Geof. Int., Vol. 27-4, 1988, pp. 641-663

GEOCHEMICAL CONSTRAINTS ON THE ORIGIN OF CALCALKALINE AND ALKALINE MAGMAS OF THE EASTERN TRANS-MEXICAN VOLCANIC BELT

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(Received: February 11, 1988)
(Accepted: October 5, 1988)

RESUMEN

Se presentan datos de elementos mayores, elementos trazas y tierras raras de rocas calco-alcalinas y alcalinas de la parte este del cinturón volcánico transmexicano (TMVB), así como conclusiones acerca de su origen y de su significado tectónico.

Las andesitas y dacitas muestran características geoquímicas que descartan su derivación de los magmas basálticos por el proceso de cristalización fraccionada.

Las distribuciones gráficas de los elementos LIL y HFS son interpretadas como indicadoras de la formación de magmas en el manto superior modificado por procesos de subducción.

Las riolitas se interpretan como resultado de la fusión parcial de la corteza continental.

ABSTRACT

This paper presents major, trace and rare earth element data for calcalkaline and alkaline rocks from the eastern Trans-Mexican Volcanic Belt (TMVB) and speculates upon their origin and geotectonic significance.

Andesites and dacites show geochemical characteristics that preclude their derivation from the basaltic magmas by crystal fractionation. The distribution patterns of the LIL-and HFS-elements are interpreted as indicative of magma formation in a subduction-modified upper mantle. The rhyolites are interpreted as partial melts of the continental crust.

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INTRODUCTION

It is still a point of debate whether the volcanic rocks of the easternmost extension of the Trans-Mexican Volcanic Belt (TMVB) are products of two different volcanic provinces.

According to Robin (1976, 1981) and Demant (1981) the calcalkaline association of the E-W trending TMVB and the N-S oriented alkaline province are overlapping.

Other investigators (*e.g.* Negendank *et al.*, 1985 and Besch *et al.*, 1987) favour the hypothesis that all rock types of the eastern TMVB are subduction related (Fig. 1).

The eastern TMVB is divided into four geological units, following Negendank *et al.* (1985), which from W to E are: the Cofre de Perote-Pico de Orizaba Range, the Altiplano Area (Oriental Basin), the Jalapa-Naolinco Area, and the Palma-Sola Massif. The volcanic rocks of the eastern TMVB are classified as alkalibasalts, "hawaiites", basalts, andesites, basaltic andesites, dacites and rhyolites, belonging to the alkaline, calcalkaline, high-K and shoshonitic series following the scheme of Peccerillo and Taylor (1976).

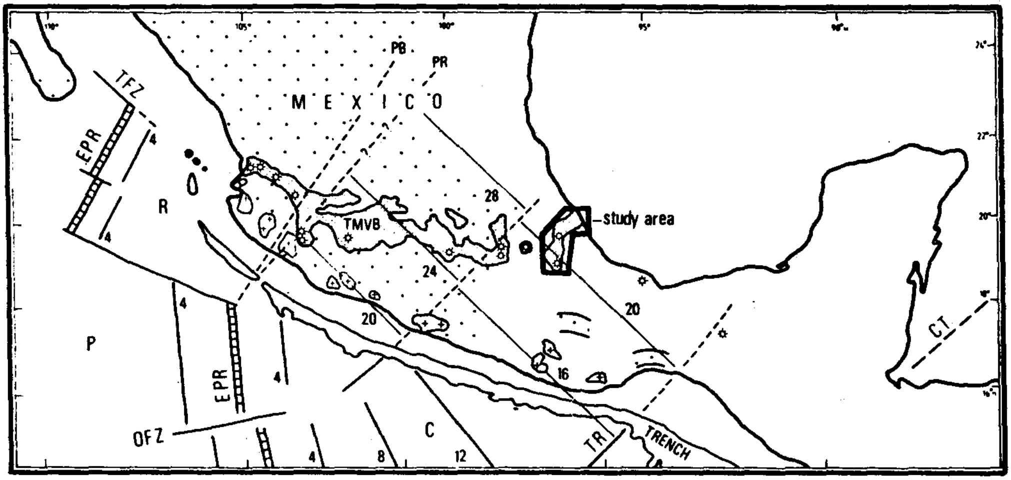

Fig. 1. Study area in context to the Trans-Mexican Volcanic Belt (TMVB) according to Negendank *et al.* 1985. C = Cocos plate, CT = Cayman trough, EPR = East Pacific Rise, P = Pacific plate, R = Rivera plate, PB = transform boundary between Rivera and Cocos plates (predicted), PR = trend of a proto-Rivera fracture zone if one was indeed present in the subducted plate, TMVB = Trans-Mexican Volcanic Belt, TFZ = Tamayo fracture zone, TR = Tehuantepec ridge.

"Hawaiites are foid-free basalts without normative nepheline and were classified as "hawaiites" according to their normative andesine contents (Ab/An ratio) to accentuate their transitional character.

Additionally, the andesites are divided into basaltic, monogenetic and stratovolcano andesites (Negendank *et al.*, 1985).

ANALYTICAL METHODS

All samples were split in a crusher fitted with cast iron jaws to pass a 30 mesh sieve and grounded in an automatic agate mortar to pass a 120 mesh nylon screen.

Major and trace element concentrations were determined by X-ray fluorescence spectrometry. The detailed experimental procedure is given by Tobschall (1975) and Negendank *et al.* (1985). Rare earth elements Ta, Hf, Th, U and Cs were determined by neutron activation analysis using the technique described by Wänke *et al.* (1977).

Accuracy and precision range as follows. Major elements: ± 0.5% except Na_2O and P_2O_5 ± 1%; trace elements, XRF: ± 5%, rare earth elements and trace elements NAA: La, Sm, Eu, Yb, Lu, Ta, Th and Hf ± 5%, for Ce, Nd, Tb, Dy, U and Cs ± 10%.

GEOCHEMISTRY OF THE VOLCANIC ROCKS

Cofre de Perote-Pico de Orizaba Range

This area (Fig. 2) is characterized by the stratovolcanoes Cofre de Perote and Pico de Orizaba. These volcanoes are built mostly of andesite and dacite lava flows (Robin and Cantagrel, 1982). Additionally, several monogenetic cinder cones erupted "hawaiites" and basaltic andesites occur in that area (Negendank *et al.*, 1985).

According to previous investigations (Negendank *et al.*, 1985) concerning the geochemistry of the volcanics, where a comagmatic relationship for all rock types is suggested, we selected samples from the different geological units with special respect to the field relationships to test this interpretation.

