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RARE EARTH ELEMENTS IN TONALITIC AND GRANODIORITIC GNEISSES AND THE FORMATION OF BASEMENT GNEISS COMPLEXES – AN EXAMPLE FROM POUSO ALEGRE, MINAS GERAIS

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ABSTRACT

The gneiss complex around and north of Pouso Alegre, Minas Gerais, consists of tonalitic to granodioritic biotite and hornblende-bearing gneisses with amphibolite bodies in the form of layers or boudins. A later group of gneisses which also make up the complex comprises relatively leucocratic rocks ranging from tonalitic and granodioritic to granitic augen gneiss containing schlieren of mafic composition and at times fragments of digested amphibolite. Complex polyphase folding has given rise to interference patterns and migmatitic structures in the gneisses as a whole. Despite the structural complexity, however, a sequential relation between the rock types can be established, the most obvious being the emplacement of augen gneiss in the earlier hornblende tonalites. In all the gneisses mineral lineation measured on foliation planes are around 50° - that is, northeast.

The later group gneisses dealt with here are tonalitic, granodioritic and granitic in composition, the latter being augen gneiss with microcline megacrysts; all of them contain variable amounts of hornblende, biotite and garnet occurring as clots or schlieren. The geochemistry of the gneisses suggests that they are comagmatic and belong to a differentiated sequence. Their rare earth element patterns are similar to compositionally equivalent Archaean gneisses with the difference that their heavy rare earth elements are less depleted, possibly owing to the assimilation of mafic material at the time of their emplacement. The overall REE patterns are strongly inclined with a distinct negative Eu anomaly for the augen gneiss. To account for the origin of these gneisses, models of melting of Archaean gneiss, eclogite, and hornblende fractionation are considered. Their generation is closely linked to the formation of basement gneiss complexes.

RESUMO

Os gnaisses nos arredores e ao norte de Pouso Alegre, Minas Gerais, consistem de hornblenda e biotita gnaisses tonalíticos e granodioríticos com corpos de anfibolitos em forma de camadas ou boundins. Um grupo tardio de gnaisses relativamente leucocráticos e variando de tonalitos até augen gnaisses graníticos também constituem o complexo gnaissico. Apesar de estruturas complexas, sequências temporais são reconhecíveis. As rochas contêm proporções variáveis de quartzo, plagioclásio e microclínio como minerais principais, e hornblenda, granada e biotita em forma de schlieren. Sua geoquímica sugere que eles são possivelmente comagmáticos pertencentes de uma sequência diferenciada. Os padrões de elementos terras raras se assemelham os dos gnaisses arqueanos com a diferença nas terras raras pesadas que são menos depletadas. Para sua formação são sugeridos modelos de fusão de gnaisses arqueanos, de eclogitos e de fracionamento de hornblenda. Sua origem está ligada com a formação de complexos gnaissicos do embasamento.

INTRODUCTION

Surely, one of the puzzling and enigmatic problems facing geologists who study Precambrian terrains is the formation of the primitive crust in Archaean and Proterozoic times. With the information available regarding the constitution of oldest known crust, and adopting the uniformitarian principle, a perusal of the literature will show that the theories set up for the formation of the early crust boil down to at the most three or four models which themselves prove to be slight variations of each other. Some of these models have been listed by Collerson and Bridgwater (1979). However, one cannot get rid of the feeling that we are still probing in the dark, and in addition to trying to answer the questions in a geochmeical way, one is plagued by doubts such as arise from our ignorance of the role of physical properties of crustal materials, tectonics and heat flow. Although some of these parameters have been taken into account in many of the models, they are far from explaining everything. This is of course impossible, since the focus of scientific enquiry, to quote freely from Heisenberg (1973), is not the behaviour of objects themselves but our knowledge of this behaviour and its accompanying phenomena. Considering crust formation for example, what if in the course of planetary evolution the tectonics were non-uniform or even pulsating giving rise to enormous "cracks" along deep fundamental weakness zones in subsequent jostling of plates, either diverging or converging, and perhaps embryonic subduction in the Archaean (Choudhuri, 1976). The results would then depend on the strength of the crust, heat flow, magmatism, etc. Perhaps some of these cracks heal within a geologically relatively short time till a gneiss complex, such as the basement gneisses everywhere, is stabilized. The idea is not entirely new, but needs some rethinking, and in an indirect relation to this problem we present here a speculative account of the formation of basement gneisses in southwestern Minas Gerais for which we draw upon field observations, petrology and a few geochemical analyses.

GENERAL CONSIDERATIONS

We frequently read that primitive sialic crust may have formed in the following way (see for example Jahn et al., 1984) - a mafic crust generated by mantle magmatism gradually gives way to felsic intrusions and eventually gneisses, either formed by partial melting of the mafic crust or its metamorphic equivalent, or by melting of subsequent old sialic crust.

