basaltic to rhyolitic volcanics of the easternmost part of the TMVB are characterized by  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios from 0.70342 to 0.70511 and  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios from 0.51250 to 0.51287. Since the volcanics are of Pliocene to Quaternary age, the measured Sr and Nd isotope ratios are taken as initial ratios. These isotope ratios are negatively correlated and, with one exception, plot on the 'mantle array'. The isotopic variation cannot be explained by simple binary mixing models or AFC-modelling. Our interpretation suggests a complex model involving mantle heterogeneities and assimilation of crustal material.

**KEY WORDS:** Volcanic rocks, Pliocene, Quaternary, TMVB, strontium, neodimium, mantle, crust, assimilation.

## INTRODUCTION

The Trans-Mexican Volcanic Belt (TMVB) is a roughly west-east trending structure presumably formed in association with the subduction of the Cocos/Rivera plate system (Robin, 1976, 1982; Demant, 1978, 1981; Pal *et al.*, 1978; Nixon, 1982; Verma, 1985, 1987a, b; Negendank *et al.*, 1985; Besch *et al.*, 1987; Nixon *et al.*, 1987; Verma and Nelson, 1989a, b). Our study area (Figure 1) lies in the easternmost extension of the TMVB, where according to several authors two different volcanic provinces, the calc-alkaline association of the W-E trending TMVB and a N-S orientated alkaline province, overlap (Robin, 1976; Demant, 1978; Thorpe, 1977; Pichler and Weyl, 1976). We present here our  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  isotope data on selected samples from the easternmost part of the TMVB and discuss their petrogenetic implications.

## GEOLOGY AND GEOCHEMISTRY

According to Negendank *et al.* (1985) the eastern TMVB can be divided into four geological units, which are

from W to E: the Altiplano Area (Oriental Basin) (approximately left half area, left of Pico de Orizaba, in Figure 2), the Cofre de Perote - Pico de Orizaba Range (right half area in Figure 2), the Jalapa-Naolinco Area (left half area in Figure 3), and the Palma Sola Massif (right half area in Figure 3). During the Pliocene to Quaternary, several strato-volcanoes, domes, lava flows, monogenetic cones and maars were formed erupting rocks belonging to the calc-alkalic, high-K and shoshonitic series. On the basis of microprobe mineral analysis of recent lavas from volcán Pico de Orizaba, Kudo *et al.* (1985) concluded that xenolithic contamination was an important petrogenetic process during their evolution.

Besch *et al.* (1988) have reported the major, trace and rare-earth element characteristics of 30 samples. In the present paper additionally the results of  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  isotope ratios are presented. The investigated rocks are located in the easternmost extension of the TMVB (locations are given in Figures 2 and 3) and have been selected from different geological units to examine the sug-

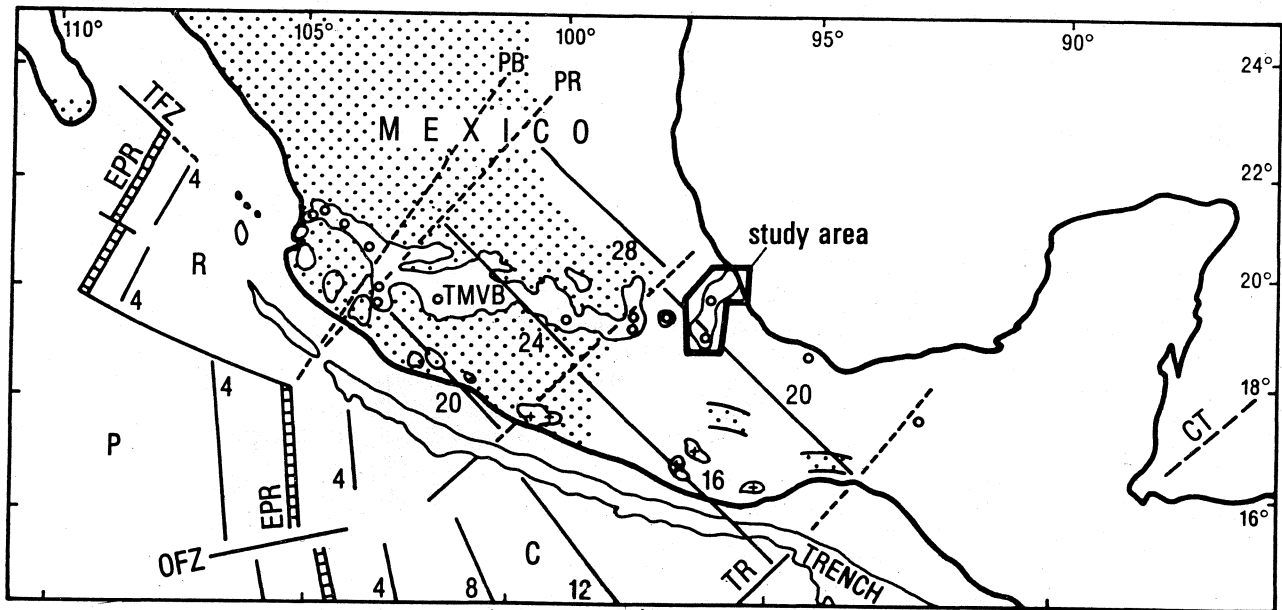


Fig. 1. A simplified map showing the study area in context of the TMVB. C = Cocos plate, CT = Cayman trough, EPR = East Pacific Rise, P = Pacific plate, R = Rivera plate, PB = transform boundary between Rivera and Cocos plates (predicted), PR = trend of proto-Rivera fracture zone if one was indeed present in the subducted plate, TMVB = Trans-Mexican Volcanic Belt, TFZ = Tamayo fracture zone, TR = Tehuantepec ridge.

gested comagmatic relationships for all rock types. The volcanic rocks are classified as alkali basalt, transitional basalt, basaltic andesite, andesite, dacite and rhyolite. The foid-free basalts without normative nepheline were considered by Negendank *et al.* (1985) as transitional basalts. Additionally, the andesites are divided into basaltic, monogenetic and stratovolcano andesites.

#### The Altiplano Area (Oriental Basin)

The central part of the Altiplano is dominated by the rhyolite domes of Cerro Derrumbadas and Cerro Pinto (Figure 2). These are surrounded by several monogenetic cones of andesitic, dacitic and, in minor amounts, transitional basaltic compositions. Rare-earth element patterns for the volcanic rocks are shown in Figure 4. All andesite types and dacites are LREE- (light rare-earth element) enriched with  $Ce/Yb_n$ -ratios clustered varying around 6.3 and have flat HREE (heavy rare-earth element) distribution. In the Oriental Basin there is no tendency for the absolute REE (rare-earth element) abundances to increase with the degree of fractionation, precluding a cogenetic relationship for the volcanics.

The REE patterns for the Cerro Derrumbadas rhyolites (Figure 4) exhibit LREE-enrichment ( $Ce/Yb_n = 111$ ), depleted HREE and a slight negative Europium anomaly. According to Besch *et al.* (1988) these patterns cannot be derived by fractionation processes involving a basaltic parental magma. The Cerro Derrumbadas rhyolite (sample NT5, Figures 2 and 4) might represent a partial melt of the continental crust involving residual garnet, amphibole and plagioclase. The Cerro Pinto rhyolite (sample NH33, Fi-

gures 2 and 4) exhibits a flat LREE ( $Ce/Yb_n = 1.4$ ) and a flat HREE distribution and has a distinct negative Europium anomaly. Even the Cerro Pinto rhyolite might represent a partial melt of the continental crust, but in contrast to the Cerro Derrumbadas rhyolite with residual orthopyroxene, clinopyroxene and plagioclase. Multi-element normalized plots (Figure 4) for the volcanics, excluding the rhyolites, reveal distinct negative anomalies of Nb, Ta, Ti, and high LILE/HFSE (large ion lithophile (LILE) vs. high field strength elements (HFSE)) ratios suggesting a subduction related petrogenesis.

#### Cofre de Perote - Pico de Orizaba Range

This area (Figure 2) is characterized by the stratovolcanoes Cofre de Perote and Pico de Orizaba. These volcanoes are built mostly of andesite and dacite lava flows. Additionally, several monogenetic cinder cones of erupted transitional basalts ('hawaiites' according to Negendank *et al.*, 1985) and basaltic andesites occur in that area. Rare-earth element patterns for the volcanic rocks are presented in Figure 4. All rock types are LREE-enriched with  $Ce/Yb_n$ -ratios varying around 5.2. Europium anomalies are absent. There is no tendency for the absolute REE abundances to increase with the degree of fractionation. This precludes a cogenetic relationship between the basalts and andesites in this area.