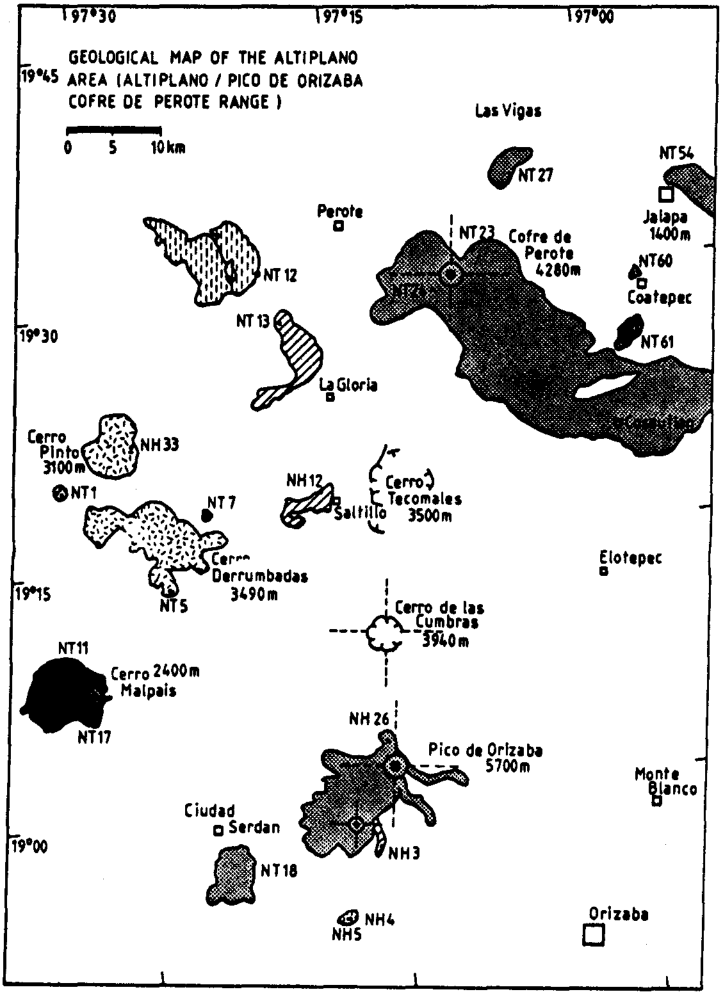

Fig. 2. Simplified geological map of the Altiplano Area (Altiplano/Pico de Orizaba-Cofre de Perote Range) modified according to Negendank *et al.*, 1985. Symbols as in Fig. 9.

Rare earth element patterns for the volcanic rocks are presented in Figure 3. 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 in-

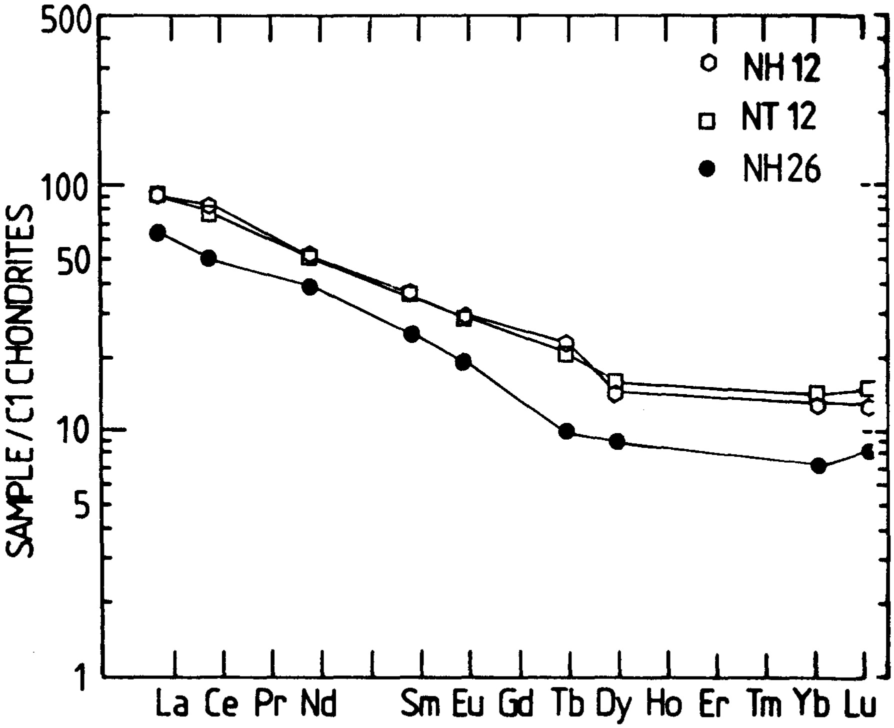

Fig. 3. Chondrite normalized REE data for Cofre de Perote-Pico de Orizaba basalts (NH 12), basaltic andesites (NT 12) and stratovolcano andesites (NH 26).

crease with the degree of fractionation, which precludes a cogenetic relationship between the basalts and andesites in this area.

Spider diagrams (Fig. 4) for the Cofre de Perote and Pico de Orizaba volcanics, normalized to primitive mantle values, as given by Jagoutz *et al.* (1979) and Wänke *et al.* (1984) for the Cofre de Perote and Pico de Orizaba volcanics display a high ratio of large ion lithophile elements (LILE) *vs* high field strength elements (HFSE) and distinct negative anomalies of Ta, Nb and for the stratovolcano andesites additionally Ti. These geochemical signatures are indicative of subduction related rocks (Pearce, 1982 and Briqueu *et al.*, 1984). The trace element patterns of the primitive basalts in this area (Fig. 5), normalized to average MORB values (Jochum, unpub-