As is often the case elsewhere, so also in southern Minas Gerais nowhere is there a mafic crust to be seen; rather, the basement contains a wide variety of gneisses grading from intemediate to felsic compositions with much mafic material. Such gneisses are also to be found in northeastern São Paulo State extending to Minas Gerais where they are more common around Pouso Alegre, and continue beyond São Gonçalo do Sapucaí probably merging with the Barbacena Complex to the northeast. At least this is how the occurrence of these gneisses is shown in Ebert's map (1984). As a first assumption, the migmatites and orthogneisses around Fortaleza de Minas also belong to this unit, and are shown in a very generalized fashion in the sketch map in Fig. 1.

In spite of structural complexity, close examination of the gneisses north of Pouso Alegre reveal sequential relations which help to decipher their history in the complex called Silvianópolis Complex by Fiori (1979). Time relations between the gneisses as established by Choudhuri et al. (1987) are given in the following table; they have, however, not been subdivided in the sketch map (Fig. 1) which gives only the main lithological units in SW Minas Gerais.

TABLE

Time relations of gneisses around Pouso Alegre.

Rock Unit	Sequence Relation
Garnet-biotite gneisses	Partial melting and migmatitic nature
Augen gneiss and leucotonalitic gneisses	Sheet-like bodies with mafic clots and schlieren, emplaced in older grey tonalitic gneiss unit
Amphibolites and garnet amphibolites	Layers and dykes enclosed in remobilized tonalitic gneisses
Migmatites and mafic-rich tonalitic gneisses and hornblende tonalites	Remobilized during Trans-Amazonic Cycle

The gneisses studies here belong to the later group of augen gneiss-leucotonalite unit as they all contain minor amounts of mafic schlieren and are quite distinct from the grey banded gneisses which they intrude; the latter contain numerous amphibolite bodies and boudins and belong to an older group. Whereas this older group is possibly Archaean, at least in part, gneisses similar to the later group have yielded Trans-Amazonic ages in neighbouring areas (Wernick et al., 1981). Complex fold styles characterize these gneisses, and in places NW foliation has been re-oriented to NE; the mineral lineations on foliation planes are generally N50E. Fig. 2 gives an idea of their general appearance in the field.

PETROGRAPHY

Except for the augen gneisses, all other gneisses contain more plagioclase than potash feldspar, and their modal compositions vary from tonalite to granite, in the classification of Streckeisen (1975). In this QAP triangle they follow the low-K_2O calc-alkaline trend of Lameyre and Bowden (1982), that is to say, they appear to mark a differentiation trend with increasing potash by still within the calc-alkaline group. Major element variation of the gneisses given further on also confirm this tendency.

Texturally the gneisses are porphyritic with megacrysts of microcline in a granoblastic quartz-feldspar matrix in the augen gneisses to granoblastic inequigranular in the tonalites and granodiorites. In the augen gneisses the microcline megacrysts take on oval shapes or are even flattened out due to strong deformation, and the quartz grains are almost polygonal to interlobate with variable amount of crushing along grain margins depending on the intensity of deformation. Mafic minerals form isolated groups of garnet, biotie and epidote with minor green hornblende most of which has been almost completely replaced by biotite. The other gneisses are quartz-feldspar mafic-rich with frequent hornblende, minor garnet and late cross-cutting biotite. The matrix sometimes contains fresh microcline which is seen to be corroding the larger plagioclase grains. At places there are biotite-epidote aggregates in which the biotite is typically worm-like or in radiating clusters indicating its late stage neoformation. Accessory minerals such as allanite, sphene, zircon, apatite and opaques are common in all the gneisses.

CHEMICAL VARIATIONS

Although only a few chemical analyses of the gneisses are available, their compositional variation as seen in a modal QAP plot is brought out more clearly in the Harker diagrams in Fig. 3 in which K_2O, TiO_2, FeO + MgO, Rb and Sr are plotted against SiO_2. In this figure, Early Proterozoic gneisses from Anderson and Cullers (1987) are also shown for the sake of comparison; Archaean gneisses from eastern Finland analysed by Martin (1987) show similar trends but are not indicated to avoid crowding. In general, Archaean gneisses have lower K_2O and are less mafic (see, e.g. Amîtsoq and Nuk gneisses from McGregor, 1979), but their Rb and Sr contents are comparable.

The most obvious element variations in the Harker diagrams are for K_2O and FeO + MgO which respectively show a direct and inverse relation to SiO_2. This relationship and the almost linear variation strongly suggest that the gneisses possibly belong to a comagmatic series and represent fractionation products of a common source. Whereas the FeO-MgO trends and absolute contents are similar to the Early Proterozoic gneisses of Anderson and Cullers (1987), the gneisses from Pouso Alegre are enriched in potash. It can be envisaged that the reason for this difference might lie in remelting of pre-existing rocks in the case of Pouso Alegre in contrast to the primitive nature of equivalent or older gneisses from basement gneiss complexes elsewhere. TiO_2 and Sr show a somewhat irregular distribution, but Rb contents increase in the same manner as K_2O - a variation which is not unexpected. More analyses are, however, needed to corroborate such variations and also to relate the chemistry of these gneisses with that of the older grey gneisses to be able to provide a satisfactory explanation for their origin.