Multi-element normalized diagrams (Figure 4) for the Cofre de Perote and Pico de Orizaba volcanics, normalized by using primitive mantle values by Jagoutz *et al.* (1979) and Wänke *et al.* (1984), display a high ratio of LILE/HFSE and distinct negative anomalies of Ta, Nb and Ti for

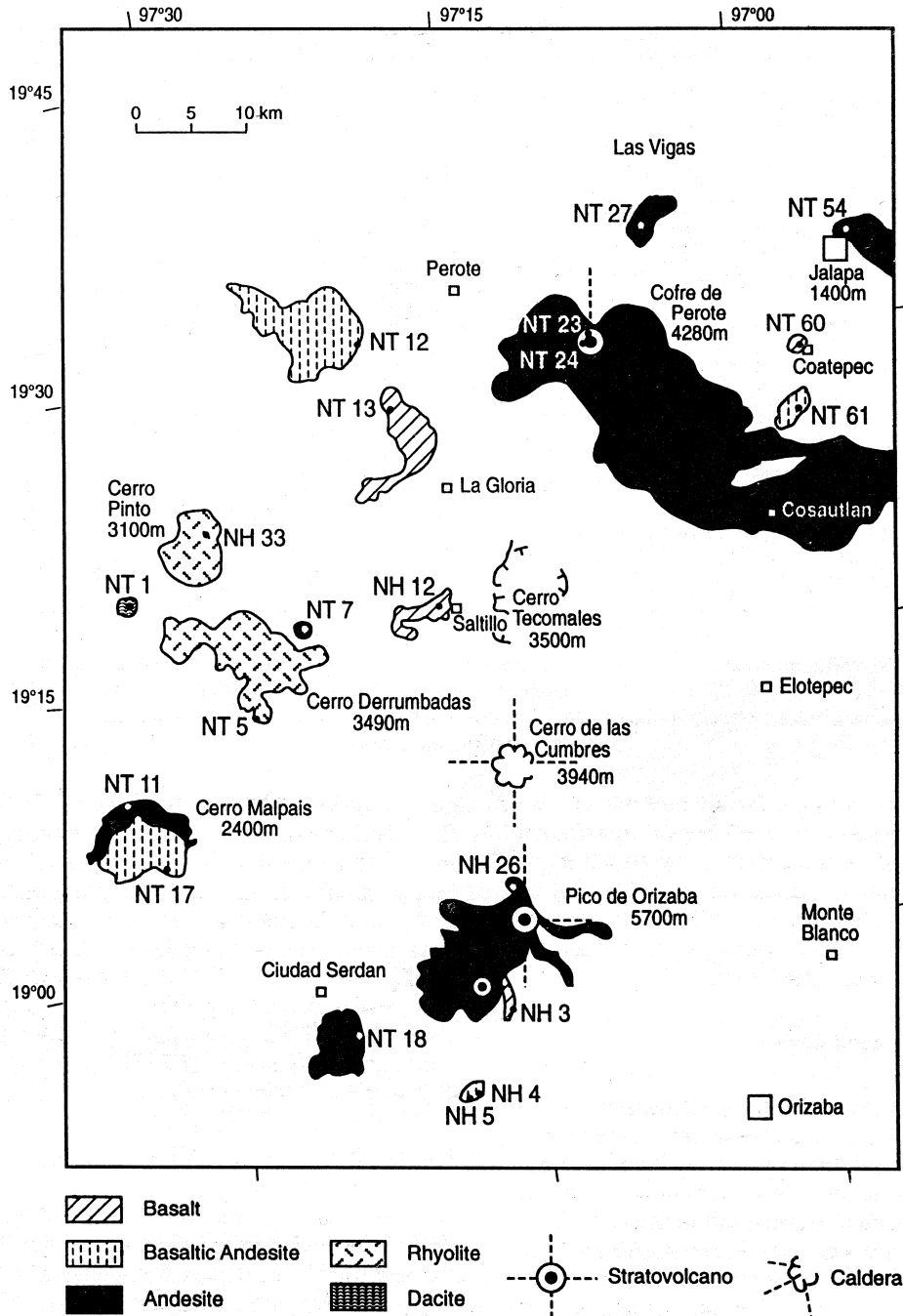


Fig. 2. Simplified geological map of the Atilplano Area (Atilplano/Pico de Orizaba-Cofre de Perote Range), modified according to Negendank *et al.* (1985).

the stratovolcano andesites. These geochemical signatures are indicative of subduction related volcanics (Pearce, 1982; Briquet *et al.*, 1984). The Morb normalized trace element patterns (Besch *et al.*, 1988) of the primitive basalts in this area (Figure 4), show a clear enrichment in LILE relative to MORB, suggesting a LILE-enriched source for the Cofre de Perote-Pico de Orizaba basalts.

#### Jalapa-Naolinco Area

The Jalapa-Naolinco Area (Figure 3) is dominated by cinder cones that erupted alkali basalts, transitional basalts

and calc-alkaline andesites. REE patterns for the volcanics are shown in Figure 4. All rock-types are LREE-enriched with Ce/Yb<sub>n</sub>-ratios varying from 4.5 (basalts) to 9.1 (alkali basalts) and exhibit flat HREE distribution. Europium anomalies are absent.

Multi-element normalized diagrams (Figure 4) show that the basalts and basaltic andesites have lower incompatible trace element concentrations than the alkaline rocks. Since fractionation would increase the concentration of incompatible elements, the derivation of calc-alkaline rocks from the alkaline rocks is excluded.

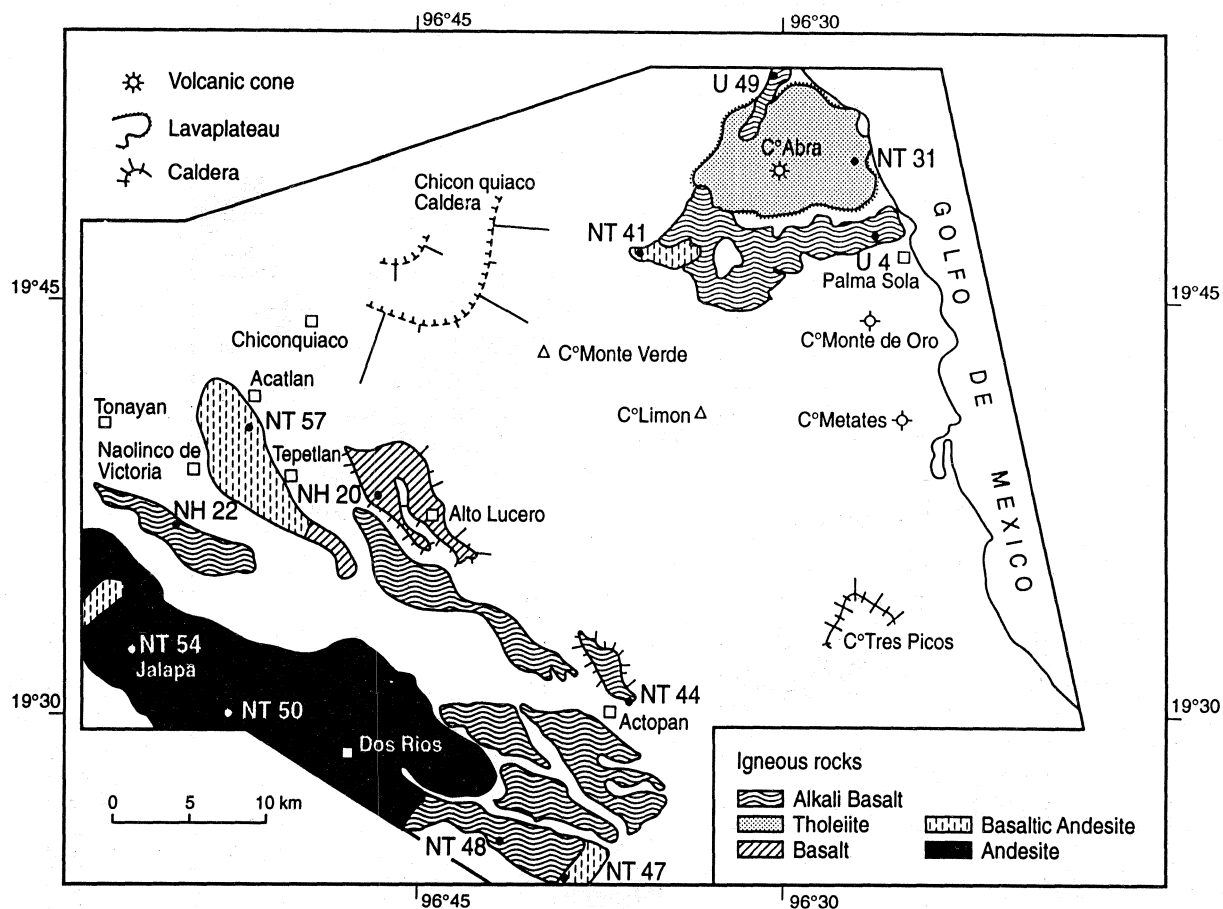


Fig. 3. Simplified geological map of the Jalapa - Chiconquiaco - Palma Sola Area, modified according to Negendank *et al.* (1985).

Additionally, according to Besch *et al.* (1988) all rock types are characterized by high LILE/HFSE ratios and distinct negative anomalies of Nb, Ta and Ti, even for the alkali basalts. This geochemical signature implies a subduction relationship for the volcanics or an involvement of a subduction-modified mantle source region. Typical intraplate volcanics induced by crustal rifting have a Ta, Nb and Ti spike (Wood, 1979). Multi-element diagrams (Figure 4) for primitive basalts and alkali basalts, normalized to average MORB, indicate that the mantle source for the volcanics was LILE-enriched.

### Palma Sola Massif

The volcanism in the Palma Sola Massif (Figure 3) is dominated by alkaline volcanics with subordinate calc-alkaline andesites and dacites. REE patterns (Figure 4) indicate LREE-enrichment in all volcanics with Ce/Yb<sub>n</sub>-ratios varying from 5.8 (basalt) to 9.3 (basaltic andesite) and a flat HREE distribution. Europium anomalies are absent. There is no tendency for the REE concentrations to increase with the degree of fractionation, precluding a cogenetic relationship.