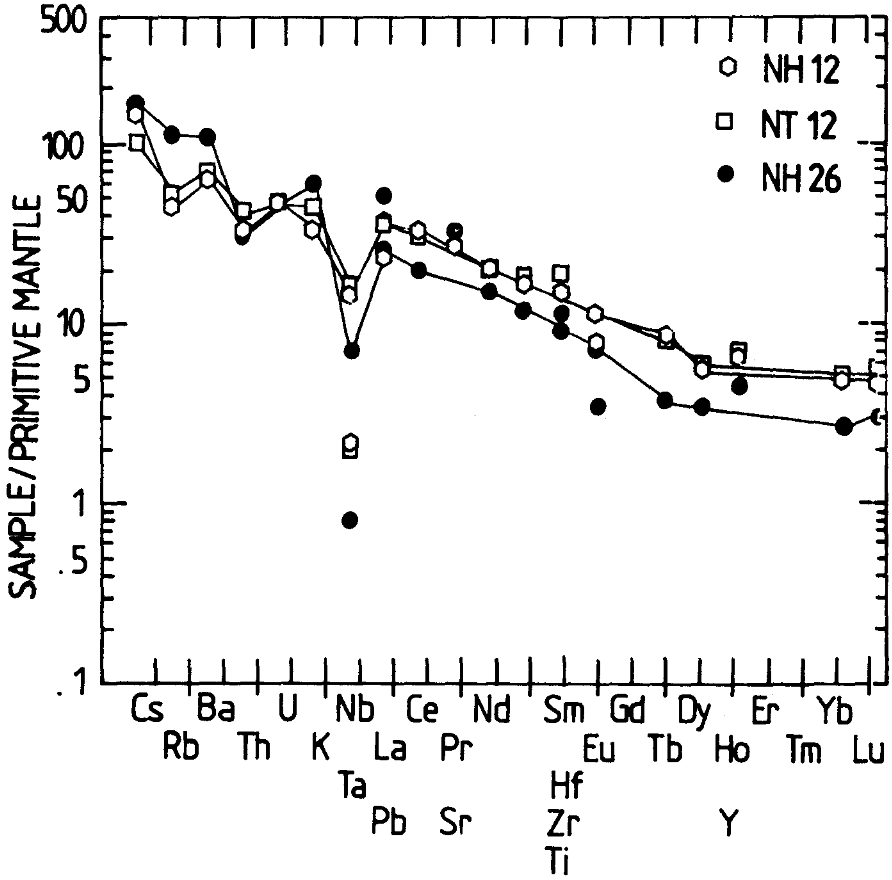

Fig. 4. Primitive-mantle normalized trace element patterns for Cofre de Perote-Pico de Orizaba basalts (NH 12), basaltic andesites (NT 12) and stratovolcano andesites (NH 26).

lished), show a clear enrichment in LIL-elements relative to MORB suggesting an LILE enriched source for the Cofre de Perote-Pico de Orizaba basalts.

The Altiplano Area (Oriental Basin)

The central part of the Altiplano is dominated by the rhyolite domes of Cerro Derrumbadas and Cerro Pinto (Fig. 2) being surrounded by several monogenetic cones

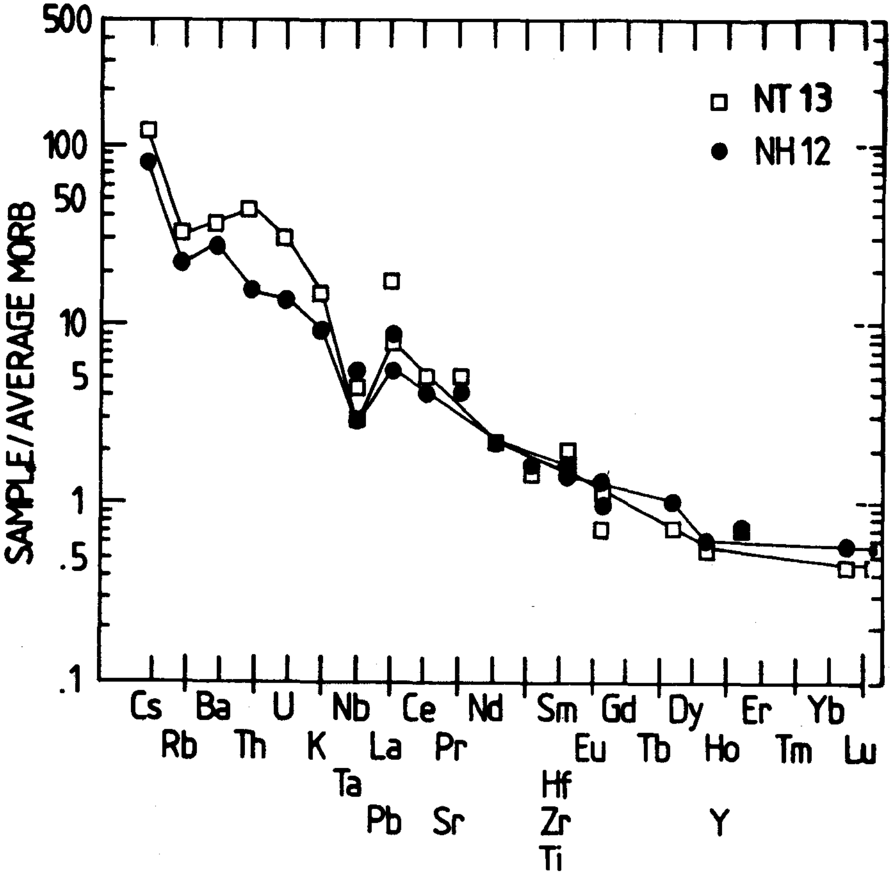

Fig. 5. Mid-ocean ridge basalt-normalized trace element patterns for two primitive basalts of the Cofre de Perote-Pico de Orizaba area.

of andesitic, dacitic and in minor amounts "hawaiitic" composition.

Rare earth element patterns for the volcanic rocks, except the rhyolites, are shown in Figure 6. All andesite types and dacites are LREE-enriched with Ce/Yb_n- ratios varying around 6.3 and flat HREE distribution. Even in the Oriental Basin there is no tendency for the absolute REE abundances to increase with the degree of fractionation precluding a cogenetic relationship for the volcanics.

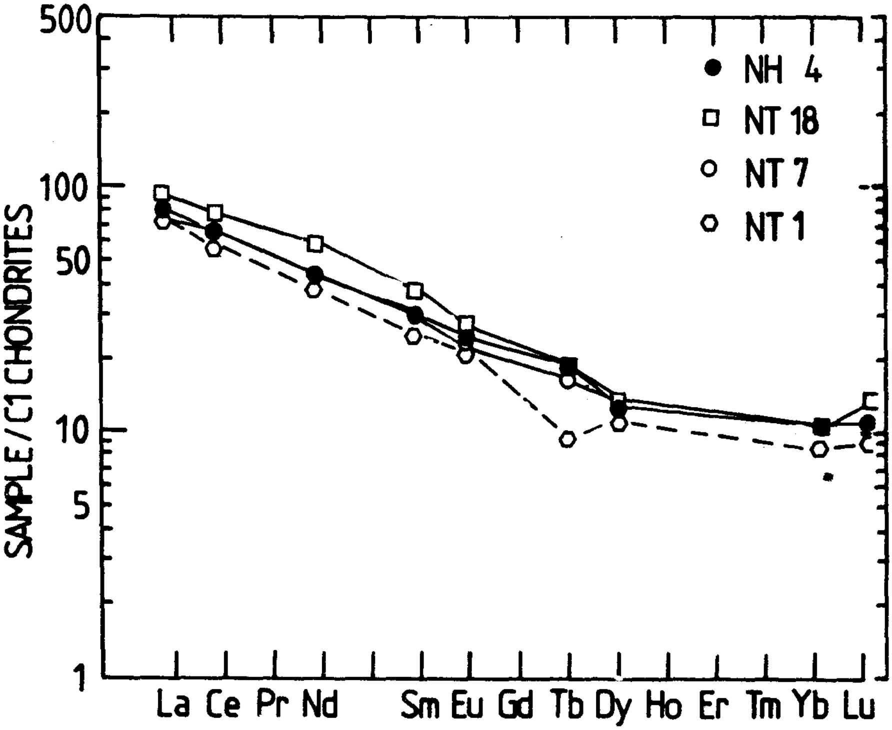

Fig. 6. Chondrite normalized REE data for Altiplano basaltic andesites (NT 18), stratovolcano andesites (NT 7) and dacites (NT 1).