No matter how we interpret the major element concentrations, the key to resolve the origin of basement gneisses seems to lie in their rare earth element (REE) patterns which have been used time and again by several authors for understanding the formation of continental crust (to quote some recent examples - Arth et al., 1978; Condie, 1981; Jahn et al., 1984; Nutman and Bridgwater, 1986; Martin, 1987).

The rare earth patterns of the gneisses are typically light rare earth (LREE) enriched and heavy rare earth (HREE) depleted as is generally observed in rocks of this kind (Fig. 4). The potash felspar-rich augen gneiss shows a prominent negative europium anomaly, but the rest lack europium anomalies, and the absence of positive anomalies indicates that there was no accumulation of plagioclase in their formation. The overall patterns are very similar to those of Early Proterozoic tonalite series analysed by Anderson and Cullers (1987) and to the high-K orogenic andesites of Gill (1981), shown as a band in Fig. 4A for comparison. Continuing such comparisons, we can see from Fig. 4B and 4C that Early Archaean grey and white gneisses from southern West Greenland are also closely parallel except that the gneisses from Pouso Alegre are much less depleted in HREE. Like other Archaean gneisses the grey gneisses and augen gneisses from eastern Finland (Martin et al., 1983) are also strongly depleted in HREE - this appears in the form of a hockey-stick pattern in contrast to the gneisses from Pouso Alegre (Fig. 5). The latter are on the whole, therefore, analogues to Early Archaean and Early Proterozoic gneisses with characteristic differences at the HREE end.

ORIGIN AND EMPLACEMENT

Several possibilities for the origin of tonalites and associated gneisses in old basement complexes are discussed by Jahn et al. (1984), Anderson and Cullers (1987) and Martin (1987). The choice of a model for the origin of these gneisses will largely depend on their REE pattern which can fingerprint the protolith magmas from which they formed. Models for their origin may be related to 1) melting of Archaean gneisses, 2) eclogite melting, 3) fractionation of basaltic magma or 4) hornblende fractionation. Jahn et al. (1984) appeal to a multi-stage derivation rather than direct extraction from melting of upper mantle whereby successive melts and their fractionation products are enriched in LREE and depleted in HREE.

Although the data presented here for the Pouso Alegre gneisses are very meagre, and many more analyses are needed to strengthen the hypothesis for their formation, we can still draw some preliminary conclusions if we put together all our observations. This is to say that the gneisses have to be regarded in the context of geology, petrography and geochemistry. It appears that we are stating the obvious; however, frequently geochemical studies are carried out with utter disregard for other relevant and important aspects of the rock types studied (surprisingly, even in international literature!). A praiseworthy exception is the excellent paper by Martin (1987). We therefoere base our conclusions on field aspects combined with major element contents and REE patterns. The latter are seemingly in agreement with the in-group fractionation suggested by the major element trends. Of the four models stated above, the one that best fits the REE patterns is the hornblende fractionation model of Nutman and Bridgwater (1986) which gives the trend illustrated in Fig. 4. The primary derivation of the protoliths of the gneisses might be from melting of older mafic-rich gneisses followed by removal of hornblende and differentiation to successively potash-rich liquids.

One of the REE characterisitics which needs some explanation is the lesser degree of HREE depletion to which attention has been drawn earlier on. To account for this feature we must fall back on geology and petrography of these gneisses. A typical aspect is the occurrence of mafic shlieren and clots of hornblende and garnet in many of these rocks which might lead one to suppose that they are restites or residual source material as in the examples discussed by Chappell et al. (1987). However, there is good reason not to jump to this conclusion if we consider the petrographic character of the surrounding rocks as well. It is easy to see that the schlieren could be the result of assimilation of mafic material at the time of emplacement of the protoliths. Being more refractory, the mafic minerals remain as clots or schlieren or are even scattered in the quartz-feldspar rich magma. This is frequently observed on the outcrop scale in many different places and we need not appeal to processes whose effects are not so evident. The fractionation of HREE in phases such as hornblende and garnet is, in our opinion, an entirely adequate explanation, for the lesser HREE depletion, specially since amphibolite and garnet amphibolites with mineralogy similar to the schlieren are common in the older gneisses in this area, and could be available for assimilation.