Multi-element diagrams (Figure 4), normalized by using primitive mantle values show distinct negative anomalies

of Nb, Ta and Ti as well as high LILE/HFSE ratios suggesting a subduction relationship. MORB normalized multi-element diagrams (Figure 4) reveal LILE-enrichment for the primitive basalts indicating a LILE-enriched mantle source.

Major element abundances of volcanic rocks from the eastern Trans Mexican Volcanic Belt indicate that the alkaline rocks and basalts were generated by crystal/liquid fractionation processes (Negendank *et al.*, 1985), whereas the andesites, dacites and rhyolites cannot be considered as final products of the same fractionation series.

The trace element patterns of the most primitive basalts were originated by partial melting of spinel-lherzolite (due to the unfractionated HREE) in the mantle wedge overlying the subduction zone whose incompatible element composition was modified by fluids and possibly sediments released from the subduction slab of the Cocos/Rivera plate association. This can even be related to an earlier plate association, e.g. a Paleopacific plate system. These fluids are richer in LILE than in Ta, Nb, Ti and other HFSE (Hole *et al.*, 1984). Another feature suggesting the derivation of magma from the mantle wedge is the depletion of Rb relative to Ba and Sr, as seen in the multi-element normalized

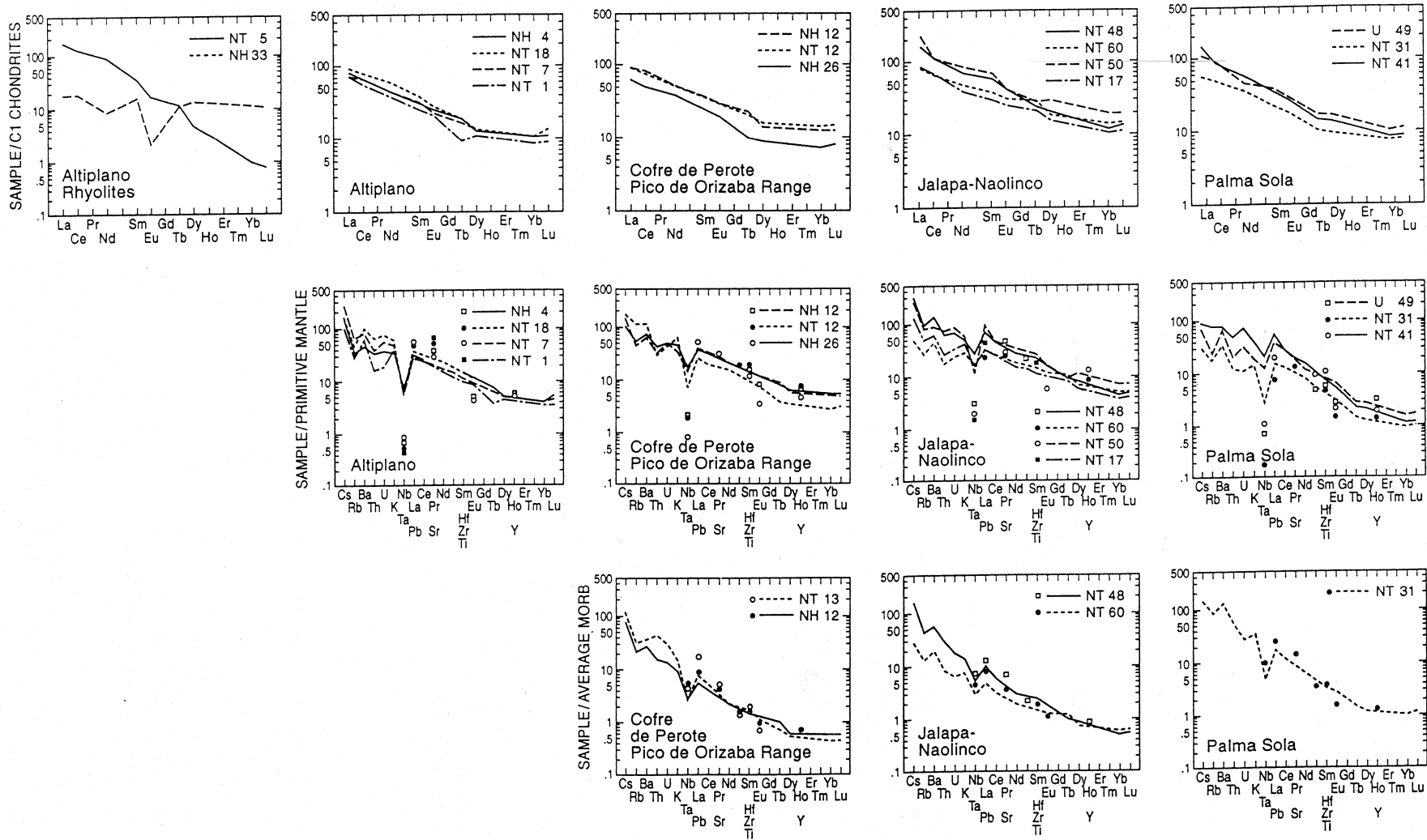


Fig. 4. Multi-element normalized diagrams of REE and trace elements of volcanics of the four geological units: Altiplano Area (Oriental Basin) (Fig. 2), Cofre de Perote -Pico de Orizaba Range (Fig. 2), Jalapa-Naolinco de Victoria Area (Fig. 3), Palma Sola Area (Fig. 3). These plots are modified according to Besch *et al.* (1988). For sample locations, names and concentration data, see Figs. 2 and 3, and Tables 1, 2 and 3.

diagrams, due to the greater incompatibility of Rb to fluids extracted from the downgoing slab (Ellam and Hawkesworth, 1987). This seems to be evident for the alkali basalts because they exhibit geochemical signatures much more similar to arc than intraplate volcanics.

The rhyolites in the eastern TMVB were interpreted as partial melts of the continental crust by Besch *et al.* (1988).

#### $^{87}\text{Sr}/^{86}\text{Sr}$ AND $^{143}\text{Nd}/^{144}\text{Nd}$ ISOTOPE RATIOS

The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of 30 selected samples (25 new and 5 published previously - Tobschall *et al.*, 1984) and  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios of 15 of these samples (10 new and 5 published previously - Tobschall *et al.*, 1984) from the easternmost extension of the TMVB have been determined using the following procedures.

Sr isotope compositions were measured on a 12", 90° sector, NBS design solid source mass spectrometer with on-line data reduction at the Zentrallaboratorium für Geochronologie, Münster. Nd isotope compositions were measured on a Finnigan MAT 261 mass spectrometer at the Max-Planck-Institut für Chemie, Mainz. The procedures used for the Sr isotope determination are given in Kramm *et al.* (1983), those for the Nd-isotopes in White and Patchett (1984), with the difference that a triple collector (in peak-jumping mode) was employed for Nd. Total procedural blanks (1.5 ng Sr and 34 pg Nd) were negligible for this study. The results of these measurements are given in Table 1. All samples are geologically very young (0.01 - 5 Ma) and hence the  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios reported in Table 1 are taken as initial ratios. Table 2 gives the major, trace and REE element abundances of these samples.

The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios for the alkali basalts, basalts, basaltic andesites, andesites and rhyolites of the easternmost extension of the TMVB range from 0.70342 to 0.70511 and are comparable with similar rocks from other areas of the TMVB (Moorbath *et al.*, 1978; Whitford and Bloomfield, 1976; Cantagrel and Robin, 1978; Verma, 1983, 1984, 1994; Verma and Armienta-H., 1985; Verma *et al.*, 1985; Verma and Verma, 1986; McBirney *et al.*, 1987; Mahood and Halliday, 1988; Verma *et al.*, 1991; Verma and Luhr, 1993). For all rock types from the easternmost extension of the TMVB, a discrete range in the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (Table 3) is found.

Our results show that  $^{87}\text{Sr}/^{86}\text{Sr}$  ( $n = 27$ ) is positively correlated with the concentration of  $\text{SiO}_2$  ( $r = 0.808$ ), Rb ( $r = 0.535$ ),  $\text{K}_2\text{O}$  ( $r = 0.557$ ) and negatively with Sr ( $r = -0.672$ ). Even after excluding the rhyolites, which possibly have a larger crustal component, basalts and andesites are characterized by a significant positive correlation of  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\text{SiO}_2$  ( $r = 0.726$ ,  $n = 25$ ). The correlation of

the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios with  $\text{SiO}_2$  (Figure 5) implies that the stratovolcano andesites acquired a crustal component during ascent. This conclusion is also compatible with the combined  $^{143}\text{Nd}/^{144}\text{Nd}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  data. The  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios for the analyzed samples from the easternmost extension of the TMVB range from 0.51250 to 0.51287. There is a significant negative correlation (Figure 6,  $r = -0.858$ ,  $n = 15$ ) between the initial  $^{143}\text{Nd}/^{144}\text{Nd}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios for the analyzed samples. The data define a trend parallel to that of the 'mantle array', and thus no clear influence of interaction with seawater or subducted oceanic crust plus sediments (both processes should result in a shift towards the right of the 'mantle array' (Hawkesworth *et al.*, 1977 and White and Hofmann, 1982) seems to be visible. This, however, holds only if a distinctly different isotope signature is added. In the case of volcanogenic sediments derived from volcanic rocks at a 'young' continental margin, which can be assumed for southern Mexico, this method probably cannot discriminate the addition.

