

A gabbroic xenolith in recent mid-oceanic ridge basalt from the East Pacific Rise at 14°S

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During a survey of the East Pacific Rise between 6°S and 30°S, a gabbroic xenolith was discovered in the basaltic lava at 14°S. The xenolith is about 2.5 cm in diameter and is composed of zoned plagioclase in a homogeneous pyroxene matrix. Accessory minerals are absent. An enrichment of Mg, Al, Ca, Ni and Cr and depletion of REE with a positive Eu anomaly indicate the xenolith to be a fragment of cumulate gabbro derived from a magma much more primitive than for the host basalt. Apparently, plagioclase phenocrysts floated and accumulated in the magma chamber for a while because of their lower specific weight crystallizing zones of differing composition from cores of An₇₈ to rims of An₆₉. Plagioclase was then entrapped optically in pyroxene which settled from the residual melt.

Anorthite content decreases continuously towards the rim of the plagioclase crystals in the xenolith, suggesting a continuous differentiation of a single melt in a magma chamber. This, together with large crystal size, absence of olivine and lack of trapped glass, suggests slow cooling in a large magma chamber with a low temperature gradient. This is in accordance with our hypothesis¹ that sheet lava is erupting from large magma chambers under the ridge crest.

Introduction and geological setting

DATA from gabbroic material at mid-oceanic ridges, especially fast and ultra-fast spreading centres is rare, but can provide insight into magma chamber processes, subridge magmatism and crystallization. The southern part of the East Pacific Rise (Figure 1) defines a constructive plate boundary where the spreading rates are as high as 19 cm/year². Vigorous volcanic activity generates flows of pillow and sheet basalts. Cruises SO 40 and SO 62 undertaken by the research ship *Sonne*, covering the axial area between 60°S and 30°S, surveyed the East Pacific Rise plate margin. Sea Beam mapping was followed by video and still photography of selected sections where active hydrothermal activity was

observed. In addition to the massive sulphides, basalt was sampled by TV-grab from 53 sites. A model for magmatism and development of spreading was suggested¹ and, a 4-stage cyclic development of spreading was inferred. In phase 1, primitive pillow lava erupting forming a steep, narrow ridge. Phase 2 was characterized by eruption of evolved sheet lava. The ridge in phase 3 was wider, with greater percentage of flange slopes and a rounded top. Phases 3 and 4 were magmatism starved. Tectonic activity formed the central graben along the ridge crest, and hydrothermal deposits formed in this graben. The initiation, maturity, and waning of the magma chamber(s) under the ridge might explain phases 1 to 4 of the cyclic development of spreading. This conforms with the observations elsewhere.

