Some Geochemical Data of the Mafic-Ultramafic Complex at Tulu Dimitri, Ethiopia, and their Genetic Significance

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With 13 Figures

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Abstract

The Upper Proterozoic Western Volcanic Belt of Ethiopia contains at Tulu Dimitri an elongate mafic-ultramafic complex, which was interpreted earlier on field evidence as an ophiolite. In view of the important regional tectonic implications a confirmation was sought by carrying out geochemical analyses on a small suite of representative rocks of the complex.

The chemical data confirm the ophiolitic identity of the Tulu Dimitri complex. REE-contents differ, however, from published standards.

Zusammenfassung

Der jung-proterozoische westliche Vulkanitgürtel in Äthiopien enthält bei Tulu Dimitri einen länglichen mafisch-ultramafischen Komplex, der vor kurzem auf Grund geologischer Feldarbeit als Ophiolit interpretiert wurde. Da dies wichtige Konsequenzen für die Deutung der regionalen geologischen Zusammenhänge hat, wurde eine Überprüfung dieser Interpretation durch gesteinsgeochemische Analysen einer Anzahl repräsentativer Proben aus dem Komplex durchgeführt. Die Resultate werden hier beschrieben.

Die chemischen Daten bestätigen die ophiolitische Natur des Tulu-Dimitri-Komplexes; die SEE-Gehalte weichen allerdings z. T. beträchtlich von den bisher bei Ophioliten bekannten ab.

Introduction

The Precambrian rocks of Western Ethiopia have been subdivided into three major domains by KAZMIN et al. (1978, 1979): An eastern and western block of high-grade gneisses flank the pan-African "Western Volcanic Belt", which wedges out southwards to the Kenyan border, but widens to the North. It is interpreted as representing a Mid-Upper Proterozoic oceanic basin between older continental blocks. Most of the magmatic and sedimentary rocks of the belt are thought to be island arc derived, but a large complex of mafic and ultramafic composition in the

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Tulu Dimitri area (fig. 1) is considered on field evidence as obducted oceanic crust. The aim of the present investigations was to contribute geochemical data on selected rocks from the complex, to provide further arguments for a decision on its ophiolitic nature. The petrographic work was carried out on 84 thin sections of Tulu Dimitri rocks provided by the Ethiopian Geological Survey Institute, while the geochemical analyses are based on 17 rock samples from the same source.

The Tulu Dimitri Complex

The mafic-ultramafic rocks of the complex occupy an area of 10–15 by 120 km. The complex is in inferred tectonic contact to the east with gneiss and migmatite of the Eastern craton. It consists of narrow bodies of ultramafic rocks, mainly serpentinite, talc- and anthophyllite-schist traceable for 20 km or more along strike, within which fault-bounded blocks of dunite and peridotite occur in close spatial association with gabbro and amphibolite. Westwards the mafic and ultramafic rocks pass upwards into a volcanosedimentary association metamorphosed in the upper greenschist to lower amphibolite facies. This includes greenstones which form sequences on their own but are also interlayered with pelitic to psammitic schist, graphitic phyllite and marble. Although, as in the south, severe tectonism precludes elucidation of the stratigraphy in detail, it seems probable that the massive greenstones probably underlie, and pass into the volcanosedimentary succession. The rocks described are intruded by slightly deformed to undeformed diorites and granites.

Rocks designated metavolcanic serpentinites occur within the overlying succession around the Tulu Dimitri dome. Such ultramafic lavas are more characteristic of Archaean ultramafic-greenstone associations. Their presence in the M.-U. Proterozoic Tulu Dimitri complex is therefore of considerable interest. Petrological and chemical evidence described in the following sections confirms the presence of high Mg ultramafic lavas.

Quarz-plagioclase porphyries possibly represent genetically related late stage acid differentiates similar to the plagiogranites of other ophiolites.

The presence of a thick succession of psammite and semi-pelite overlying the gabbro unit reflects the deposition of clastics derived from adjacent continental cratons within the volcanic trough during closure.

KAZMIN et al. (1979) infer that the ophiolitic slabs were emplaced along steep westward inclined thrusts, and that the presence of ultramafic rocks in tight overturned synclines points to nappe formation at an early stage, as they are involved in the main folding.

A preliminary geological map of the Tulu Dimitri complex compiled by the Ethiopian Geological Survey has recently become available (M. BERHE, written communication). Although the structure of the complex is still not fully understood this map further illustrates the probable ophiolitic nature of the complex.