It can be seen from Figure 5 that the Sr isotopic compositions for the different rock types of the easternmost TMVB shows distinct range at fairly constant  $\text{SiO}_2$  values. In other words, there is a 'vertical' variation of  $^{87}\text{Sr}/^{86}\text{Sr}$  against  $\text{SiO}_2$  superimposed on the overall positive correlation mentioned earlier. Furthermore, there is no correlation between the Mg-values and the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios for each specific rock type. These results argue against simple AFC-modelling (DePaolo, 1981) to explain the isotopic variations. Even for the most primitive samples (Mg-values ~ 68) some scatter in the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios is observable suggesting mantle heterogeneities. We tested several end-member possibilities (depleted as well as enriched mantle, based on the trace element data, several crustal model compositions and DSDP sites 487/488 sediments (S.P. VERMA, unpublished data) in simple binary mixing models in which the degree of curvature of predicted hyperbolic curves depends on the ratio of Sr/Nd in the selected end-members (DePaolo and Wasserburg, 1979).

The results of our calculations (Figure 7) are compatible with assimilation of upper crustal material during the uprise and magmatic evolution of the rock types. It should, however, be kept in mind that we do not have information about the composition of the lower crust beneath the easternmost TMVB. Our calculations show that the possibility of sedimentary input cannot be eliminated. The volcanic rocks in the easternmost TMVB are underlain by sedimentary rocks and so we cannot clearly discriminate the source of the sedimentary input, whether the subducted sediments or the underlying sedimentary rocks.

#### CONCLUSIONS

These isotopic data stimulate an intricate petrogenetic model that should include: (i) different heterogeneous mantle reservoirs, (ii) assimilation of continental crust, and probably (iii) recycling of subducted sediments.

Table 1

Isotope and trace element data for the volcanics of the easternmost TMVB

| Sample <sup>+</sup> | Rock type <sup>*</sup>              | SiO <sub>2</sub> | Rb <sup>**</sup> | Sr <sup>**</sup> | <sup>87</sup> Sr/ <sup>86</sup> Sr <sup>***</sup> | <sup>143</sup> Nd/ <sup>144</sup> Nd <sup>****</sup> |
|---------------------|-------------------------------------|------------------|------------------|------------------|---|--|
| NT 44               | alkali basalt                       | 43.5             | 27               | 1111             | 0.70361 ± 8                                       |  |
| U 4                 | alkali basalt                       | 46.7             | 26               | 953              | 0.70364 ± 9                                       |  |
| U 49                | alkali basalt                       | 47.9             | 30               | 838              | 0.70342 ± 9                                       | 0.512866 ± 13  |
| NT 48               | alkali basalt                       | 48.7             | 50               | 858              | 0.70394 ± 4                                       | 0.512842 ± 16  |
| NT 31               | tholeiite                           | 52.2             | 21               | 593              | 0.70424   | 0.512683   |
| NH 22               | basalt                              | 49.6             | 14               | 385              | 0.70346 ± 8                                       |  |
| NT 60               | basalt                              | 49.8             | 14               | 464              | 0.70414 ± 4                                       | 0.512753 ± 19  |
| NH 12               | basalt                              | 50.6             | 21               | 511              | 0.70385 ± 7                                       | 0.512790 ± 17  |
| NH 20               | basalt                              | 52.2             | 96               | 931              | 0.70408 ± 5                                       |  |
| NH 3                | basalt                              | 52.4             | 18               | 548              | 0.70439 ± 3                                       |  |
| NT 13               | basalt                              | 52.8             | 35               | 619              | 0.70393 ± 6                                       |  |
| NT 57               | basaltic<br>andesite                | 52.7             | 16               | 598              | 0.70425 ± 8                                       |  |
| NT 41               | basaltic<br>andesite                | 52.8             | 69               | 868              | 0.70371 ± 7                                       | 0.512816 ± 14  |
| NH 4                | basaltic<br>andesite                | 53.3             | 18               | 701              | 0.70374 ± 6                                       | 0.512621 ± 28  |
| NT 17               | basaltic<br>andesite                | 53.4             | 27               | 525              | 0.70424 ± 6                                       |  |
| NT 12               | basaltic<br>andesite                | 53.4             | 29               | 503              | 0.70415 ± 8                                       | 0.512771 ± 21  |
| NH 5                | basaltic<br>andesite                | 53.7             | 17               | 691              | 0.70392 ± 9                                       |  |
| NT 61               | monogenetic<br>basaltic<br>andesite | 53.9             | 32               | 570              | 0.70405 ± 5                                       |  |
| NT 47               | monogenetic<br>andesite             | 54.4             | 100              | 406              | 0.70429 ± 8                                       |  |
| NT 54               | monogenetic<br>andesite             | 56.3             | 34               | 497              | 0.70443   | 0.512690   |
| NT 18               | monogenetic<br>andesite             | 56.9             | 25               | 899              | 0.70374 ± 6                                       |  |

Table 1 (Cont.)

| Sample <sup>+</sup> | Rock type*             | SiO <sub>2</sub> | Rb** | Sr** | <sup>87</sup> Sr/ <sup>86</sup> Sr*** | <sup>143</sup> Nd/ <sup>144</sup> Nd*** |
|---------------------|------------------------|------------------|------|------|---------------------------------------|---|
| NT 50               | monogenetic andesite   | 57.1             | 45   | 540  | 0.70434 ± 7                           |   |
| NT 11               | monogenetic andesite   | 57.2             | 39   | 484  | 0.70456                               | 0.512613                                |
| NT 27               | monogenetic andesite   | 58.1             | 73   | 528  | 0.70430 ± 6                           |   |
| NT 7                | stratovolcano andesite | 60.6             | 37   | 585  | 0.70473 ± 8                           | 0.512626 ± 14                           |
| NT 23               | stratovolcano andesite | 61.1             | 66   | 427  | 0.70428 ± 7                           |   |
| NT 24               | stratovolcano andesite | 62.1             | 74   | 454  | 0.70421                               | 0.512731                                |
| NH 26               | stratovolcano andesite | 62.6             | 39   | 608  | 0.70488 ± 8                           | 0.512567                                |
| NT 5                | rhyolite               | 71.6             | 100  | 282  | 0.70511 ± 8                           | 0.512496 ± 14                           |
| NH 33               | rhyolite               | 73.9             | 192  | 7    | 0.70506 ± 4                           | 0.512557 ± 17                           |

<sup>+</sup> Sample locations are as follows:

Alkali basalt: NT44 and NT48 from Actopan area (Fig. 3); U4 and U49 from Palma Sola area (Fig. 3).

Tholeiite: NT31 from Palma Sola area (Fig. 3).

Basalt: NH22 from Naolinco de Victoria area (Fig. 3); NT60 from Coatepec area (Fig. 2); NH12 from Saltillo area (Fig. 2); NH20 from Alto Lucero area (Fig. 3); NH3 from Ciudad Serdán - Orizaba area (Fig. 2); NT13 from La Gloria area (Fig. 2).

Basaltic andesite: NT57 from Acatlán area (Fig. 3); NT41 from Palma Sola area (Fig. 3); NH4 and NH5 from Ciudad Serdán - Orizaba area (Fig. 2); NT17 from Cerro Malpais area (Fig. 2); NT12 from Perote area (Fig. 2).

Monogenetic basaltic andesite: NT61 from Coatepec area (Fig. 2).

Monogenetic andesite: NT47 from south of Actopan (Fig. 3); NT54 and NT50 from Jalapa area (Fig. 3); NT18 from Ciudad Serdán area (Fig. 2); NT11 from Cerro Malpais area (Fig. 2); NT27 from Las Vigas area (Fig. 2).

Stratovolcano andesite: NT7 from Cerro Derrumbadas area (Fig. 2); NT23 and NT24 from Cofre de Perote area (Fig. 2); NH26 from Pico de Orizaba area (Fig. 2).

Rhyolite: NT5 from Cerro Derrumbadas area (Fig. 2); NH33 from Cerro Pinto area (Fig. 2).



Table 1 (Cont.)

According to the subdivision of the easternmost TMVB into geological units, proposed by Negendank *et al.* (1985), the samples are distributed as follows:

|  |   |
|--|---|
| The Altiplano area (Oriental Basin):     | NH12, NT13, NH4, NH5, NT17, NT12, NT18, NT11, NT7, NH5 and NH33 (approximately left half area, left of Pico de Orizaba, in Fig. 2). |
| Cofre de Perote - Pico de Orizaba range: | NT60, NH3, NT61, NT27, NT23, NT24 and NH26 (right half area in Fig. 2).   |
| Jalapa - Naolinco area:                  | NT44, NT48, NH22, NH20, NT57, NT47, NT54 and NT50 (left half area in Fig. 3).   |
| Palma Sola Massif:                       | U4, U49, NT31 and NT41 (right half area in Fig. 3).   |

\* The classification is based on a  $K_2O-SiO_2$  diagram (Negendank *et al.*, 1985; Peccerillo and Taylor, 1976).

\*\* Measured by XRF (Cherry *et al.*, 1967, 1970); the total propagated analytical errors range as follows  $SiO_2 = 0.5$  rel. %, Rb and Sr = 5 rel. %

\*\*+ The  $^{87}Sr/^{86}Sr$  ratios are normalized to  $^{86}Sr/^{88}Sr = 0.11940$  and adjusted to SRM 987  $^{87}Sr/^{86}Sr$  ratio of 0.71014. The measured ratio for the SRM standard was  $0.71041 \pm 0.00004$  during the period of study. The errors for the Sr isotopic ratios are expressed as two standard deviations of the mean.