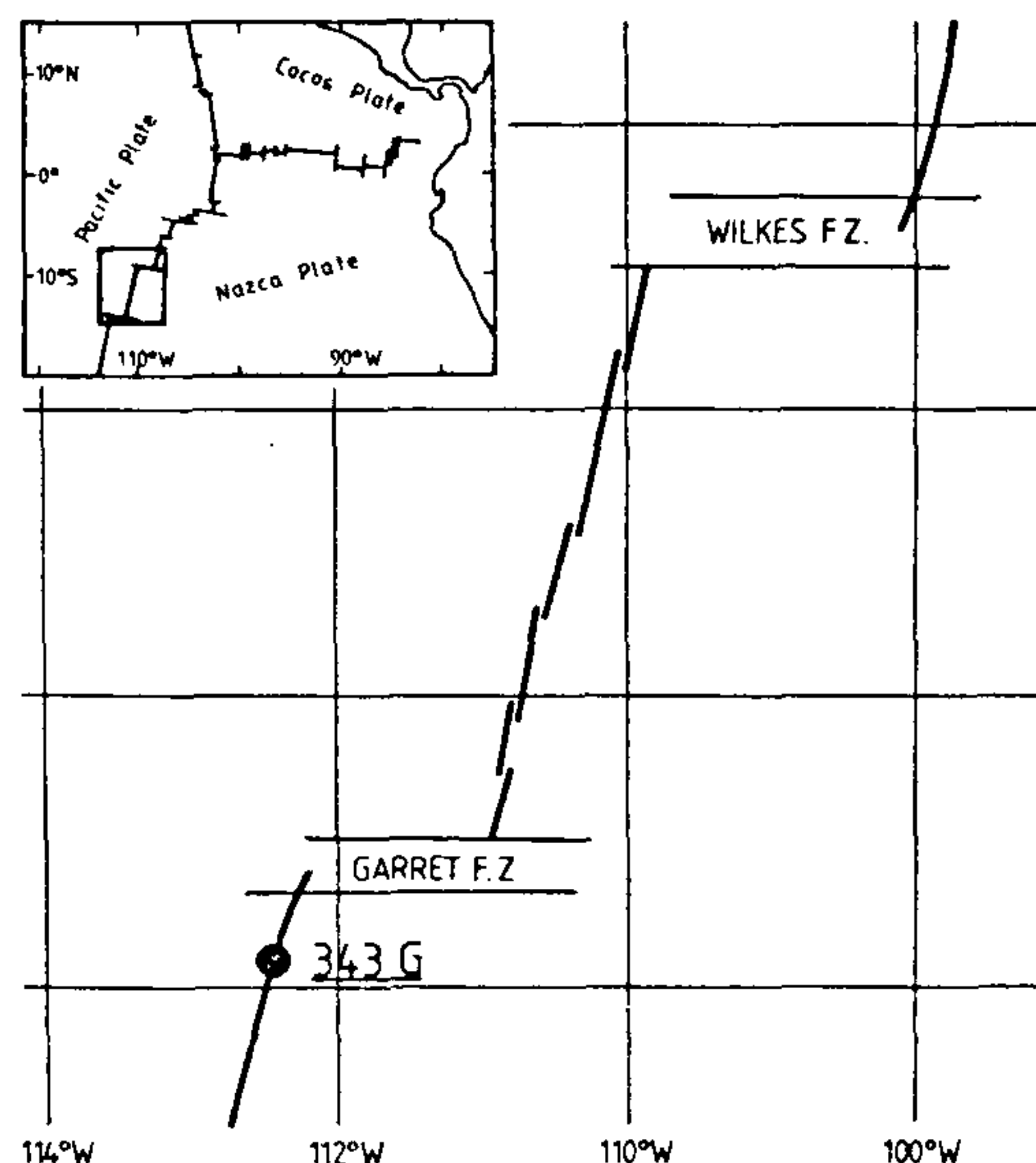


Figure 1. Sketch of the course of the southern part of East Pacific Rise with the sampling position of basalt that included the gabbroic xenolith.



Figure 2. *a*, Hand specimen showing the gabbro xenolith in basalt; *b*, Thin section of gabbro showing a typical poikilitic texture. Magnification 1:10; *c*, Thin section showing the sharp gabbro-basalt contact. Magnification 1:10.

analogous steep ridges are underlain by a small narrow magma chamber and rounded ridges by a wide shallow magma chamber with near-horizontal form³.

There are numerous descriptions of geochemically distinct basalts from the East Pacific Rise⁴⁻⁸. The

chemical variation in these basalts has been related to inhomogeneities of the mantle source material. As the material was sampled exclusively from the spreading axis, efforts were made to recover xenoliths as they would give information of the deeper levels of the oceanic crust. Xenoliths were rare and only one sample was found in 53 grab sites.

Description of sample and analytical procedures

The xenolith, a coarse-grained gabbro aggregate of about 2.5 cm diameter, was found about 30 mm inside the surface of a sheet lava basalt specimen (Figure 2*a*). The basalt was grabbed at 13°59'S, 112°29'W and at a water depth of 2637 m from the top of a rounded ridge covered with sheet lava from an active spreading zone (Figure 1). The sample was cut into two halves, one of which has been kept for reference. From the other half, a thin section was prepared and the remaining xenolith material was extracted with a diamond drill for analyses. Whole rock major and trace elements were determined by XRF, and REEs by ICP-MS. Chemical analyses of core and rim zones of selected mineral grains were made by Cameca/Camebax 799 microprobe. Similar procedures were adopted to analyse the host basalt.

The analyses were referred to international standards, the accuracy being more than 2% for the main components and more than 5% for the trace elements. Accuracy of microprobe analyses is considered to be within 2–5% for the main components and more than 10% for the minor elements.

Petrography and mineral chemistry

Xenolith

The xenolith is a coarse-grained gabbro aggregate with a poikilitic texture wherein large laths of plagioclase (35 to 40% of the volume of the xenolith) are embedded in a groundmass of clinopyroxenes (Figure 2*b*). Plagioclase laths are euhedral without any evidence of resorption and display prominent zoning. Accessory minerals are absent. The contact between the xenolith and the host rock is sharp (Figure 2*c*) with some micro veins of basaltic glass penetrating into the gabbro.

Table 1 shows results of microprobe analyses on plagioclase and pyroxens. Plagioclase is zoned, with anorthite content ranging from An₇₈ in the core to An₆₉ in the rim zone. Clinopyroxene has a more homogeneous composition with minimal differences between core and rim (i.e. Wo₄₃ and Wo₄₀ or En₄₈₋₄₉ Of₉₋₁₁ Wo₄₃₋₄₀ respectively).

Basalt

The host basalt of the xenolith has a slightly porphyritic texture with isolated microcrysts of plagioclase. Small

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Table 1. Composition of pyroxene and plagioclase in gabbro xenolith and in host rock from the location 343 G. Composition of olivine in host rock of same location

	Pyroxenes compositions			Olivine composition	
	Gabbro xenolith		Host-rock	Host-rock	
	Early	Late	Late 1	Late 2	Late
SiO ₂	51.61	52.00	50.77	48.83	40.02
TiO ₂	0.65	0.59	1.30	1.98	—
Al ₂ O ₃	2.69	2.52	5.33	5.17	0.11
FeO _i	5.87	6.72	10.82	17.22	16.00
MnO	0.15	0.19	0.38	0.36	0.27
MgO	17.22	17.58	14.79	9.44	43.14
CaO	21.28	19.84	15.91	16.13	0.46
Na ₂ O	0.21	0.26	0.68	0.78	—
Cr ₂ O ₃	0.31	0.30	0.02	0.08	—
Sum	100.00	100.00	100.00	100.00	100.00
Fe ₂ O ₃ *	2.97	2.39	—	—	—
Ca	42.62	39.91	35.17	37.53	Fo 82.02
Mg	47.93	49.20	48.48	30.56	Fa 17.06
Fe*	9.45	10.89	19.35	31.91	Tph 0.29 Lar 0.63

Fe₂O₃* = according to ref. 17.