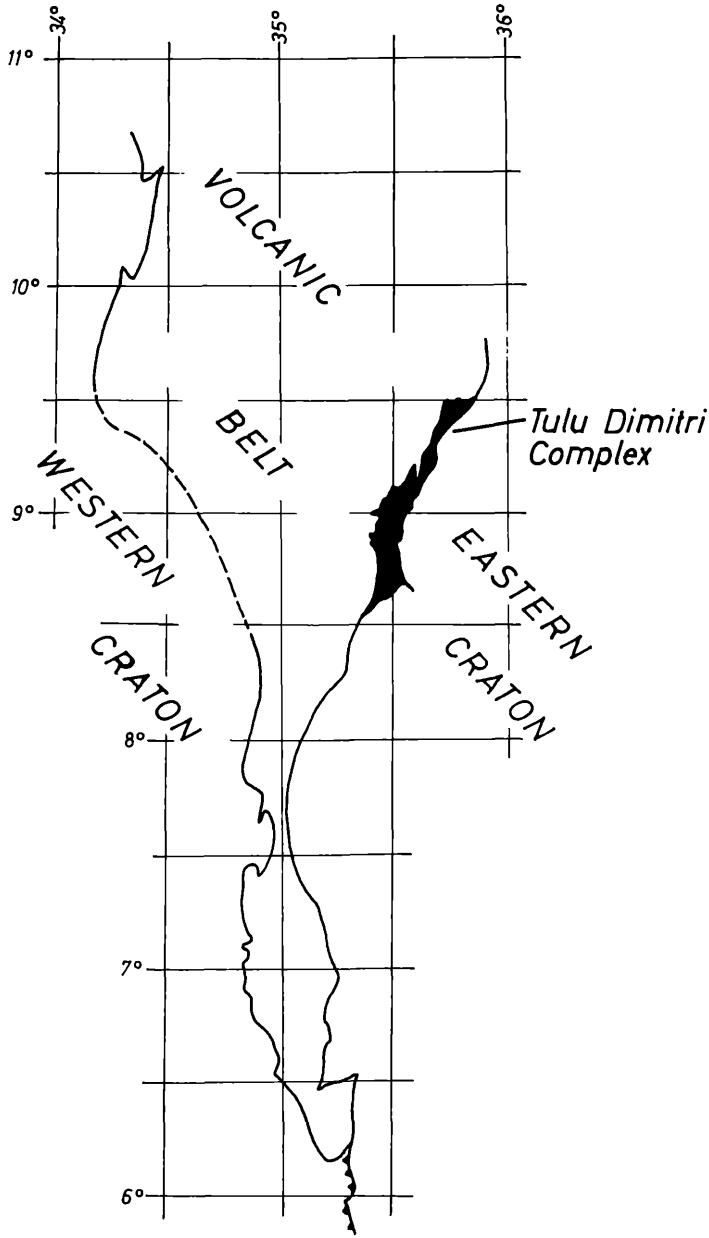

Fig. 1: Geology of the Western Volcanic Belt of Ethiopia, after KAZMIN et al. (1980).

The approximate location of samples described in the following sections was given by A. J. WARDEN (1981).

Petrography of the Tulu Dimitri complex

Both igneous and sedimentary members of this suite display original and secondary metamorphic textures. Formation of the latter was accompanied by the generation of mineral assemblages characteristic of metamorphism up to the lower amphibolite facies. The mineral assemblages and paragenesis of the main rock types were described in detail by A. J. WARDEN (1981). Cataclasis and deformation of mylonitic intensity is common in many of the rocks of the Western Volcanic Belt.

Ultramafic rocks

Although most ultramafic rocks are serpentinised, and commonly show evidence of shearing and low grade metamorphism indicated by such minerals as antigorite and talc, relict forsterite grains survive in some instances within a boxwork of serpentine minerals. An original cumulate texture may be inferred for such rocks. The olivines are commonly rimmed by talc, carbonate, and opaque minerals. Opaque minerals occur interstitially and form layers in some specimen.

Magnetite of secondary origin is the most abundant opaque phase. It frequently pseudomorphs crystals of chromite, although in rare cases primary chromite survives in an unaltered state. In some instances the chrome spinel picotite forms relict cores surrounded and rimmed by magnetite.

The Cr is thought to have migrated out leaving Fe behind. The irregular spongy form of the picotite cores is possibly due to the development of solution channels during this process and is typical of the birbirites which carry associated platinoids in the south of the Western Belt (AUGUSTHITIS, 1965). Birbirites are also developed in the Tulu Dimitri area. Microprobe analyses are required to support the tentative conclusions regarding the secondary alteration of the spinels (A. J. WARDEN & E. F. STUMPFL, in preparation).

Talc occurs in patches and along shear partings, and turbid carbonates also feature as a patchy alteration product. The mineralogical characteristics indicate that these rocks are serpentinised dunites.

A few specimen with euhedral pyroxene pseudomorphs were probably derived from pyroxene peridotite. A relatively fresh specimen of harzburgite from cumulate rocks in the upper part of the ultramafic unit consists mainly of forsteritic olivine (2V suggests approximately 15 % Fa), together with strongly pleochroic orthopyroxene and some diopside.

A rock consisting of a felted mass of green to colourless tremolite and patches of secondary hornblende with secondary opaque minerals may

represent metapyroxenite. Undeformed veins containing calcic plagioclase, calcite and epidote suggest metamorphism in the lower amphibolite facies.

Serpentinite has been converted to anthophyllite schist in highly tectonised zones, particularly near faults bounding the Central Volcanic Belt, for example at the western contact beyond the Tulu Dimitri area. It was not however, recorded in the rock suite from Tulu Dimitri. Anthophyllite indicates metamorphism at around 670° C (WINKLER, 1979), which is appreciably higher than that sustained by the ultramafic rocks of the Tulu Dimitri complex.