Granitic melts may be generated under the most varied geological circumstances. In high-grade terrains, regional metamorphism can lead to partial melting in pelitic gneisses if the necessary temperatures are exceeded (Winkler, 1976), and even for orthogneisses temperatures for initial partial melting need not go beyond the 680 to 750°C/4 to 5 kb range. To obtain entire melts of tonalitic composition, however, temperatures in excess of 1000°C are required (Wyllie, 1977), and in the case of vapour-absent melting of tonalitic gneisses to produce granitic melts in the deep continental crust the temperature must surpass 950°C as demonstrated by Rutter and Wyllie (1988). Field evidence suggests that the gneisses studied here were emplaced (or injected) as large sheet-like bodies in a tonalite-amphibolite terrain. We assume that this could take place if enough heat for melting is supplied to middle and deep crustal mafic-rich gneisses and amphibolites to generate the protoliths, and that this could happen by mantle upwelling to subcrustal levels. Tonalite magma generation at this level would then heal large-scale regional weakness zones or "cracks" to further consolidate and stabilize the gneiss complex. Accompanying deformatiion at these levels also contributes considerably to the formation of such basement gneiss complexes. The question remains whether these zones were sites of previous rifting and volcanism which left scars healed by subsequent magmatic events.

CONCLUSION

As a contribution to the problem of formation of basement gneiss complexes, we have shown that a later group of gneisses which invaded older gneisses around Pouso Alegre probably belong to a comagmatic series grading from tonalitic to granodioritic compositions. Their REE patterns are comparable to Early Archaean and Early Proterozoic gneisses elsewhere, and can be best explained by assuming generation of tonalitic magmas followed by hornblende fractionation.

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REFERENCES

ANDERSON, J.L. & CULLERS, R.L. 1987 - Crust-enriched, mantle-derived tonalites in the Early Proterozoic Penokean orogen of Wisconsin. Journ. Geol. 95, 139-154.

ARTH, J.G.; BAKER, F.; PETERMAN, Z.E. & FRIEDMAN, I. 1978 - Geochemistry of the gabbro-diorite-tonalite-trondhjemite suite of southwest Finland and its implications for the origin of tonalitic and trondhjemitic magmas. Jour. Petrol. 19, 289-316.

CHAPPELL, B.W.; WHITE, A.J.R. & WYBORN, D. 1987 - The importance of residual source material (restite) in granite petrogenesis. Jour. Petrol. 28, 1111-1138.

CHOUDHURI, A. 1976 - Evolution of the Proterozoic belt in northern Guiana - A hypothesis for a greenstone belt. XXIX Cong. Bras. Geol. Ouro Preto, An. 4, 303-312.

CHOUDHURI, A.; YASUDA, S. & CELLIGOI, A. 1987 - Time relations of amphibolites, tonalites and augen gneisses around Pouso Alegre: Event sequence in the gneiss complex. An. 4º Simp. Geol. Minas Gerais, Belo Horizonte, 312-328.

COLLERSON, K.D. & BRIDGWATER, D. 1979 - Metamorphic development of early Archaean tonalitic and trondhjemitic gneisses, Saglek area, Labrador. In: Trondhjemites, dacites and related rocks 205-273. Barker (ed.) Elsevier Publ., Amsterdam.

CONDIE, K.C. 1981 - Archaean greenstone belts. Elsevier Publ. Amsterdam.

CROSTA, A.P.; CHOUDHURI, A.; SZABO, G.A.J. & SCHRANK, A. 1986 - Relações entre tipos litológicos e suas estruturas regionais nos terrenos arqueanos e proterozóicos do sudoeste de Minas Gerais. XXXIV Congr. Bras. Goiânia. An. vol. 2, 710-721.

EBERT, H. 1984 (in memoriam) Os paraibides entre São João del Rei e Itapira e a bifurcação entre Paraibides e Araxaides. Publ. SBG-SP nº 12/1984.

FIORI, A.P. 1979 - Geologia da região de Pouso Alegre - Machado: Análise estrutural de dobramentos superpostos. Tese de Doutoramento - IG/USP.

GILL, J.B. 1981 - Orogenic andesites and plate tectonics. Springer Verlag, New York.

HEISENBERG, W. 1973 - Schritte uber Grenzen. Piper Verlag, München.

JAHN, B.M.; VIDAL, P. & KRÖNER, A. 1984 - Multi-chronometric ages and origin of Archaean tonalitic gneisses in Finnish Lapland: a case for long crustal residence time. Contr. Mineral. Petrol. 86, 398-408.

LAMEYERE, J. & BOWDEN, P. 1982 - Plutonic rock types series: discrimination of various granitoid series and related rocks. J. Volcanol. geotherm. Res. 14, 169-186.

MARTIN, H. 1987 - Petrogenesis of Archaean trondhjemites, tonalites and granodiorites from eastern Finland: Major and trace element geochemistry. Jour. Petrol. 28, 921-953.

MARTIN, H.; CHAUVEL, C. & JAHN, B.M. 1983 - Major and trace element geochemistry and crustal evolution of Archaean granodioritic rocks from eastern Finland. Precambrian Res. 21, 159-180.