Fe* = Fe²⁺ Fe³⁺ + Mn

Plagioclase compositions

	Gabbro xenolith		Host-rock		
	Early	Late	Early	Late	Late N
SiO ₂	48.54	50.74	48.66	50.58	55.93
TiO ₂	—	0.05	0.06	0.05	0.23
Al ₂ O ₃	32.70	31.10	32.52	31.03	26.88
FeO _i	0.52	0.63	0.61	0.92	1.56
CaO	15.66	13.82	15.48	13.80	9.12
Na ₂ O	2.58	3.61	2.65	3.60	0.10
K ₂	—	0.03	0.02	0.03	0.10
Sum	100.00	100.00	100.00	100.00	100.00
Or (% wt.)	—	0.20	0.11	0.18	0.60
Ab (% wt.)	21.94	30.76	22.60	30.72	53.33
An (% wt.)	78.06	69.03	77.29	69.10	46.06

Early = core of phenocrystals

Late = groundmass or rim of phenocrystals

Late N = small radiating quenched crystals.

radiating laths of plagioclase associated with pyroxene and rare olivine micro grains are present as a quenched phase. The groundmass consists of dark glass.

Microprobe analyses of the plagioclase phenocrysts (Table 2) show a composition and zonation similar to the plagioclase from the gabbro xenolith (An₇₇ to An₆₉ from core to rim respectively). Lower anorthite contents (An₄₆) were also observed, but only in the quenched radiating laths of plagioclase.

Pyroxene from the host basalt is not as homogeneous in its chemical composition as the pyroxene from the gabbroic xenolith. Significant differences, especially in Mg and (Fe²⁺ + Mn + Fe³⁺) are observed in different quenched micrograins within the basaltic glass. In general, their bulk composition differs from the composition of pyroxenes from the gabbroic xenolith, revealing lower Ca and higher (Fe²⁺ + Fe³⁺ + Mn). The Cr content is significantly lower in pyroxene from basalt.

Table 2.

	Gabbro xenolith	Host-rock
SiO ₂	51.30	50.83
TiO ₂	0.43	1.52
Al ₂ O ₃	16.41	14.92
FeO _i	4.18	10.26
MnO	0.11	0.19
MgO	8.43	7.50
CaO	16.94	11.65
Na ₂ O	2.14	2.82
K ₂ O	0.04	0.17
P ₂ O ₅	< 0.01	0.12
mg	0.803	0.596
V	212	323
Co	33	51
Cr	962	453
Ni	2123	93
Zn	49	111
Ga	19	21
Cu	69	61
Y	9	30
Zr	16	96
Sr	99	134
La	1.0	4.2
Ce	2.6	12
Pr	0.40	1.9
Nd	2.5	10
Sm	1.0	3.6
Eu	0.47	1.22
Tb	0.22	0.63
Ho	0.37	1.0
Er	0.96	2.8
Tm	0.15	0.48
Yb	1.2	3.4
Lu	0.16	0.47

Olivine is present only in the basaltic host rock as small quenched grains and has a composition of 82 mole% Fo. This olivine appears to be in equilibrium with the host rock; calculated Fo content is very similar to that observed (i.e. 82% vs 83%) assuming (Fe/Mg)_{ol} (Fe/Mg)_{liq} = 0.30 Fe₂O₃ = 0.15 (refs 9,10).

Whole rock chemistry

The bulk chemical analyses (Table 2) show marked differences in their composition of the gabbroic xenolith as compared to the host basalt. The xenolith is lower in Fe, Ti, Mn, P, Na, K, V, Y, Zr, Co and Zn and higher in Mg, Al, Ca, Ni and Cr (Figures 3 and 4). The chondrite-normalized REE pattern of the xenolith is shown in Figure 5, where an overall lower REE content and a positive Eu-anomaly is clear as compared to the host basalt. The whole rock chemical composition of the host basalt (Table 2, and Figures 3 and 4) corresponds to N-MORB type erupted along the East Pacific Rise between 6° and 30°S. The trace element contents and chondrite-normalized REE pattern of host basalt (Figure 5) are typical for sheet lava erupted during the second phase of development of cyclic spreading in the area⁷.