The REE patterns for the Cerro Derrumbadas rhyolite (Fig. 7) exhibits LREE-enrichment (Ce/Yb_n= 111), depleted HREE and a slight negative Europium-anomaly. These patterns cannot be interpreted by fractionation processes involving a basaltic parental magma. The Cerro Derrumbadas rhyolite represents a partial melt of the continental crust involving residual garnet, amphibole and plagioclase. The Cerro Pinto rhyolite (Fig. 7) exhibits flat LREE (Ce/Yb_n = 1.4), flat HREE distribution and a distinct negative Europium anomaly. Even the Cerro Pinto rhyolite represents a partial melt of the continental crust, but in contrast to the Cerro Derrumbadas rhyolite with residual orthopyroxene, clinopyroxene and plagioclase. Spider diagrams (Fig. 8) for the volcanics, excluding the rhyolites, reveal distinct negative anomalies of Nb, Ta, Ti, and high LILE/HFSE ratios suggesting a subduction relationship.

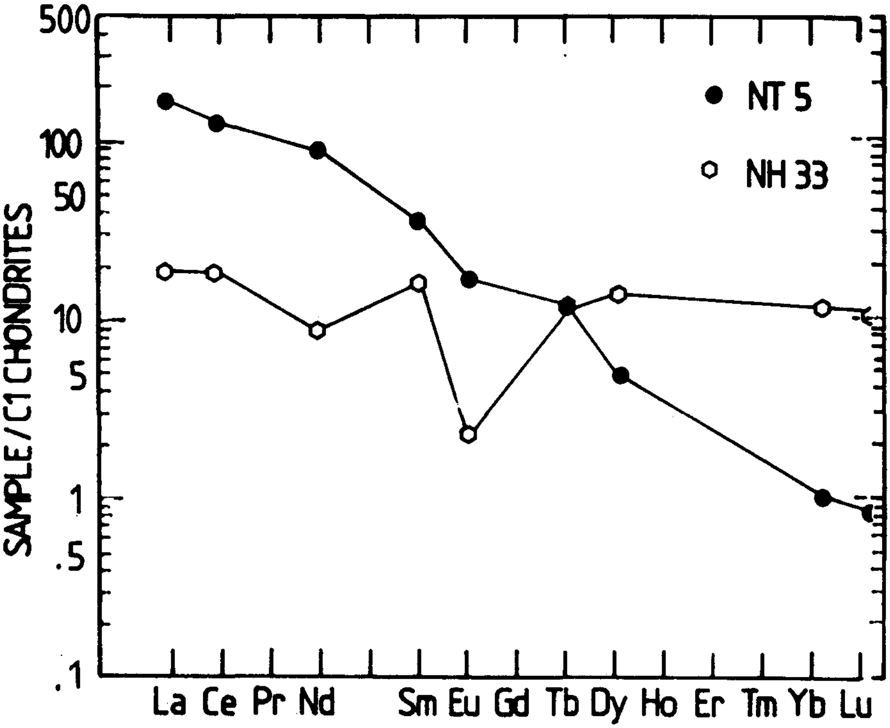

Fig. 7. Chondrite normalized REE data for Cerro Derrumbadas rhyolite (NT 5) and Cerro Pinto rhyolite (NH 33).

Jalapa-Naolinco-Area

The Jalapa-Naolinco-Area (Fig. 9) is dominated by cinder cones that erupted alkali basalts, "hawaiites" and calcalkaline andesites.

REE patterns for the volcanics are shown in Fig. 10. All rock-types are LREE-enriched with Ce/Yb_n-ratios varying from 4.5 (basalts) to 9.1 (alkali basalts) and exhibit flat HREE distribution. Europium anomalies are absent.

Spider diagrams (Fig. 11), normalized to primitive mantle values, exhibit that the basalts and basaltic andesites have lower incompatible trace element concentrations

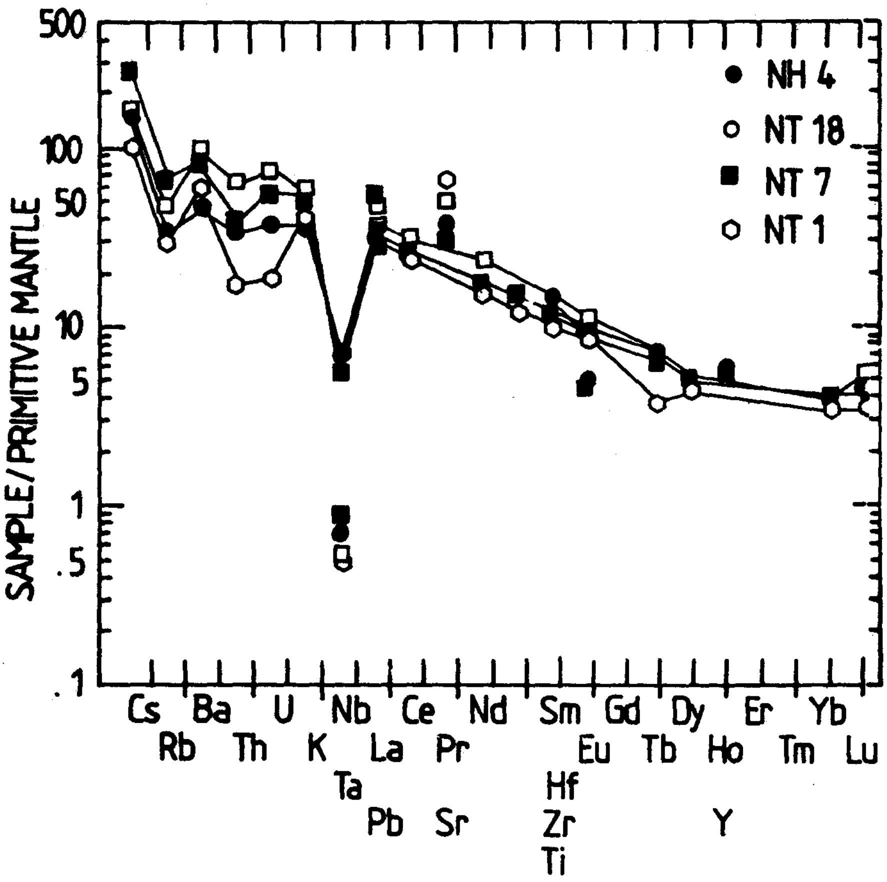

Fig. 8. Primitive-mantle normalized trace element patterns for Altiplano basaltic andesites (NH 4), monogenetic andesites (NT 18), stratovolcano andesites (NT 7) and dacites (NT 1).

than the alkaline rocks. Since fractionation would increase the concentrations of incompatible elements, the derivation of calcalkaline rocks from the alkaline rocks is excluded.