\*\*\* The  $^{143}Nd/^{144}Nd$  ratios are normalized to  $^{146}Nd/^{144}Nd = 0.72190$ . The measured value for the La Jolla Standard was  $0.511833 \pm 0.000012$  (n = 82) during the period of study.

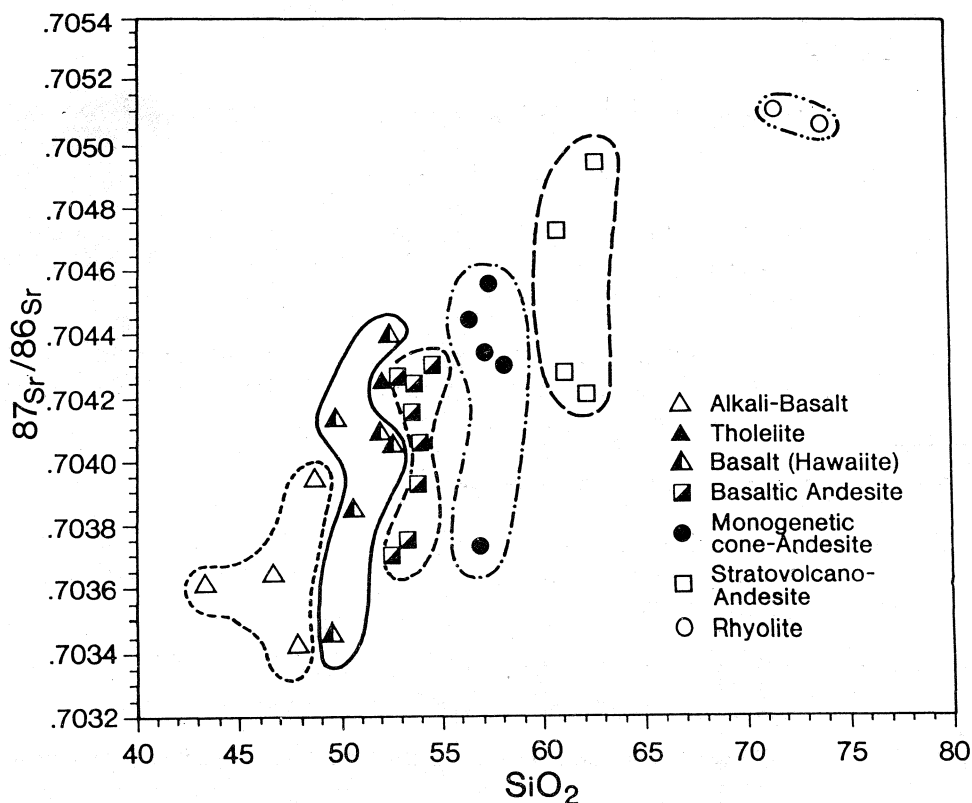


Fig. 5.  $^{87}Sr/^{86}Sr$  versus  $SiO_2$  for the volcanics of the eastern TMVB.

Table 2

Major, trace and REE element abundances (according to Negendank *et al.*, 1985) of selected samples from the eastern Trans-Mexican Volcanic Belt

|                                | NH 33        | NT 5          | NT 1          | NH 26         | NT 24         |
|--------------------------------|--------------|---------------|---------------|---------------|---------------|
| SiO <sub>2</sub>               | 73,9         | 71,6          | 63,1          | 62,6          | 62,1          |
| TiO <sub>2</sub>               | 0,03         | 0,15          | 0,72          | 0,66          | 0,92          |
| Al <sub>2</sub> O <sub>3</sub> | 14,0         | 15,7          | 17,1          | 18,1          | 16,6          |
| Fe <sub>2</sub> O <sub>3</sub> | 0,2          | 1,45          | 4,47          | 2,09          | 2,32          |
| FeO                            | 0,49         | 0,92          | 0,19          | 2,77          | 2,73          |
| MnO                            | 0,14         | 0,04          | 0,08          | 0,08          | 0,08          |
| MgO                            | 0,09         | 0,28          | 2,42          | 2,35          | 3,15          |
| CaO                            | 0,49         | 1,81          | 5,86          | 4,44          | 5,38          |
| Na <sub>2</sub> O              | 4,47         | 4,62          | 4,13          | 4,63          | 3,89          |
| K <sub>2</sub> O               | 4,09         | 3,44          | 1,3           | 1,89          | 2,68          |
| P <sub>2</sub> O <sub>5</sub>  | 0,04         | 0,08          | 0,25          | 0,19          | 0,23          |
| H <sub>2</sub> O+              | 2,0          | 0,07          | 0,25          | 0,26          | 0,31          |
| CO <sub>2</sub>                | 0,03         | 0,08          | 0,24          | 0,15          | 0,05          |
| <b>Sum</b>                     | <b>99,97</b> | <b>100,24</b> | <b>100,11</b> | <b>100,21</b> | <b>100,44</b> |
| Cr                             | 4            | 4             | 15            | 14            | 44            |
| Co                             | < 1          | 3             | 9             | 12            | 14            |
| Ni                             | 5            | 4             | 10            | 8             | 30            |
| Cu                             | <1           | 2             | 13            | 19            | 28            |
| Zn                             | 46           | 68            | 57            | 58            | 59            |
| Rb                             | 192          | 100           | 16            | 39            | 74            |
| Sr                             | 22           | 275           | 1125          | 598           | 454           |
| Y                              | 24           | 9             | 20            | 18            | 22            |
| Zr                             | 667          | 150           | 54            | 109           | 209           |
| Nb                             | 23           | 14            | 4             | 5             | 16            |
| Ba                             | < 50         | 898           | 409           | 712           | 611           |
| La                             |              | 25            | 16            | 11            | 25            |
| Ce                             | 10           | 75            | 36            | 29            | 53            |
| Pb                             | 19           | 17            | 6             | 9             | 12            |
| Th                             | 7            | 10            | 2             | 1             | 12            |
| La                             |              |               | <b>19</b>     | <b>16</b>     |               |
| Ce                             |              |               | <b>36</b>     | <b>31</b>     |               |
| Nd                             |              |               | <b>18</b>     | <b>18</b>     |               |
| Sm                             |              |               | <b>3,9</b>    | <b>3,8</b>    |               |
| Eu                             |              |               | <b>1,2</b>    | <b>1,1</b>    |               |
| Tb                             |              |               | <b>0,36</b>   | <b>0,36</b>   |               |
| Dy                             |              |               | <b>2,9</b>    | <b>2,2</b>    |               |
| Yb                             |              |               | <b>1,4</b>    | <b>1,2</b>    |               |
| Lu                             |              |               | <b>0,23</b>   | <b>0,2</b>    |               |
| Sc                             |              |               | <b>8</b>      | <b>9</b>      |               |
| Cs                             |              |               | <b>0,7</b>    | <b>1,1</b>    |               |
| Hf                             |              |               | <b>3,4</b>    | <b>3,3</b>    |               |
| Th                             |              |               | <b>2</b>      | <b>2,6</b>    |               |
| U                              |              |               | <b>0,4</b>    | <b>1</b>      |               |
| Ta                             |              |               | <b>0,2</b>    | <b>0,3</b>    |               |

Table 2 (Cont.)