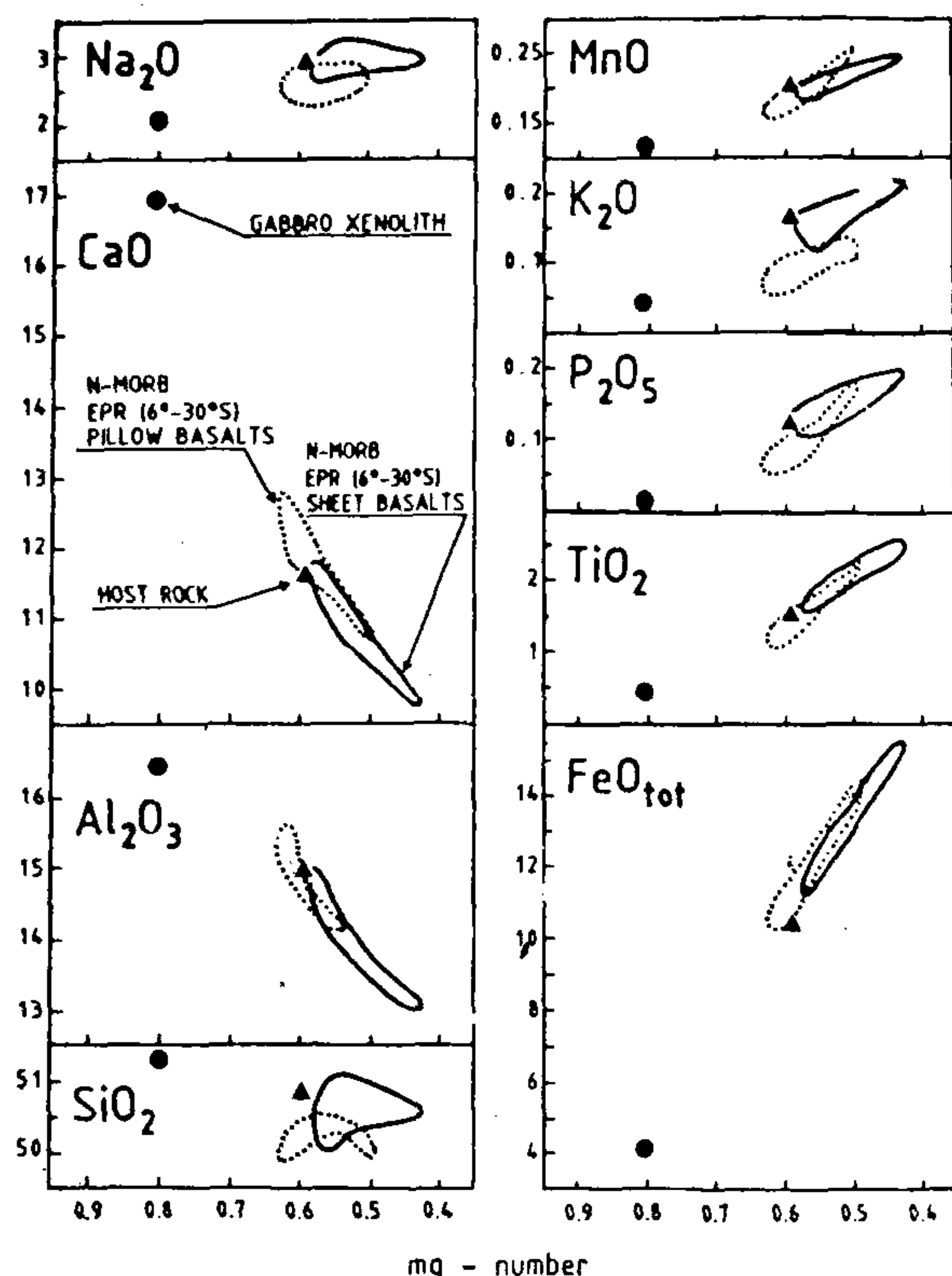


Figure 3. Variation diagrams of mg-values vs major elements (wt%) for gabbro xenolith, host rock and N-MORB type pillow and sheet lavas from southern East Pacific Rise (6°-30°S).

Discussion

The sharp contact of the gabbroic xenolith with the host basalt suggests that the gabbro did not crystallize from the same basaltic magma in which it was entrapped, but is related to previous magmatic activity. The Mg number (atomic Mg/Mg + Fe⁺² assuming Fe₂O₃/FeO = 0.15) is 0.802 for the gabbro and 0.596 for the basaltic host rock. N-MORB basalts which erupted as pillow lavas along the southern part of the East Pacific Rise have Mg-number in the range of 0.63 to 0.53 (median 0.62-0.60) while those erupted as sheet lavas have Mg number between 0.58 and 0.43 (typically 0.58-0.52)⁷. The host basalt is a sheet lava and represents the less evolved magma found along the EPR. The high Mg-values of the gabbroic xenolith show that it is significantly more than its host rock.