Additionally, 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 geochem-

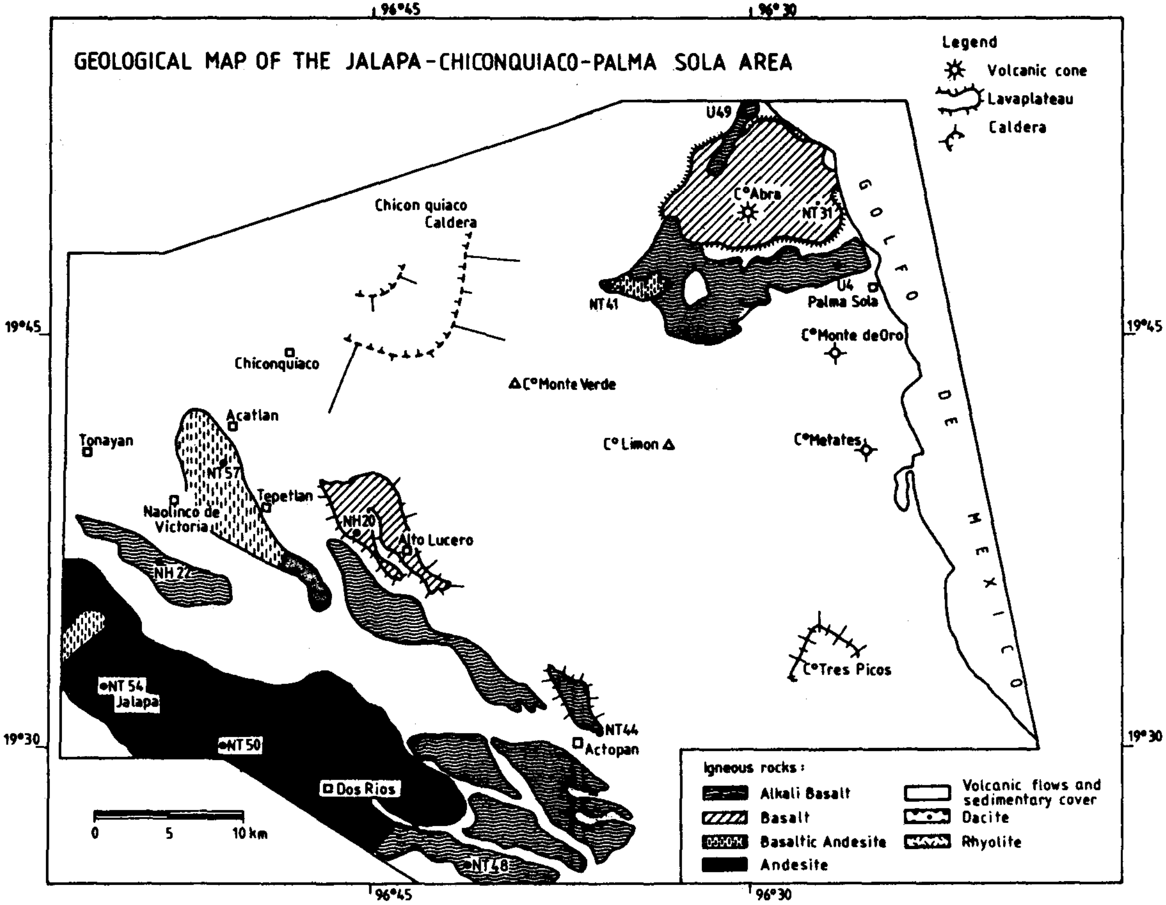

Fig. 9. Simplified geological map of the Jalapa-Chiconquiaco-Palma-Sola Area, modified according to Negendank *et al.*, 1985.

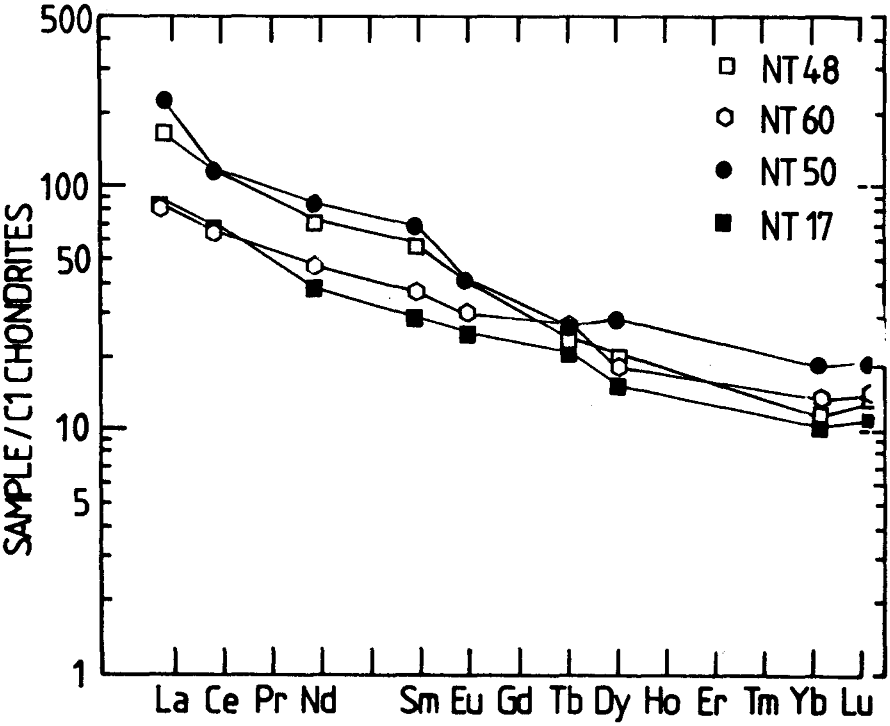

Fig. 10. Chondrite normalized REE data for Jalapa-Naolinco alkali basalts (NT 48), basalts (NT 60), basaltic andesites (NT 17) and monogenetic andesites (NT 50).

ical signature indicates the subduction relationship for the volcanics. Typical intraplate volcanics induced by crustal rifting have a Ta, Nb and Ti spike (Wood, 1979).

Spider diagrams (Fig. 12) 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 (Fig. 9) is dominated by alkaline volcanics, subordinate are calcalkaline andesites and dacites.