MASUDA, A.; NAKAMURA, N. & TANAKA, T. 1973 - Fine structures of mutually normalized rare-earth patterns of chondrites. Geochim. Cosmochim. Acta 37, 239-244.

McGREGOR, V.R. 1979 - Archaean gray gneisses and the origin of the continental crust: evidence from the Godthåb region, West Greenland. In: Trondhjemites, dacites and related rocks. 169-204. Barker (ed.), Elsevier Publ. Amsterdam.

NUTMAN, A.P. & BRIDGWATER, D. 1986 - Early Archaean Amîtsoq tonalites and granites of the Isukasia area, southern West Greenland: development of the oldest-known sial. Contr. Mineral. Petrol. 94, 137-148.

RUTTER, M.J. & WYLLIE, P.J. 1988 - Melting of vapour-absent tonalite at 10 kb to simulate dehydration melting in the deep crust. Nature, 331, 159-160.

STRECKEISEN, A. 1975 - To each plutonic rock its proper name. Earth Sci. Rev. 12, 1-33.

WERNICK, E.; ARTUR, A.C. & FIORI, A.P. 1981 - Reavialiação de dados geocronológicos da região nordeste do Estado de São Paulo e unidades equivalentes dos Estados de Minas Gerais e Rio de Janeiro. Atas 3º Simp. Regional Geol. Curitiba, 1, 328-342.

WINKLER, H.G.F. 1976 - Petrogenesis of metamorphic rocks. 4th. Ed. Springer Verlag, New York.

WYLLIE, P.J. 1977 - Crustal anatexis: An experimental review. Tectonophysics 43, 41-71.

FIGURE CAPTIONS

Fig. 1 Geological sketch map of southwestern Minas Gerais (after Crosta et al., 1986) with main lithological units - 1 = migmatites, tonalites and orthogneisses, 2 = granulite, 3 = metasediments and paragneisses, 4 = pink, potassic migmatites and granitic rocks, 5 = alkaline complex of Poços de Caldas; arrows show sense of movement along regional faults, barbs represent thrust faults. G = Guaxupé, P = Poços de Caldas, PA = Pouso Alegre, S = Silvianópolis.

Fig. 2 General aspect of migmatites in the field.

Fig. 3 Element variation in Harker diagrams. Fields of tonalites from Anderson and Cullers (1987) - hatchured fields with vertical lines & blanks are foliated tonalites, diagonal = host gneisses.

Fig. 4 REE patterns for Pouso Alegre gneisses: R/C = rock/chondrite using normalizing values of Masuda et al. (1973).

A. Thick lines are tonalitic to granodioritic gneisses of this study, hatchured band is trend of high-K orogenic andesites from Gill (1981), dashed line shows pattern obtained by 20% hornblende fractionation after Nutman and Bridgwater (1986).

B. & C. Blank band represents pattern for Pouso Alegre gneisses, while vertically hatchured fields are white and grey gneisses from Greenland (Nutman and Bridwater, 1986).

Fig. 5 REE patterns for Pouso Alegre gneisses (blank band) compared to A. grey gneisses and B. augen gneisses from eastern Finland (Martin et al., 1983).