In almost all of the variation diagrams (Figures 3, 4 and 6) the gabbro xenolith lies on a linear fractionation trend defined by the host rock and N-MORB type basalts from the EPR. Strong enrichment in Ni and Cr observed in the xenolith cannot be easily explained if the xenolith crystallized from a magma has evolved as the

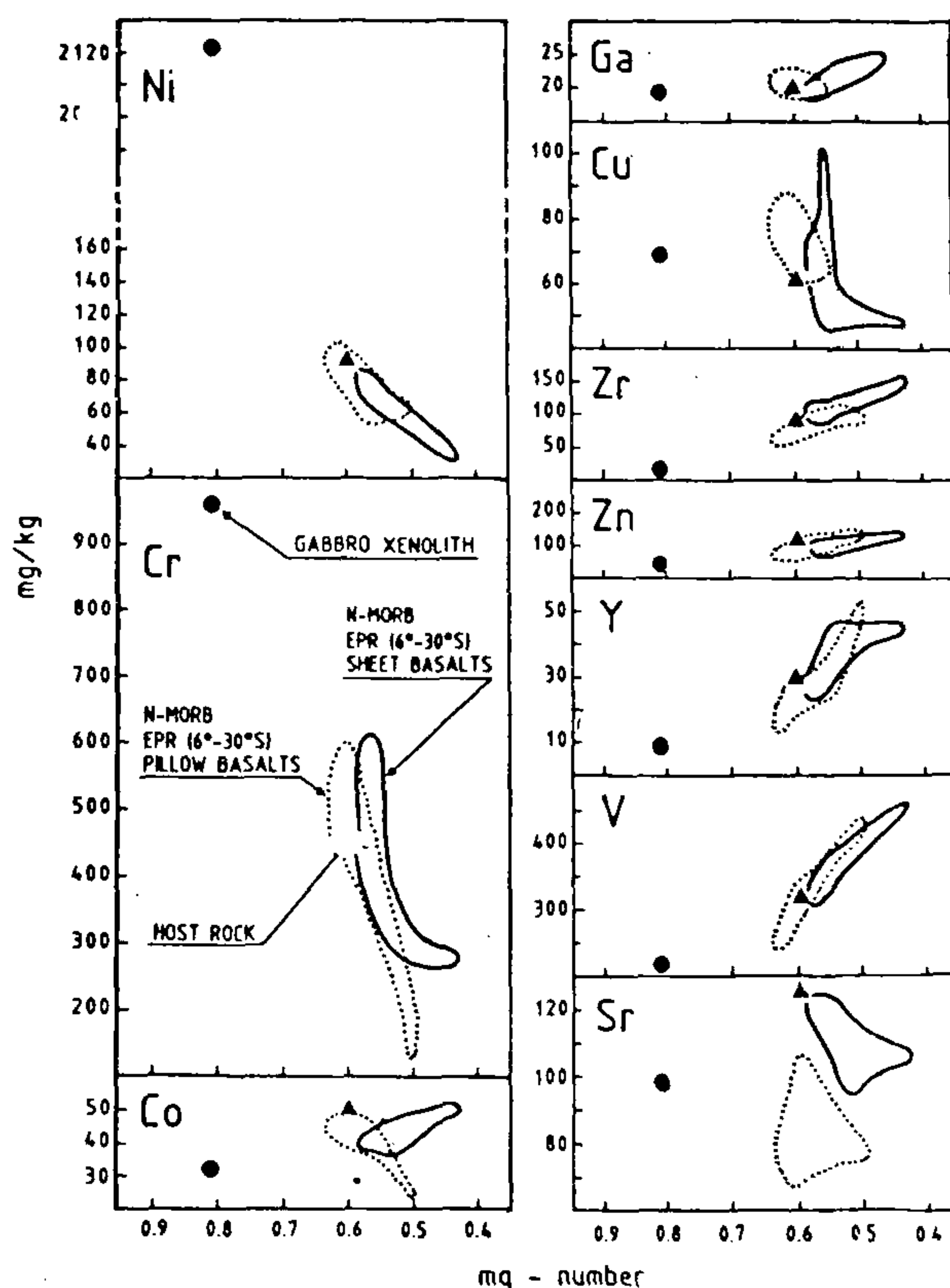


Figure 4. Variation diagrams of mg-values vs trace elements (ppm) for gabbro xenolith, host rock and N-MORB type pillow and sheet lavas from southern East Pacific Rise (6°-30°S).

host rock. The bulk enrichment of REE in the host basalt as compared to the gabbroic xenolith can also be explained by fractionation enrichment of incompatible REE in the residual liquid. The moderately positive Eu anomaly in the xenolith is typical of cumulate gabbros, a consequence of plagioclase accumulation.

These chemical features suggest that the xenolith is a crystal accumulate of a relatively primitive magma, closer in composition to the present magma of basalts erupted along the EPR. Gabbro and basalt appear to be congenetic (Figures 5 and 6), restite and residual liquid from the same primitive melt. The sharp contact and the injected glass veinlets are consistent with settling and consolidation of the gabbroic crystal mush, later spilled off into the remaining basaltic magma.