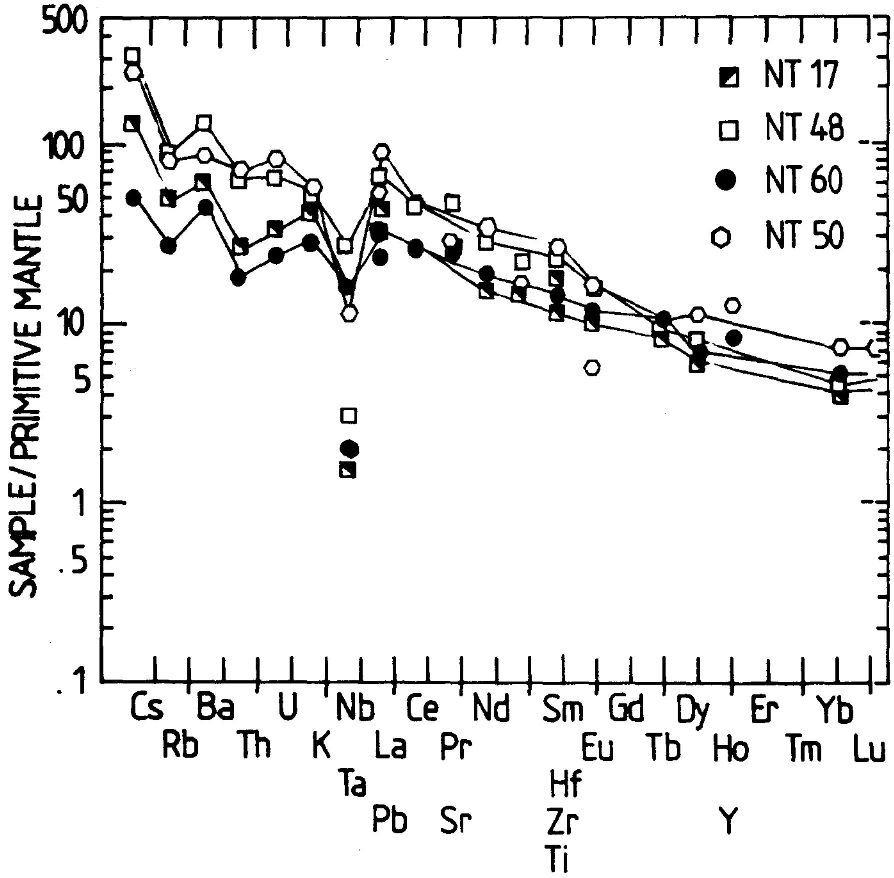

Fig. 11. Primitive mantle normalized trace element patterns for Jalapa-Naolinco alkali basalts (NT 48), basalts (NT 60), basaltic andesites (NT 17) and monogenetic andesites (NT 50).

REE patterns (Fig. 13) for all the volcanics indicate LREE-enrichment with Ce/Yb_n-ratios varying from 5.8 (basalt) to 9.3 (basaltic andesite) and flat HREE distribution. Europium anomalies are absent.

Even in the Palma-Sola-Massif there is no tendency for the REE concentrations to increase with the degree of fractionation, precluding a cogenetic relationship.

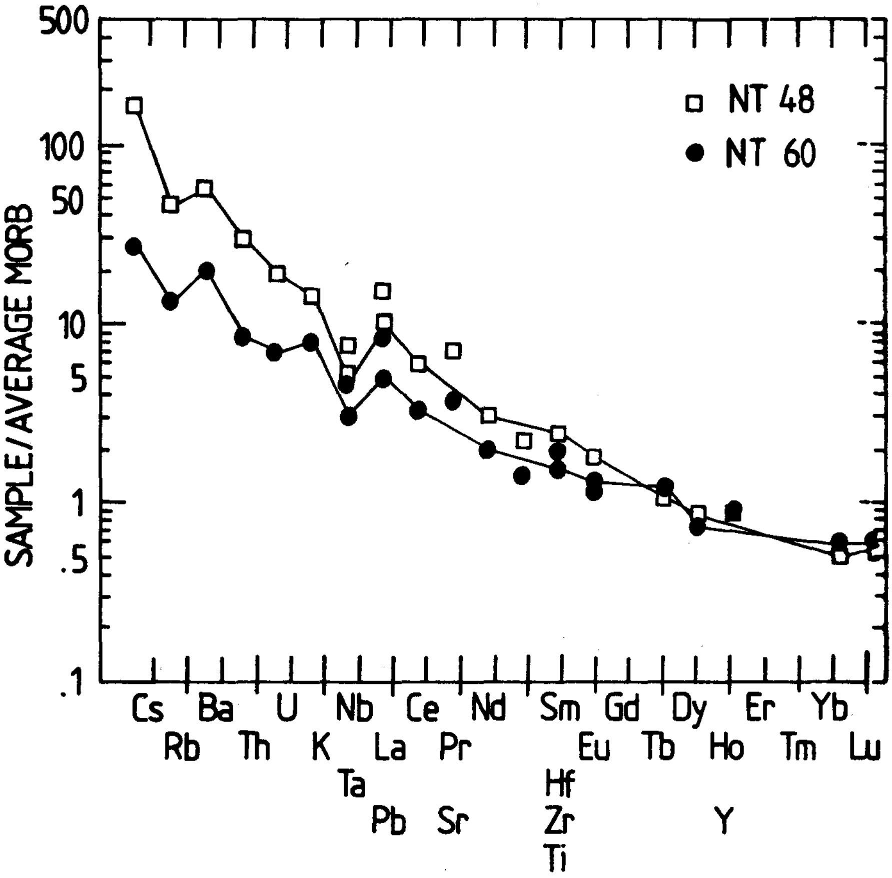

Fig. 12. Mid-ocean ridge basalt normalized trace element patterns for Jalapa-Naolinco alkali basalts (NT 48) and basalts (NT 60).

Spider diagrams (Fig. 14), for all volcanics, normalized to primitive mantle values show distinct negative anomalies of Nb, Ta and Ti as well as high LILE/HFSE ratios suggesting a subduction relationship.

Spider diagrams (Fig. 15), normalized to average MORB values reveal LILE-enrichment for the primitive basalts indicating a LILE-enriched mantle source.

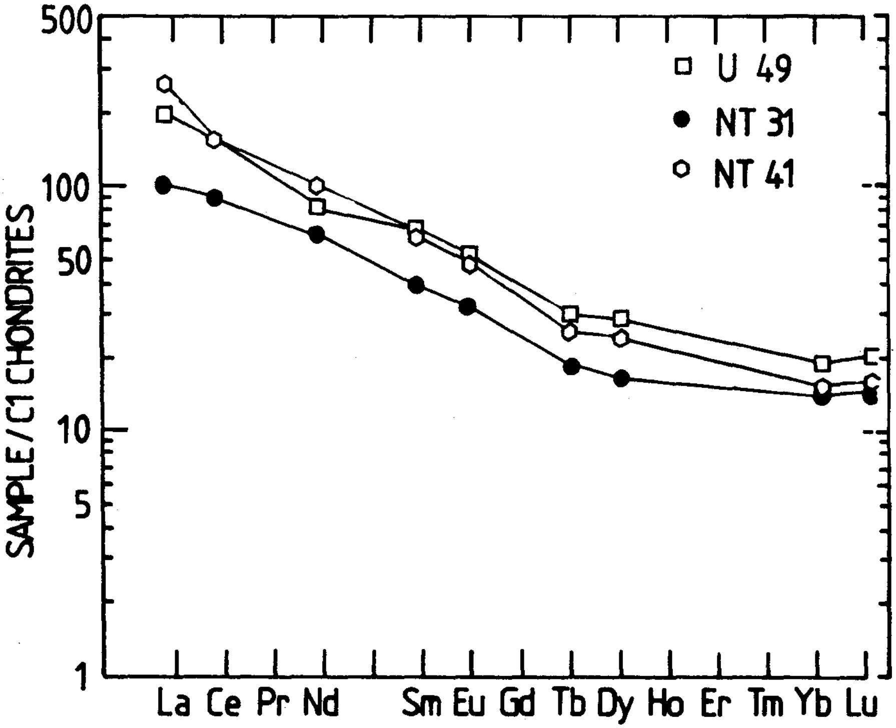

Fig. 13. Chondrite normalized REE data for Palma-Sola alkali basalts (U 49), basalts (NT 31) and basaltic andesites (NT 41).