|                                | NT 23         | NT 7          | NT 27        | NT 11        | NT 50         |
|--------------------------------|---------------|---------------|--------------|--------------|---------------|
| SiO <sub>2</sub>               | 61,1          | 60,6          | 58,1         | 57,2         | 57,1          |
| TiO <sub>2</sub>               | 1,09          | 0,85          | 1,03         | 1,13         | 1,08          |
| Al <sub>2</sub> O <sub>3</sub> | 16,4          | 18,1          | 16,5         | 16,6         | 17,0          |
| Fe <sub>2</sub> O <sub>3</sub> | 1,99          | 1,75          | 2,68         | 1,34         | 4,73          |
| FeO                            | 3,96          | 3,57          | 3,67         | 5,36         | 2,5           |
| MnO                            | 0,1           | 0,09          | 0,01         | 0,11         | 0,12          |
| MgO                            | 2,73          | 2,82          | 3,96         | 5,0          | 4,36          |
| CaO                            | 5,04          | 5,9           | 6,68         | 6,57         | 7,04          |
| Na <sub>2</sub> O              | 4,05          | 4,23          | 3,82         | 3,87         | 3,73          |
| K <sub>2</sub> O               | 2,57          | 1,65          | 2,4          | 1,76         | 1,8           |
| P <sub>2</sub> O <sub>5</sub>  | 0,27          | 0,22          | 0,27         | 0,37         | 0,29          |
| H <sub>2</sub> O <sup>+</sup>  | 0,89          | 0,22          | 0,38         | 0,38         | 0,59          |
| CO <sub>2</sub>                | 0,05          | 0,04          | 0,26         | 0,15         | 0,05          |
| <b>Sum</b>                     | <b>100,24</b> | <b>100,04</b> | <b>99,76</b> | <b>99,84</b> | <b>100,39</b> |
| Cr                             | 26            | 24            | 86           | 119          | 86            |
| Co                             | 16            | 14            | 18           | 25           | 20            |
| Ni                             | 13            | 9             | 21           | 67           | 30            |
| Cu                             | 15            | 11            | 23           | 26           | 33            |
| Zn                             | 70            | 61            | 65           | 79           | 74            |
| Rb                             | 66            | 39            | 74           | 39           | 47            |
| Sr                             | 413           | 578           | 503          | 484          | 527           |
| Y                              | 25            | 21            | 25           | 25           | 48            |
| Zr                             | 222           | 139           | 207          | 190          | 185           |
| Nb                             | 13            | 4             | 13           | 12           | 8             |
| Ba                             | 685           | 507           | 598          | 548          | 526           |
| La                             | 17            | 7             | 20           | 16           | 43            |
| Ce                             | 53            | 30            | 67           | 48           | 76            |
| Pb                             | 11            | 9             | 12           | 6            | 9             |
|                                | 9             | 3             | 14           | < 1          | 8             |
| La                             |               | <b>18</b>     |              |              | <b>54</b>     |
| Ce                             |               | <b>40</b>     |              |              | <b>72</b>     |
| Nd                             |               | <b>21</b>     |              |              | <b>40</b>     |
| Sm                             |               | <b>4,6</b>    |              |              | <b>10,6</b>   |
| Eu                             |               | <b>1,3</b>    |              |              | <b>2,4</b>    |
| Tb                             |               | <b>0,61</b>   |              |              | <b>1</b>      |
| Dy                             |               | <b>3,4</b>    |              |              | <b>7,4</b>    |
| Yb                             |               | <b>1,7</b>    |              |              | <b>3,2</b>    |
| Lu                             |               | <b>0,27</b>   |              |              | <b>0,48</b>   |
| Sc                             |               | <b>12</b>     |              |              | <b>18</b>     |
| Cs                             |               | <b>1,9</b>    |              |              | <b>1,8</b>    |
| Hf                             |               | <b>4,3</b>    |              |              | <b>4,7</b>    |
| Th                             |               | <b>3,5</b>    |              |              | <b>6,1</b>    |
| U                              |               | <b>1,2</b>    |              |              | <b>1,8</b>    |
| Ta                             |               | <b>0,35</b>   |              |              | <b>0,6</b>    |

Table 2 (Cont.)

|                                | NT 18         | NT 54        | NT 47         | NT 61         | NH 5          |
|--------------------------------|---------------|--------------|---------------|---------------|---------------|
| SiO <sub>2</sub>               | 56,9          | 56,3         | 54,4          | 53,9          | 53,7          |
| TiO <sub>2</sub>               | 0,95          | 1,06         | 2,16          | 1,55          | 0,97          |
| Al <sub>2</sub> O <sub>3</sub> | 15,8          | 16,5         | 15,9          | 17,8          | 15,7          |
| Fe <sub>2</sub> O <sub>3</sub> | 2,63          | 3,69         | 6,56          | 6,02          | 2,39          |
| FeO                            | 4,03          | 3,07         | 3,19          | 2,54          | 5,08          |
| MnO                            | 0,11          | 0,11         | 0,13          | 0,13          | 0,12          |
| MgO                            | 5,64          | 5,88         | 3,15          | 4,4           | 8,69          |
| CaO                            | 8,28          | 7,04         | 6,15          | 7,73          | 8,71          |
| Na <sub>2</sub> O              | 3,44          | 3,74         | 4,05          | 3,93          | 3,11          |
| K <sub>2</sub> O               | 1,77          | 1,53         | 2,94          | 1,56          | 1,14          |
| P <sub>2</sub> O <sub>5</sub>  | 0,27          | 0,27         | 1,02          | 0,37          | 0,25          |
| H <sub>2</sub> O <sup>+</sup>  | 0,51          | 0,57         | 0,32          | 0,35          | 0,25          |
| CO <sub>2</sub>                | 0,05          | 0,04         | 0,07          | 0,08          | 0,05          |
| <b>Sum</b>                     | <b>100,38</b> | <b>99,80</b> | <b>100,04</b> | <b>100,36</b> | <b>100,16</b> |
| Cr                             | 102           | 161          | 24            | 29            | 318           |
| Co                             | 22            | 23           | 27            | 27            | 27            |
| Ni                             | 24            | 93           | 23            | 30            | 91            |
| Cu                             | 36            | 29           | 96            | 34            | 51            |
| Zn                             | 71            | 72           | 104           | 88            | 70            |
| Rb                             | 26            | 34           | 100           | 34            | 18            |
| Sr                             | 861           | 497          | 403           | 546           | 666           |
| Y                              | 22            | 21           | 54            | 28            | 23            |
| Zr                             | 92            | 156          | 538           | 200           | 93            |
| Nb                             | 4             | 13           | 31            | 15            | 5             |
| Ba                             | 464           | 459          | 778           | 437           | 287           |
| La                             | 13            | 16           | 38            | 22            | 10            |
| Ce                             | 40            | 50           | 110           | 54            | 34            |
| Pb                             | 8             | 8            | 21            | 8             | 5             |
| Th                             | 4             | 3            | 21            | 5             | 1             |
| La                             | <b>22</b>     |              |               |               |               |
| Ce                             | <b>40</b>     |              |               |               |               |
| Nd                             | <b>28</b>     |              |               |               |               |
| Sm                             | <b>5,8</b>    |              |               |               |               |
| Eu                             | <b>1,6</b>    |              |               |               |               |
| Tb                             | <b>0,7</b>    |              |               |               |               |
| Dy                             | <b>3,5</b>    |              |               |               |               |
| Yb                             | <b>1,8</b>    |              |               |               |               |
| Lu                             | <b>0,34</b>   |              |               |               |               |
| Sc                             | <b>23</b>     |              |               |               |               |
| Cs                             | <b>1,1</b>    |              |               |               |               |
| Hf                             | <b>4,4</b>    |              |               |               |               |
| Th                             | <b>5,5</b>    |              |               |               |               |
| U                              | <b>1,6</b>    |              |               |               |               |
| Ta                             | <b>0,22</b>   |              |               |               |               |

Table 2 (Cont.)

|                                | NT 12         | NT 17         | NH 4          | NT 41        | NT 13         |
|--------------------------------|---------------|---------------|---------------|--------------|---------------|
| SiO <sub>2</sub>               | 53,4          | 53,4          | 53,3          | 52,8         | 52,8          |
| TiO <sub>2</sub>               | 1,48          | 1,37          | 0,97          | 1,92         | 1,09          |
| Al <sub>2</sub> O <sub>3</sub> | 18,1          | 16,5          | 15,7          | 17,7         | 16,2          |
| Fe <sub>2</sub> O <sub>3</sub> | 1,58          | 1,5           | 2,55          | 6,41         | 1,48          |
| FeO                            | 6,68          | 6,5           | 4,99          | 2,72         | 5,94          |
| MnO                            | 0,13          | 0,13          | 0,12          | 0,16         | 0,13          |
| MgO                            | 4,66          | 7,13          | 9,01          | 2,88         | 8,58          |
| CaO                            | 8,24          | 7,77          | 8,81          | 6,64         | 8,45          |
| Na <sub>2</sub> O              | 3,69          | 3,67          | 3,03          | 4,64         | 3,1           |
| K <sub>2</sub> O               | 1,41          | 1,35          | 1,12          | 2,53         | 1,65          |
| P <sub>2</sub> O <sub>5</sub>  | 0,33          | 0,36          | 0,25          | 0,77         | 0,40          |
| H <sub>2</sub> O+              | 0,33          | 0,44          | 0,37          | 0,54         | 0,33          |
| CO <sub>2</sub>                | 0,04          | 0,19          | 0,05          | 0,05         | 0,19          |
| <b>Sum</b>                     | <b>100,07</b> | <b>100,31</b> | <b>100,27</b> | <b>99,76</b> | <b>100,34</b> |
| Cr                             | 49            | 213           | 341           | 13           | 378           |
| Co                             | 27            | 29            | 28            | 24           | 29            |
| Ni                             | 29            | 105           | 105           | 7            | 163           |
| Cu                             | 34            | 35            | 31            | 25           | 55            |
| Zn                             | 83            | 81            | 74            | 87           | 73            |
| Rb                             | 31            | 27            | 18            | 74           | 35            |
| Sr                             | 488           | 515           | 673           | 847          | 595           |
| Y                              | 29            | 26            | 23            | 35           | 25            |
| Zr                             | 185           | 167           | 94            | 290          | 177           |
| Nb                             | 11            | 11            | 5             | 34           | 10            |
| Ba                             | 395           | 427           | 279           | 861          | 598           |
| La                             | 10            | 16            | 11            | 32           | 25            |
| Ce                             | 38            | 48            | 31            | 101          | 70            |
| Pb                             | 6             | 7             | 6             | 8            | 8             |
| Th                             | 4             | 3             | 2             | 9            | 9             |
| La                             | <b>22</b>     | <b>21</b>     | <b>20</b>     | <b>62</b>    | <b>31</b>     |
| Ce                             | <b>48</b>     | <b>41</b>     | <b>40</b>     | <b>95</b>    | <b>60</b>     |
| Nd                             | <b>24</b>     | <b>18</b>     | <b>21</b>     | <b>40</b>    | <b>24</b>     |
| Sm                             | <b>5,5</b>    | <b>4,5</b>    | <b>4,7</b>    | <b>8</b>     | <b>5,9</b>    |
| Eu                             | <b>1,6</b>    | <b>1,4</b>    | <b>1,4</b>    | <b>2</b>     | <b>1,5</b>    |
| Tb                             | <b>0,78</b>   | <b>0,8</b>    | <b>0,68</b>   | <b>2,3</b>   | <b>0,6</b>    |
| Dy                             | <b>4</b>      | <b>4</b>      | <b>3,3</b>    | <b>0,92</b>  | <b>3,5</b>    |
| Yb                             | <b>2,3</b>    | <b>1,8</b>    | <b>1,8</b>    | <b>6,1</b>   | <b>1,7</b>    |
| Lu                             | <b>0,37</b>   | <b>0,28</b>   | <b>0,28</b>   | <b>2,6</b>   | <b>0,27</b>   |
| Sc                             | <b>21</b>     | <b>19</b>     | <b>26</b>     | <b>0,4</b>   | <b>22</b>     |
| Cs                             | <b>0,7</b>    | <b>0,9</b>    | <b>1</b>      |              | <b>1,5</b>    |
| Hf                             | <b>4,9</b>    | <b>3,9</b>    | <b>3,3</b>    |              | <b>4,3</b>    |
| Th                             | <b>3,5</b>    | <b>2,3</b>    | <b>2,9</b>    |              | <b>8</b>      |
| U                              | <b>1</b>      | <b>0,7</b>    | <b>0,8</b>    |              | <b>2,2</b>    |
| Ta                             | <b>0,8</b>    | <b>0,6</b>    | <b>0,28</b>   |              | <b>0,7</b>    |