Gabbroic xenolith reveals textural and chemical characters similar to those shown in 'type A' xenolith from the Northern Gorda Ridge¹¹ whose genesis was also related to cumulate processes in the magma chamber, presumably near the top of the chamber. On the basis of the volume proportion of liquid trapped in crystallized aggregates¹², classified cumulate gabbros are adcumulates (0-7%), mesocumulates (7-25%) and orthocumulates (> 25%). Using this classification, the studied xenolith

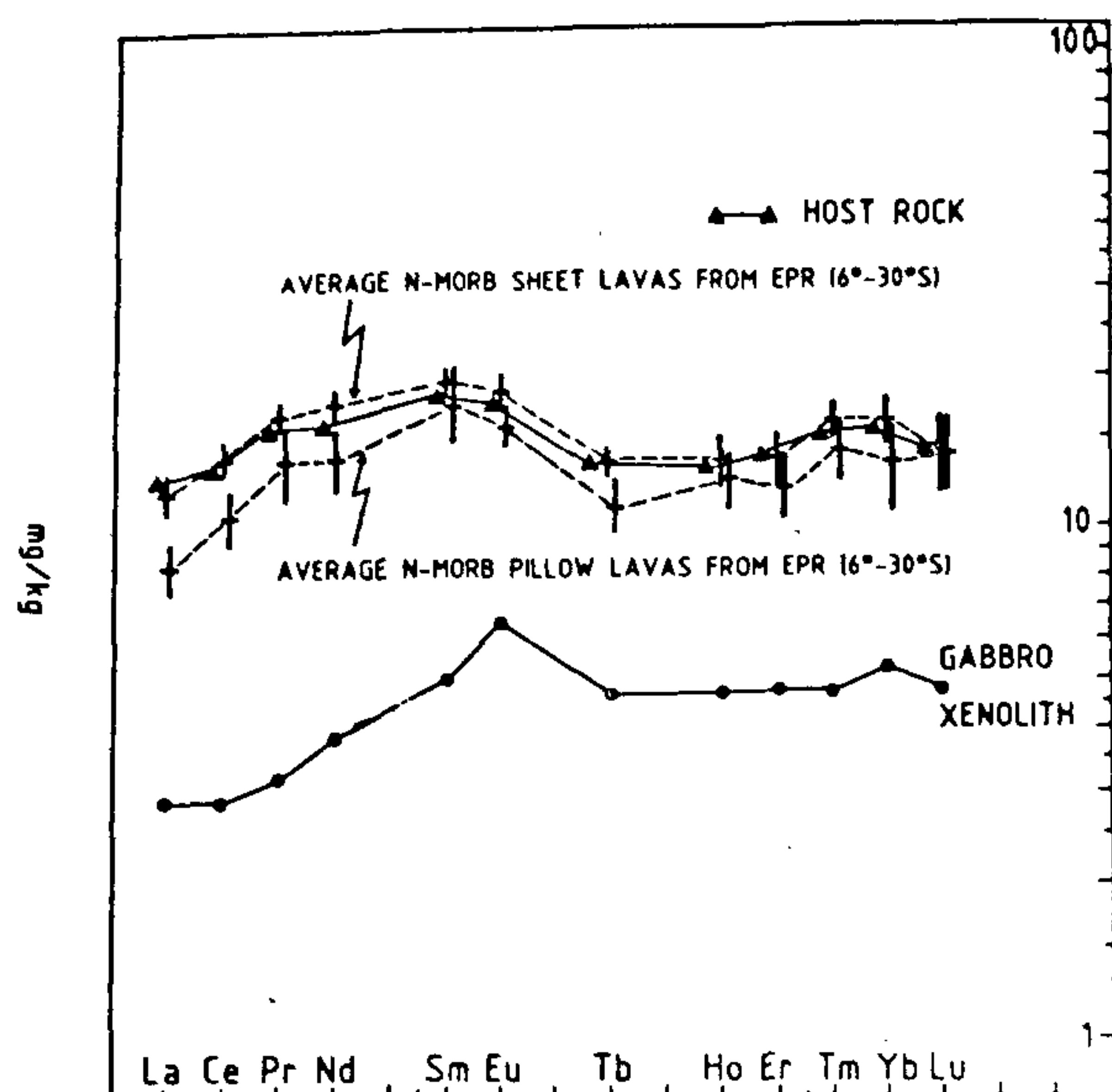


Figure 5. Chondrite-normalized rare earth elements¹⁸ for bulk gabbro xenolith material and for host basalt. Mean values for sheet lava and pillow lava are data from ref. 7.

belongs to adcumulates type without any trapped liquid. Studies conducted on large blocks of cumulate gabbro dredged from the South West Indian Ridge show that such cumulative processes may produce layers characterized by different crystal associations, as observed in ophiolites¹³⁻¹⁶. In fact, of 28 layers investigated by Meyer¹⁶, 6 were void of olivine, containing only plagioclase and pyroxene as main components. Two of the six olivine free layers did not contain accessory minerals, the same being the case in presently studied gabbroic xenolith. The bulk chemical composition of the xenolith as well as the composition of the plagioclase and pyroxenes, is within the range of compositions of corresponding layers in cumulate gabbro from the South West Indian Ridge.