CONCLUSIONS

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

The trace element patterns of the most primitive basalts are products of partial melting of a spinell-lherzolite (due to the unfractionated HREE), part of the mantle wedge overlying the subduction zone whose incompatible element composition was

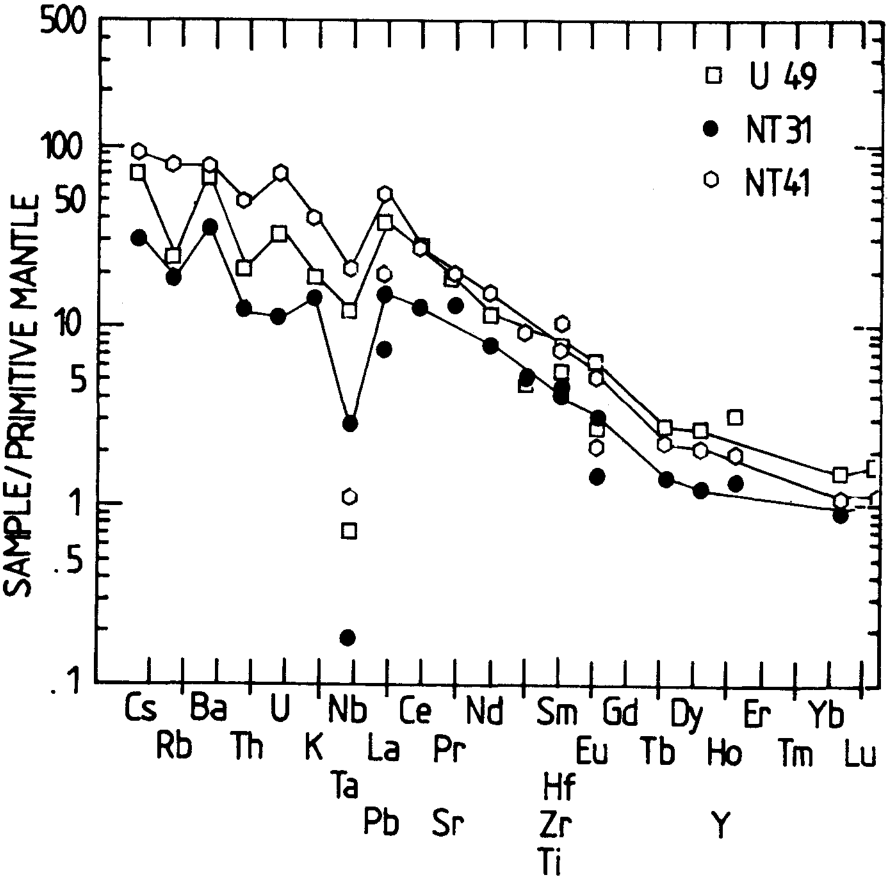

Fig. 14. Primitive mantle normalized trace element patterns for Palma-Sola alkali basalts (U 49), basalts (NT 31) and basaltic andesites (NT 41).

modified by fluids and possibly sediments released from the subducting slab of the Cocos/Rivera plate association. Possibly this can even be related to an earlier plate association, *e.g.* the Paleopacific plate association. These fluids are richer in LILE than in Ta, Nb, Ti and other HFSE (Hole *et al.*, 1984). Another hint for magma derivation from the mantle wedge is the depletion of Rb relative to Ba and Sr, visible

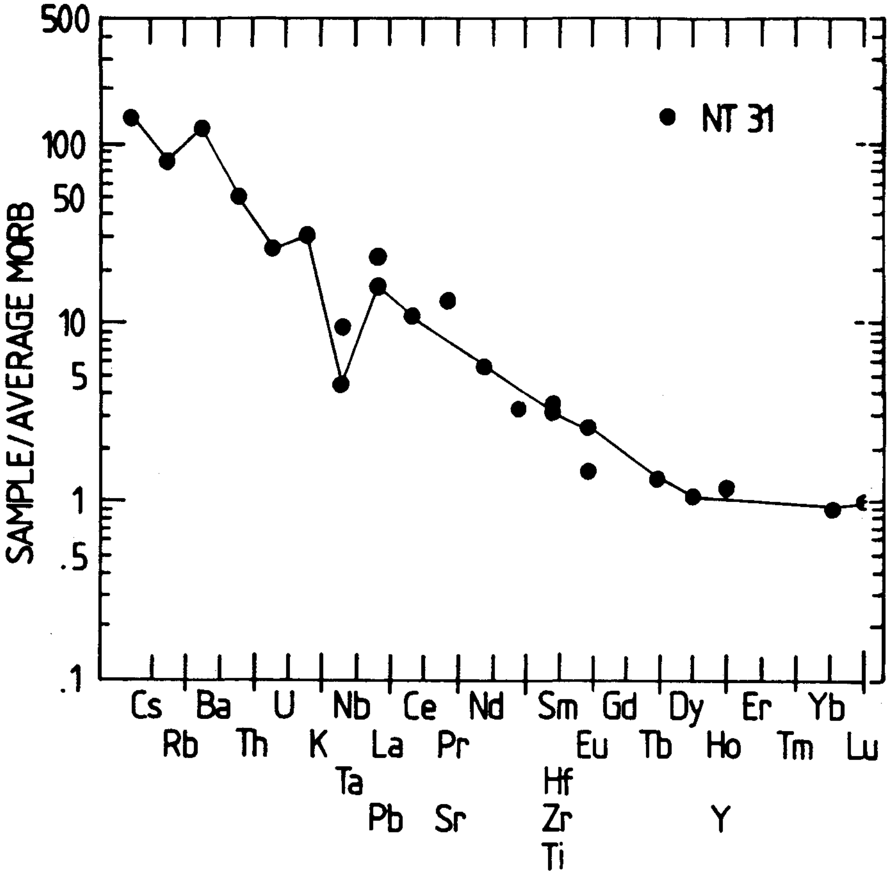

Fig. 15. Mid-ocean ridge basalt normalized trace element pattern for a Palma-Sola basalt (NT 31).

in the spider diagrams, due to greater incompatibility of Rb to fluids extracted from the downgoing slab (Ellam and Hawksworth, 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 are interpreted as partial melts of the continental crust.