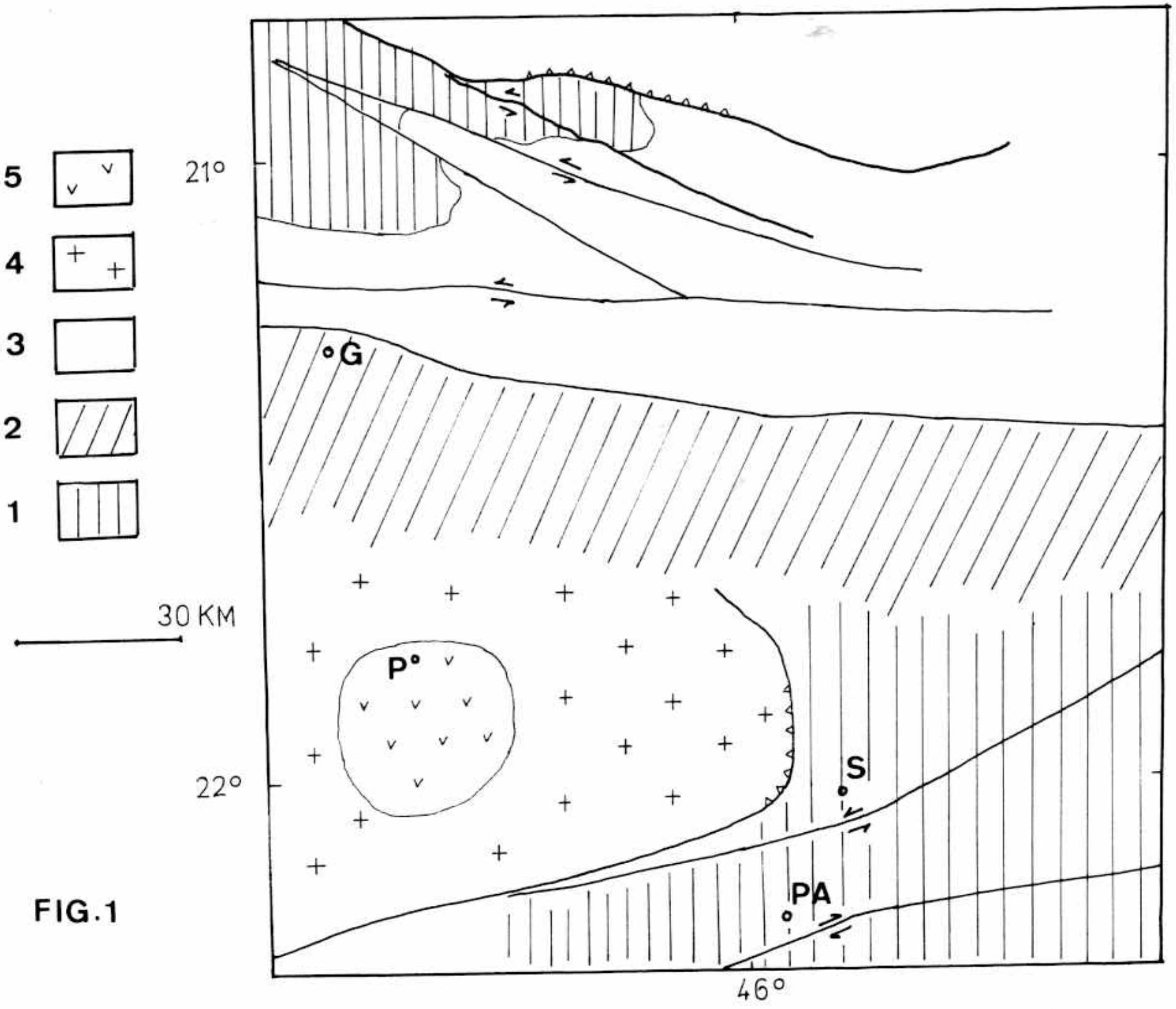

FIG.1

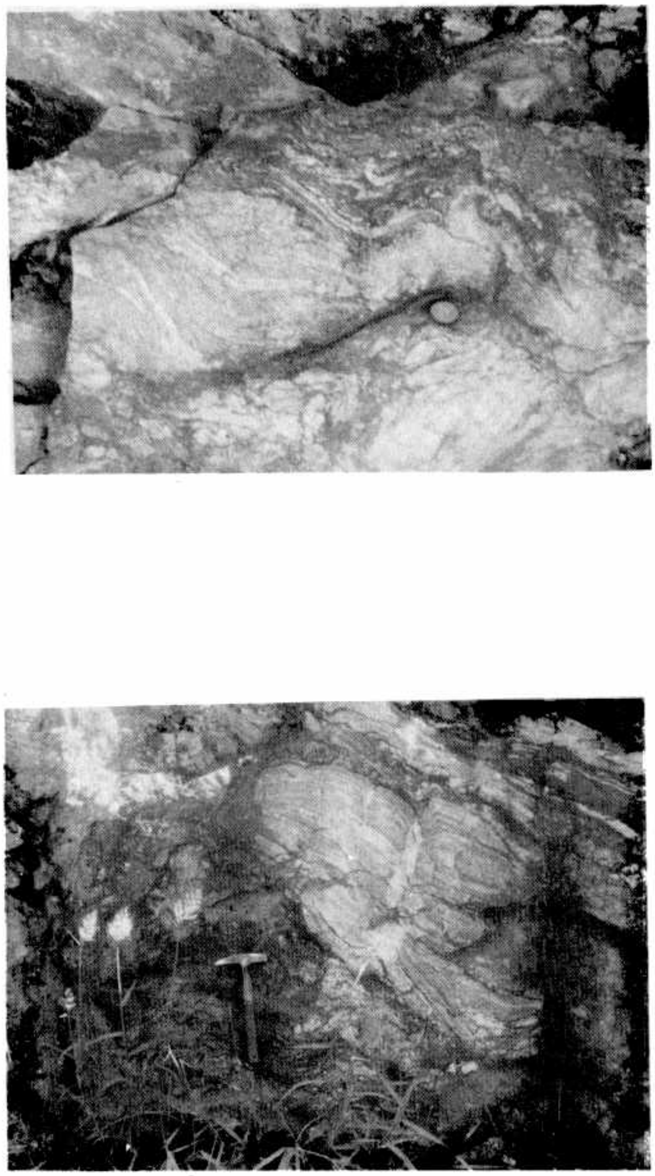

FIG. 2

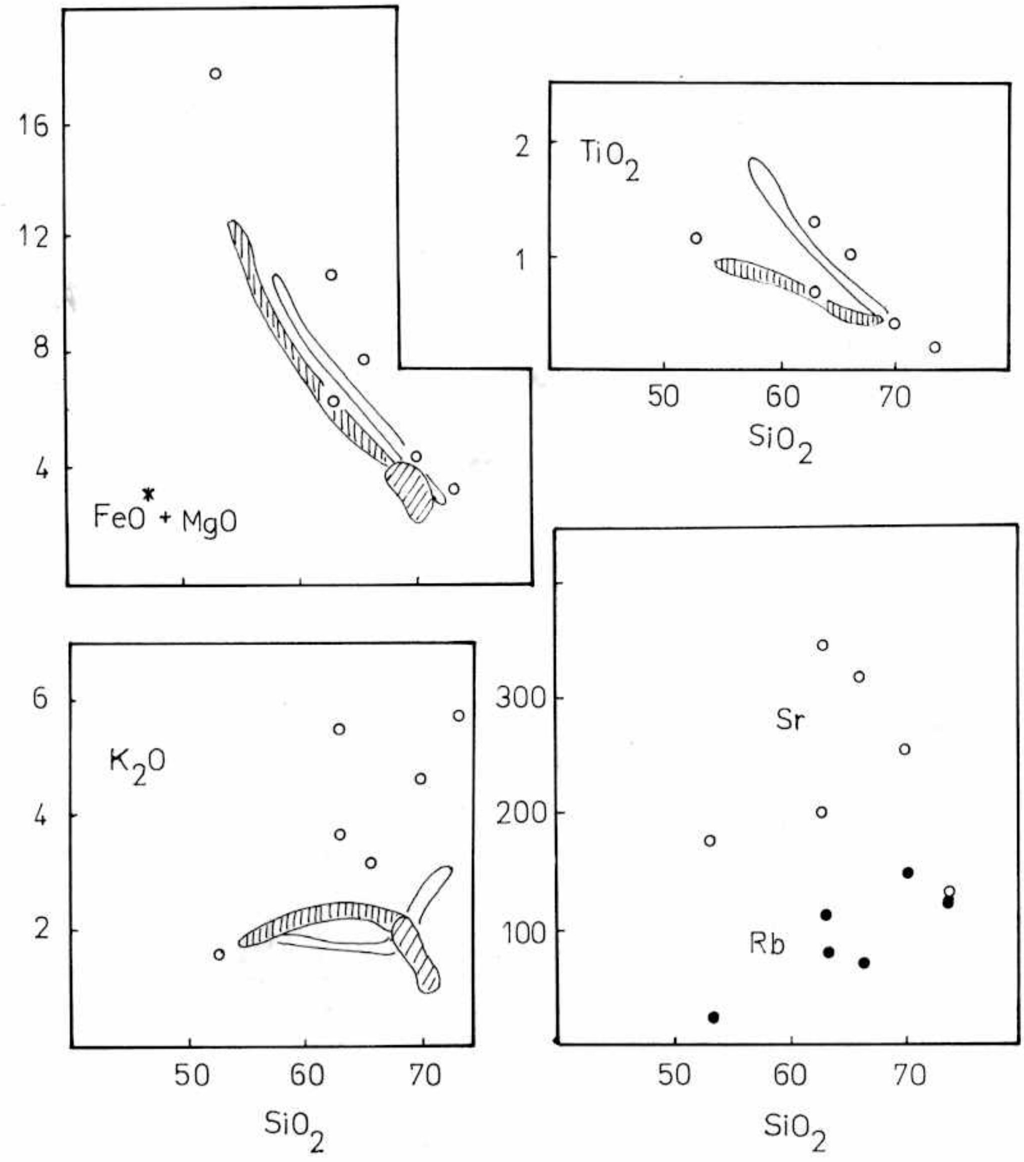
16
12
8
4
FeO* + MgO
2
1
TiO2
50
60
70
SiO2
6
4
2
K2O
50
60
70
SiO2
300
200
100
Sr
Rb
50
60
70
SiO2