The zonation of plagioclase in the gabbroic xenolith, in contrast to the homogeneity of coexisting pyroxene, can be attributed to the buoyancy of the plagioclases in the liquid part of magma chamber. Alternatively, this can be explained by the assumption that the xenoliths, if present, could have been digested by the remaining magma during the upward journey from the present magma chamber. Sufficient residence time was thus available to the xenolith prior to MORB eruption. Elthon¹⁴ invokes the longer contact of plagioclase with magma in the chamber in comparison to denser phases such as clinopyroxene and olivine. Plagioclase, having a density similar to the basaltic liquid, floats in the magma, whereas clinopyroxenes and olivines settle due

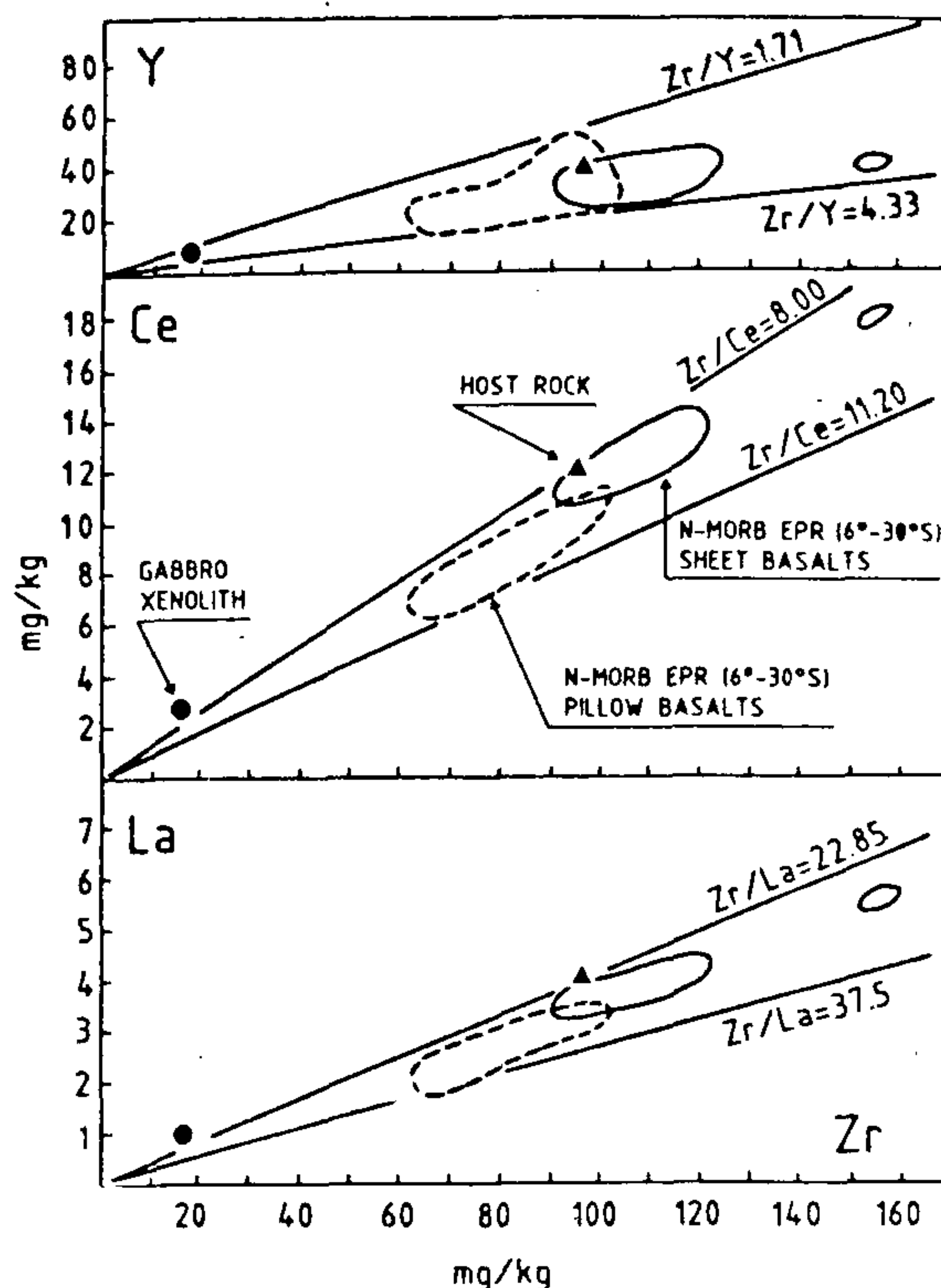


Figure 6. Variation diagrams of Zr vs La, Ce, Y for gabbro xenolith, host rock and N-MORB type pillow and sheet lavas from EPR (6°-30°S).

to their higher density. This could explain the zonation in plagioclases in the xenolith: floating in the magma for a longer period of time, they reflect the changing composition of the crystallizing basaltic liquid. Magmatic plagioclase was entrapped in gabbroic pyroxene and preserved as phenocrysts in basalt, hence the very close similarity in the range of zonation in the plagioclase phenocrysts from basalt and xenolith. Small quenched plagioclase crystals in basalt are the ones which rapidly formed in evolved magma during cooling after eruption; this is consistent with their significantly higher albite content. Clinopyroxene from the xenolith did not have the same long history of contact with basaltic liquid. It settled down in the course of crystallization because of its higher density and is therefore quite homogeneous, reflecting the composition of its parental magma only during the short time of its crystallization.