Table 1

Major and trace element abundances of selected samples from the Eastern Trans-Mexican Volcanic Belt.

Sample	U 49	NT 48	NT 60	NH12	NT 31	NT 13	NT 41
SiO_2	47.9	48.7	49.8	50.6	52.2	52.8	52.8
TiO_2	2.21	1.85	1.89	1.49	1.37	1.09	1.92
Al_2O_3	17.1	17.2	16.4	15.9	16.9	16.2	17.7
Fe_2O_3	9.29	8.84	7.73	3.16	3.75	1.48	6.41
FeO	1.99	1.49	3.75	6.13	4.47	5.94	2.72
MnO	0.25	0.15	0.17	0.15	0.14	0.13	0.16
MgO	4.83	5.68	6.87	8.38	5.33	8.58	2.88
CaO	9.35	9.75	8.45	9.20	9.56	8.45	6.64
Na_2O	3.47	3.22	3.34	3.41	3.60	3.10	4.64
K_2O	1.45	1.66	0.93	1.09	1.17	1.65	2.53
P_2O_5	0.75	0.64	0.39	0.35	0.33	0.40	0.77
H_2O^+	0.97	0.39	0.68	0.13	0.37	0.33	0.54
CO_2	0.05	0.07	0.04	0.15	0.98	0.19	0.05
Total	99.6	99.6	100.4	100.1	100.2	100.3	99.8
Cs	.8	2.1	.3	1.0	.4	1.5	.9
Rb	27	50	14	24	25	35	69
Ba	739	796	263	386	448	507	787
Th	4.3	5.5	1.6	2.8	2.9	8.0	7.9
U	1.5	1.4	.5	1.0	.6	2.2	2.6
Nb	23	18	11	10	8	10	34
Ta	1.7	1.2	.7	.8	.6	.7	2.3
Pb	4	7	4	4	4	8	8
Sr	838	858	464	511	665	619	868
Hf	4.8	6.3	4.2	4.6	5.0	4.3	7.5
Zr	183	214	181	146	160	177	290
Y	49	32	33	26	27	25	35

La	47	39	19	21	24	31	61
Ce	93	70	40	50	54	60	94
Nd	38	33	22	23	29	24	47
Sm	10	9	5	5	6	6	9
Eu	3.0	2.3	1.7	1.7	1.8	1.5	2.7
Tb	1.1	.9	1.0	.8	.7	.6	.9
Dy	7.4	5.3	4.7	3.7	4.2	3.5	6.1
Yb	3.3	2.0	2.3	2.2	2.4	1.7	2.6
Lu	.52	.33	.36	.32	.38	.27	.40

Sample	NH 4	NT 12	NT 17	NT 18	NT 50	NT 27	NT 7
SiO_2	53.3	53.4	53.4	56.9	57.1	58.1	60.6
TiO_2	.97	1.48	1.37	.95	1.08	1.03	.85
Al_2O_3	15.7	18.1	16.5	15.8	17.0	16.5	18.1
Fe_2O_3	2.55	1.58	1.50	2.63	4.73	2.68	1.75
FeO	4.99	6.68	6.50	4.03	2.50	3.67	3.57
MnO	.12	.13	.13	.11	.12	.10	.09
MgO	9.01	4.66	7.13	5.64	4.36	3.96	2.82
CaO	8.81	8.24	7.77	8.28	7.04	6.68	5.90
Na_2O	3.03	3.96	3.67	3.44	3.73	3.82	4.23
K_2O	1.12	1.41	1.35	1.77	1.80	2.40	1.65
P_2O_5	.25	.33	.36	.27	.29	.27	.22
H_2O^+	.37	.33	.44	.51	.59	.38	.22
CO_2	.05	.04	.19	.05	.05	.26	.04
Total	100.3	100.3	100.3	100.4	100.4	99.9	100.0
Cs	1.0	.7	.9	1.1	1.8	2.8	1.9
Rb	18	29	27	25	45	73	37
Ba	301	426	377	561	397	598	517
Th	2.9	3.5	2.3	5.5	6.1	9.7	3.5
U	.7	1.0	.7	1.6	1.8	3.0	1.2
Nb	5	11	11	4	8	13	4
Ta	.2	.8	.6	.2	.6	.9	.3
Pb	6	6	7	8	9	12	9
Sr	701	503	525	899	540	528	585
Hf	3.3	4.9	3.9	4.4	4.7	5.2	4.3

Zr	94	185	167	92	185	207	139
Y	23	29	26	22	48	25	21
La	20	22	21	22	54	30	18
Ce	40	48	42	48	72	62	40
Nd	20	23	18	27	40	31	21
Sm	4	5	4	5	10	6	4
Eu	1.4	1.6	1.4	1.6	2.4	1.6	1.3
Tb	.6	.7	.7	.7	1.0	.4	.6
Dy	3.3	4.0	4.0	3.5	7.4	3.7	3.4
Yb	1.8	2.3	1.8	1.8	3.2	1.7	1.7
Lu	.28	.37	.28	.34	.48	.29	.27

Sample	**NH 26**	**NT 1**	**NT 5**	**NH 33**
SiO_2	62.6	63.1	71.6	73.9
TiO_2	.66	.72	.15	.03
Al_2O_3	18.1	17.1	15.7	14.0
Fe_2O_3	2.09	4.47	1.45	.20
FeO	2.77	.19	.92	.49
MnO	.08	.08	.04	.14
MgO	2.35	2.42	.28	.09
CaO	4.44	5.86	1.81	.49
Na_2O	4.63	4.13	4.62	4.47
K_2O	1.89	1.30	3.44	4.09
P_2O_5	.19	.25	.08	.04
H_2O^+	.26	.25	.07	2.00
CO_2	.15	.24	.08	.03
Total	100.2	100.1	100.2	100.0

Cs	1.1	.6	3.2	10.7
Rb	60	16	106	162
Ba	664	361	1009	
Th	2.6	1.5	8.9	3.7
U	1.0	.3	2.8	5.9
Nb	5	4	14	23
Ta	.3	.2	.8	2.2
Pb	9	6	17	19
Sr	608	1201	282	7
Hf	3.3	3.4	4.9	1.9
Zr	109	54	150	67
Y	18	20	9	24
La	15	18	39	4
Ce	31	36	77	11
Nd	18	18	41	4
Sm	3	3	5	2
Eu	1.1	1.2	1.0	0.1
Tb	.3	.3	.4	.4
Dy	2.2	2.9	1.2	3.6
Yb	1.2	1.4	.1	2.0
Lu	.20	.23	.02	.27

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