FIG. 3

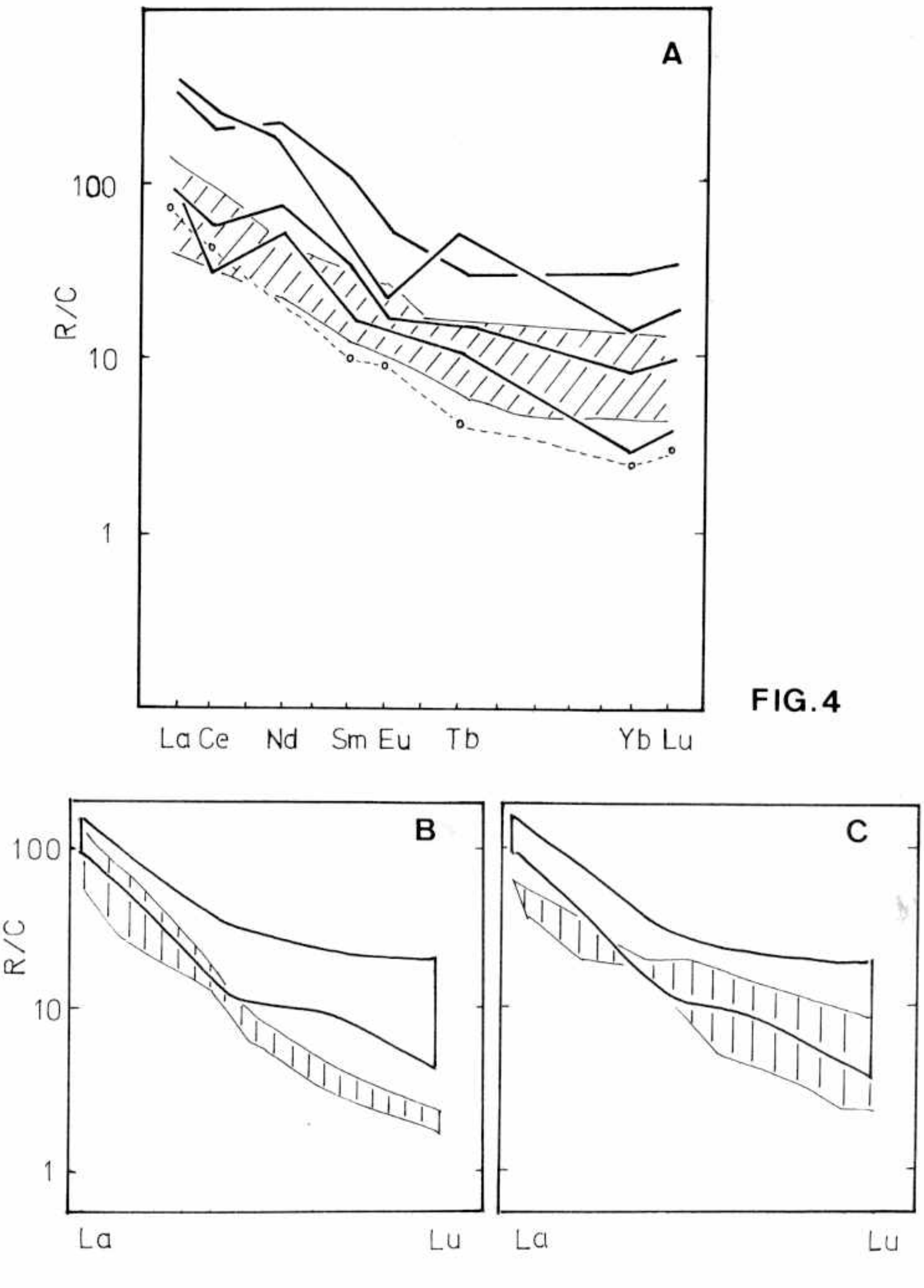

FIG. 4

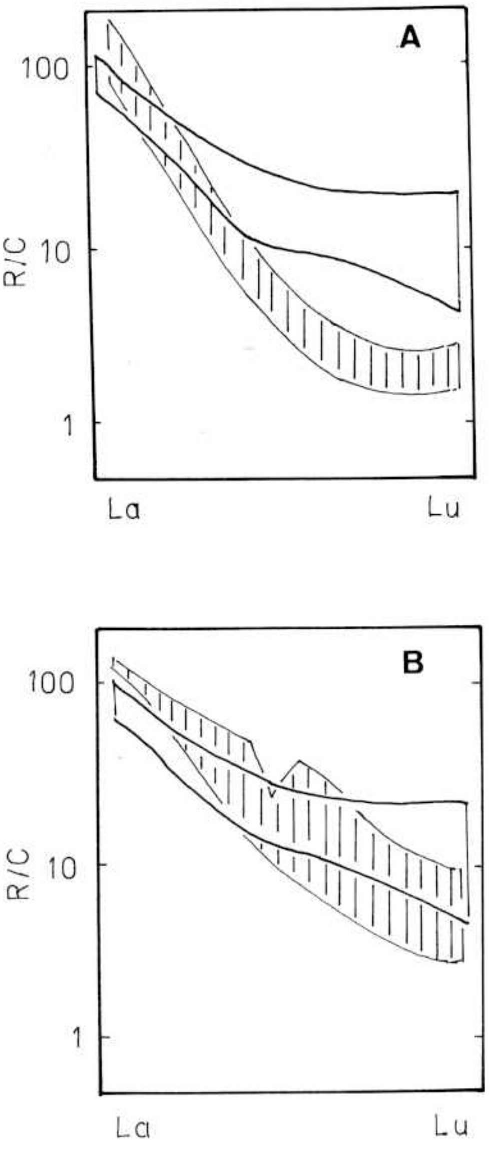

FIG. 5