There are no indications of magma mixing in the composition of the gabbroic xenolith, such as partial resorption or oscillatory or inverse zoning of plagioclase. The magma chamber may have been large, and/or filled by a single pulse or parental melt, which differen-

tiated *in-situ*. Further, the total absence of interstitial glass hints at slow cooling without turbulent magma circulation. Strong enrichment of Ni and Cr in the gabbroic xenolith in comparison with the host rock, shows that the xenolith crystallized from a more primitive stage of magma. It perhaps formed deeper and earlier, in the base or wall of the chamber or even a feeder dyke, and was carried to its final position in a more evolved, cogenetic melt.

Conclusions

The gabbroic xenolith crystallized from a primitive state of magma, in a magma chamber under the rounded ridge covered with sheet lava of a higher degree of evolution. Our hypothesis² and the seismic imaging of magma chambers on the northern part of the East Pacific Rise³ imply that rounded ridge segments are underlain by a large flat mature magma chamber in which a huge amount of liquid–solid fractionation takes place.

There are several points which suggest that the studied gabbroic xenolith is a fragment of cumulate gabbro which crystallized in a large magma chamber with well-developed fractionation processes.

1. The high Ni and Cr contents and a higher Mg-number show that the xenolith crystallized from a primitive magma. Since the host basalt and other sheet basalts from the EPR between 6° and 30°S are highly evolved^{7,8}, this shows that extensive fractionation took place, suggesting a large, long-lived magma chamber.
2. The lack of trapped liquid, in conjunction with a large crystal size, suggests slow cooling in a large magma chamber.
3. The presence of euhedral plagioclase with distinctive compositional zoning and without inverse zoning or dissolution, enclosed by homogeneous clinopyroxene, as well as absence of olivine, suggests plagioclase flotation and accumulation near the top of the chamber. Plagioclase is more bouyant than olivine and would settle more slowly than olivine. A perfect separation of plagioclase from olivine, as observed in the described xenolith, would need a large, undisturbed magma chamber to de-

velop within a low temperature gradient. Further, the positive Eu-anomaly indicates plagioclase accumulation to be an important process in the formation of cumulate gabbro. None of the features is sufficient evidence in themselves but, taken together, they are consistent with the existence of a large magma chamber with a low temperature gradient and extensive fractionation under the rounded sheet lava ridges.

1. Holler, G. and Marchig, V. and the Shipboard Scientific Party, *Geol. Jb.*, 1990, **B75**, 3–22.
2. Lonsdale, P., *J. Geophys. Res.*, 1989, **94**, 12197, 12225.
3. Detrick, R. S., Buhl, P., Vera, E., Mutter, J., Orcutt, J., Madsen, J. and Brocher, T., *Nature*, 1987, **326**, 35–41.
4. Macdougall, J. D. and Lugmair, G. W., *Earth Planet. Sci. Lett.*, 1986, **77**, 273–284.
5. Fontignie, D. and Schilling, J. G., *Chem. Geol.*, 1991, **89**, 207–241.
6. Sinton, J. M., Smaglik, S. M., Mahoney, J. J. and Macdonald, K. C., *J. Geophys. Res.*, 1991, **96**, 6133–6155.
7. Marchig, V., Bellieni, G. and Milovanovic, D., *Neues Jb. Mineral.*, 1996 (in press).
8. Bellieni, G., Milovanovic, D. and Marchig, V., *Eur. J. Geol.*, 1996 (in press).
9. Roeder, P. L. and Emslie, R. F., *Contrib. Mineral. Petrol.*, 1970, **29**, 275–289.
10. Wilkinson, J. F. G. and Binns, R. A., *Contrib. Mineral. Petrol.*, 1977, **65**, 199–212.
11. Davis, A. S. and Clague, D. A., *J. Geophys. Res.*, 1990, **95**, 10885–10905.
12. Irvine, T. N., in *Physics of Magmatic Processes* (ed Hargraves, A. B.), Princeton Univ. Press, Princeton, 1980, pp. 325–387.
13. Ethlon, D., Casey, J. F. and Komor, S., *J. Geophys. Res.*, 1982, **87**, 8717–8734.
14. Elthon, D., *Geochim. Cosmochim. Acta*, 1984, **48**, 753–768.
15. Komor, S. C., Elthon, D. and Casey, J. F., *Contrib. Mineral. Petrol.*, 1987, **95**, 278–300.
16. Meyer, P. S., Dick, H. J. B. and Thompson, G., *Contrib. Mineral. Petrol.*, 1989, **103**, 44–63.
17. Papike, J. J., Cameron, K. and Baldwin, K., *Bull. Geol. Soc. Am.*, 1974, **6**, 1053–1054.
18. Wakita, H., Ray, P. and Schmidt, R. A., *Proceedings of the Second Lunar Science Conference*, 1971, pp. 1319–1329.

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