Table 2 (Cont.)

|                                | NT 60         | NH 22         | NT 48        | U 49         | U 4          | NT 44        |
|--------------------------------|---------------|---------------|--------------|--------------|--------------|--------------|
| SiO <sub>2</sub>               | 49,80         | 49,60         | 48,70        | 47,90        | 46,70        | 43,50        |
| TiO <sub>2</sub>               | 1,89          | 1,60          | 1,85         | 2,21         | 2,39         | 1,50         |
| Al <sub>2</sub> O <sub>3</sub> | 16,40         | 16,60         | 17,20        | 17,10        | 15,40        | 13,60        |
| Fe <sub>2</sub> O <sub>3</sub> | 7,73          | 1,80          | 8,84         | 9,29         | 8,54         | 4,57         |
| FeO                            | 3,75          | 8,37          | 1,49         | 1,99         | 3,03         | 4,89         |
| MnO                            | 0,17          | 0,16          | 0,15         | 0,25         | 0,17         | 0,17         |
| MgO                            | 6,87          | 7,82          | 5,68         | 4,83         | 5,85         | 10,50        |
| CaO                            | 8,45          | 9,67          | 9,75         | 9,35         | 10,30        | 14,30        |
| Na <sub>2</sub> O              | 3,34          | 3,45          | 3,22         | 3,47         | 3,33         | 2,88         |
| K <sub>2</sub> O               | 0,93          | 0,71          | 1,66         | 1,45         | 1,27         | 0,57         |
| P <sub>2</sub> O <sub>5</sub>  | 0,39          | 0,27          | 0,64         | 0,75         | 0,72         | 0,87         |
| H <sub>2</sub> O+              | 0,68          | 0,18          | 0,39         | 0,97         | 0,96         | 2,20         |
| CO <sub>2</sub>                | 0,04          | 0,08          | 0,07         | 0,05         | 0,58         | 0,10         |
| <b>Sum</b>                     | <b>100,44</b> | <b>100,31</b> | <b>99,64</b> | <b>99,61</b> | <b>99,24</b> | <b>99,65</b> |
| Cr                             | 229           | 255           | 110          | 100          | 244          | 303          |
| Co                             | 45            | 41            | 36           | 43           | 42           | 39           |
| Ni                             | 118           | 95            | 38           | 51           | 120          | 143          |
| Cu                             | 46            | 55            | 37           | 43           | 49           | 18           |
| Zn                             | 109           | 87            | 92           | 89           | 87           | 78           |
| Rb                             | 15            | 14            | 50           | 30           | 26           | 27           |
| Sr                             | 455           | 381           | 823          | 828          | 934          | 1071         |
| Y                              | 33            | 29            | 32           | 49           | 29           | 29           |
| Zr                             | 181           | 144           | 214          | 183          | 167          | 125          |
| Nb                             | 11            | 9             | 18           | 23           | 28           | 65           |
| Ba                             | 283           | 189           | 803          | 739          | 538          | 1045         |
| La                             | 11            | 5             | 23           | 46           | 26           | 49           |
| Ce                             | 34            | 25            | 68           | 109          | 80           | 141          |
| Pb                             | 4             | 2             | 7            | 4            | 4            | 8            |
| Th                             | < 1           | < 1           | 6            | 4            | 4            | 14           |
| La                             | <b>20</b>     |               | <b>40</b>    |              |              |              |
| Ce                             | <b>41</b>     |               | <b>71</b>    |              |              |              |
| Nd                             | <b>22</b>     |               | <b>34</b>    |              |              |              |
| Sm                             | <b>5,7</b>    |               | <b>9</b>     |              |              |              |
| Eu                             | <b>1,7</b>    |               | <b>2,3</b>   |              |              |              |
| Tb                             | <b>1</b>      |               | <b>0,9</b>   |              |              |              |
| Dy                             | <b>4,7</b>    |               | <b>5,3</b>   |              |              |              |
| Yb                             | <b>2,3</b>    |               | <b>2</b>     |              |              |              |
| Lu                             | <b>0,36</b>   |               | <b>0,33</b>  |              |              |              |
| Sc                             | <b>23</b>     |               | <b>23</b>    |              |              |              |
| Cs                             | <b>0,3</b>    |               | <b>2,1</b>   |              |              |              |
| Hf                             | <b>4,2</b>    |               | <b>6,3</b>   |              |              |              |
| Th                             | <b>1,6</b>    |               | <b>5,5</b>   |              |              |              |
| U                              | <b>0,5</b>    |               | <b>1,4</b>   |              |              |              |
| Ta                             | <b>0,7</b>    |               | <b>1,2</b>   |              |              |              |

Table 2 (Cont.)

|                                | NT 57         | NH 3          | NH 20        | NT 31         | NH 12         |
|--------------------------------|---------------|---------------|--------------|---------------|---------------|
| SiO <sub>2</sub>               | 52,7          | 52,4          | 52,2         | 52,2          | 50,6          |
| TiO <sub>2</sub>               | 1,26          | 0,90          | 1,36         | 1,37          | 1,49          |
| Al <sub>2</sub> O <sub>3</sub> | 18,0          | 16,1          | 16,5         | 16,9          | 15,9          |
| Fe <sub>2</sub> O <sub>3</sub> | 5,57          | 2,90          | 3,58         | 3,75          | 3,16          |
| FeO                            | 2,55          | 5,02          | 4,01         | 4,47          | 6,13          |
| MnO                            | 0,13          | 0,13          | 0,14         | 0,14          | 0,15          |
| MgO                            | 5,74          | 8,94          | 6,03         | 5,33          | 8,38          |
| CaO                            | 8,58          | 8,96          | 7,8          | 9,56          | 9,2           |
| Na <sub>2</sub> O              | 3,73          | 3,39          | 3,41         | 3,60          | 3,41          |
| K <sub>2</sub> O               | 1,1           | 1,1           | 3,24         | 1,17          | 1,09          |
| P <sub>2</sub> O <sub>5</sub>  | 0,34          | 0,20          | 0,58         | 0,33          | 0,35          |
| H <sub>2</sub> O+              | 0,50          | 0,29          | 0,77         | 0,37          | 0,13          |
| CO <sub>2</sub>                | 0,07          | 0,05          | 0,08         | 0,98          | 0,15          |
| <b>Sum</b>                     | <b>100,27</b> | <b>100,38</b> | <b>99,70</b> | <b>100,17</b> | <b>100,14</b> |
| Cr                             | 119           | 309           | 242          | 86            | 327           |
| Co                             | 26            | 32            | 24           | 26            | 34            |
| Ni                             | 63            | 142           | 102          | 44            | 128           |
| Cu                             | 33            | 56            | 46           | 35            | 47            |
| Zn                             | 82            | 74            | 85           | 82            | 76            |
| Rb                             | 18            | 18            | 96           | 21            | 21            |
| Sr                             | 584           | 521           | 906          | 593           | 500           |
| Y                              | 27            | 21            | 34           | 27            | 26            |
| Zr                             | 170           | 89            | 325          | 160           | 146           |
| Nb                             | 12            | 4             | 38           | 8             | 10            |
| Ba                             | 465           | 438           | 1384         | 444           | 302           |
| La                             | 12            | 9             | 48           | 13            | 10            |
| Ce                             | 49            | 29            | 126          | 43            | 37            |
| Pb                             | 6             | 7             | 12           | 4             | 4             |
| Th                             | 3             | 2             | 15           | < 1           | 2             |
| La                             |               |               |              | <b>24</b>     | <b>22</b>     |
| Ce                             |               |               |              | <b>55</b>     | <b>50</b>     |
| Nd                             |               |               |              | <b>30</b>     | <b>24</b>     |
| Sm                             |               |               |              | <b>6</b>      | <b>5,3</b>    |
| Eu                             |               |               |              | <b>1,8</b>    | <b>1,7</b>    |
| Tb                             |               |               |              | <b>0,69</b>   | <b>0,83</b>   |
| Dy                             |               |               |              | <b>4,2</b>    | <b>3,7</b>    |
| Yb                             |               |               |              | <b>2,4</b>    | <b>2,2</b>    |
| Lu                             |               |               |              | <b>0,38</b>   | <b>0,32</b>   |
| Sc                             |               |               |              |               | <b>29</b>     |
| Cs                             |               |               |              |               | <b>1</b>      |
| Hf                             |               |               |              |               | <b>4,6</b>    |
| Th                             |               |               |              |               | <b>2,8</b>    |
| U                              |               |               |              |               | <b>1</b>      |
| Ta                             |               |               |              |               | <b>0,8</b>    |

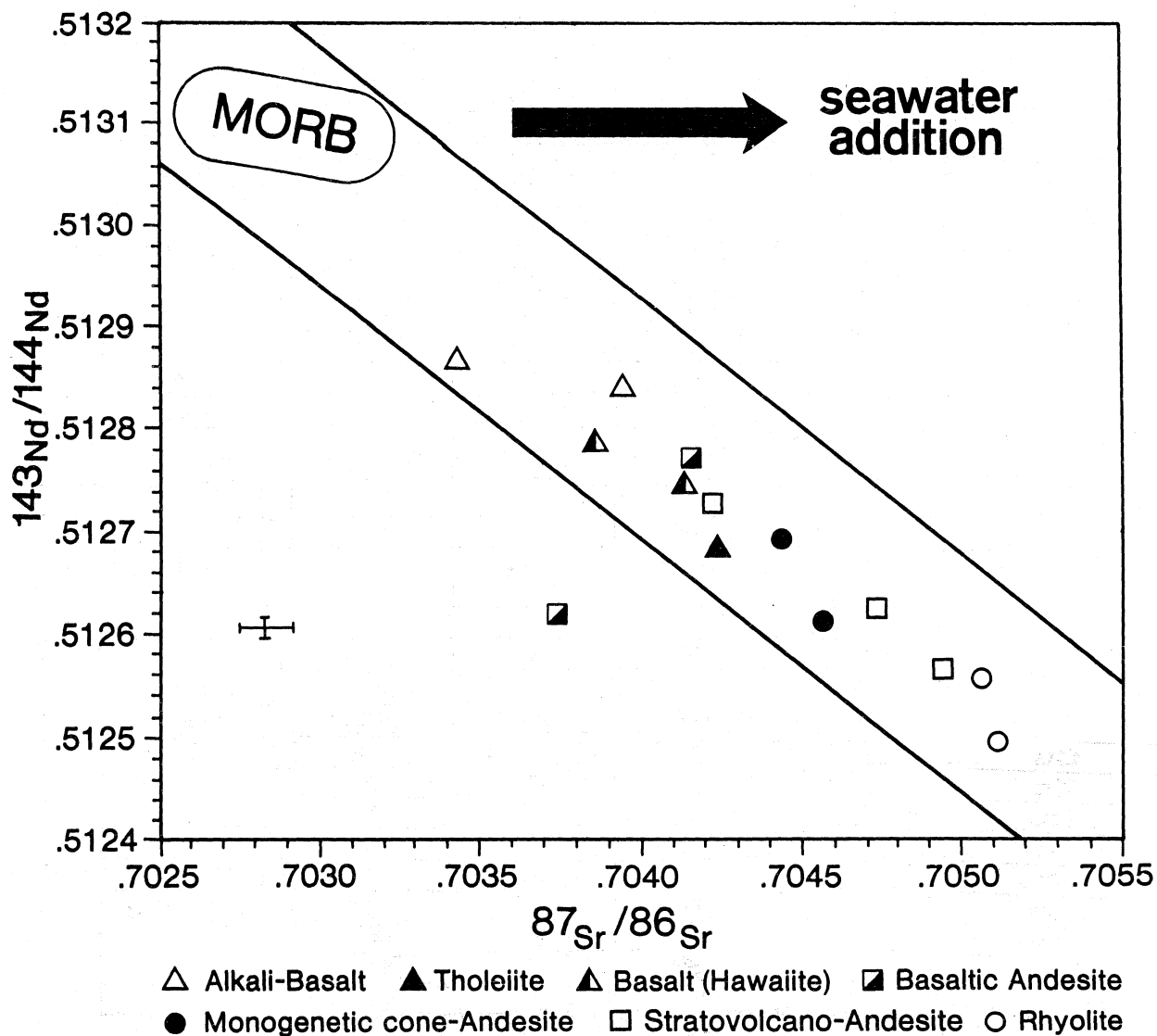


Fig. 6.  $^{143}\text{Nd}/^{144}\text{Nd}$  versus  $^{87}\text{Sr}/^{86}\text{Sr}$ . The solid lines envelop the 'mantle array' (using the average values from Zindler *et al.*, 1982), TMVB data are plotted.

Table 3

Sr isotopic variation for the easternmost TMVB

|                         |                           |
|-------------------------|---------------------------|
| alkali basalts          | 0.70342 - 0.70394 (n = 4) |
| basalts                 | 0.70346 - 0.70439 (n = 6) |
| basaltic andesites      | 0.70370 - 0.70429 (n = 8) |
| monogenetic andesites   | 0.70374 - 0.70456 (n = 5) |
| stratovolcano andesites | 0.70421 - 0.70488 (n = 5) |
| rhyolites               | 0.70506 - 0.70511 (n = 2) |



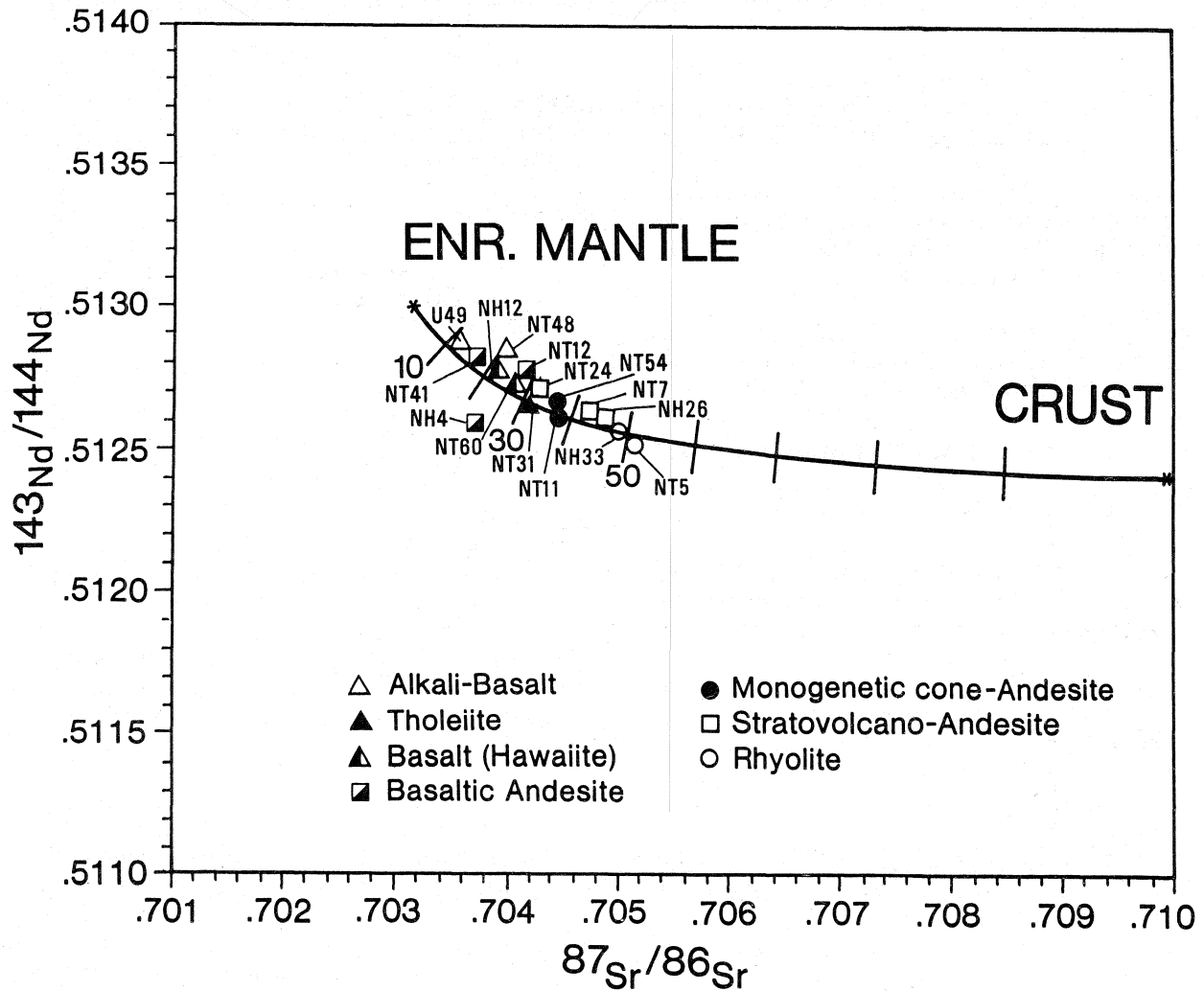


Fig. 7. Two component mixing model for the eastern TMVB, assuming  $(\text{Sr}/\text{Nd})_{\text{EM}}/(\text{Sr}/\text{Nd})_{\text{CC}} = 3$  (EM = enriched mantle component; CC = crustal component). Estimates of the isotope ratios of the crustal end-member are based on S.P. VERMA's unpublished data.

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