Talc-carbonate and talc-tremolite rocks

Associated with the ultramafites are rocks in which little or no primary fabric survives. They consist of talc, antigorite, poorly defined patches of carbonate, and scattered magnetite. Talc associated with serpentine minerals occurs in random orientation and in schistose foliae. In one specimen it forms 65 % of the rock and is associated with interstitial chlorite, some rutile and magnetite.

Various talc-tremolite rocks are represented. They contain colourless tremolite, talc, chlorite, pale green uralitic amphibole and secondary magnetite. In one instance the original mafic minerals are seen to be pseudomorphed by tremolite and opaques. The groundmass consists of chlorite, opaque minerals, epidote and a minor amount of quartz.

The original ultramafic rock types of these metamorphic derivatives cannot be readily ascertained. Some may have been peridotites, while others were probably transitional to mafic members of the suite.

The moderately strong metamorphism producing these mineral assemblages with rising pT followed serpentinisation and is consistent with the regional metamorphism of up to lower amphibolite facies noted in this area.

Mafic intrusives

At least two generations of gabbroic rocks are associated with the Tulu Dimitri ultramafic suite. One is strongly metamorphosed and probably coeval, while the other comprises a group of younger, fresh, unmetamorphosed intrusions.

The older intrusions range from mafic to anorthositic gabbro (modal colour index: 70–20), and include olivine-, clinopyroxene-, and less common probably noritic types, with primary hornblende in some cases. They are generally coarse textured although primary fabrics are largely overprinted and obliterated by secondary metamorphic ones which render identification difficult.

The older gabbros consist of a decussate mass of tremolitic amphibole with epidote (in some instances clinozoisite), chlorite and minor calcite. Relict ophitic texture is common. Serpentinite pseudomorphs suggest the presence of olivine in some gabbros while

relict grains of clinopyroxene commonly survive in the cores of crystals largely replaced by uralitic and/or tremolitic amphibole, and green hornblende in a few instances, plus chlorite. Pyroxene pseudomorphs showing similar alteration in a few cases contain relict grains of orthopyroxene with schiller structure in one specimen.

Plagioclase is mostly strongly saussuritised. Calcite is also commonly present, and in one specimen alteration products include acicular amphibole and chlorite.

Some primary plagioclase with a composition of bytownite (An_{72}) survives in one specimen of noritic gabbro, though it is mostly altered, and has a composition of andesine.

Both primary and secondary magnetite are present. In some rocks the former is rimmed by sphene suggesting the original mineral was titano-magnetite while secondary skeletal opaques were formed by the alteration of olivine and pyroxene.

Some minor intrusions cutting the Tulu Dimitri complex consisting of olivine, clinopyroxene, primary olive brown amphibole and labradorite (An_{30}) are probably coeval with the gabbros, and have also undergone metamorphism accompanied by extensive development of secondary amphibole.

The later suite of gabbros which intrude the Tulu Dimitri complex probably post-date the metamorphism as they have fresh igneous textures. They include troctolitic and anorthositic varieties consisting of olivine, clinopyroxene showing schiller structure, brown hornblende, brown biotite and labradorite (An_{55}). The primary and secondary opaque phases are probably mainly titanomagnetite and magnetite.

Also grouped within the mafic category are problematical rocks which are petrographically dioritic but have a silica content characteristic of gabbros. They are mineralogically similar to the older gabbros, except that the plagioclase has a composition in the oligoclase to andesine range (An_{30-35}). However, this could be due to depletion of the anorthite content as in the case of some of the gabbros.

As in the older gabbros metamorphism has produced decussate, and in some instances granoblastic fabrics. The mafic minerals are extensively replaced by secondary amphiboles and the plagioclase is mostly strongly saussuritised. Both primary and secondary opaque phases are present and in one sample pyrite with associated chalcopyrite was recorded. These sulphides were probably redistributed into micro-shears during late stage tectonism postdating the main metamorphism.

Granitic rocks

Some granites may represent the original plagiogranitic end members of the Tulu Dimitri suite which have undergone late stage potash metasomatism. Others belong to a post-tectonic suite of younger granites. The only specimen available for study is well foliated and

consists of strongly sericitised plagioclase, tabular quartz and biotite with fresh late stage xenoblastic microcline and string perthite. Although pre-, or syntectonic, it is unlikely on chemical grounds discussed later, that this is a metasomatised plagiogranite.

Metabasalts

These rocks have a similar mineralogy to the older gabbros. Some varieties are porphyritic, but primary textural features are blurred by metamorphism. They consist mainly of secondary blue-green amphibole, showing in some instances a slight preferred orientation. Epidote and chlorite are common. Plagioclase is heavily altered and replaced by albite and calcite in most cases. Both primary and secondary opaque phases, mostly magnetite and titanomagnetite were recorded, and some specimen contain a little secondary quartz. One specimen contains probable phenocrysts pseudomorphed by aggregates of tremolite, and in some instances chlorite in a matrix consisting of tremolite, chlorite and sericite. This rock which contains no relict plagioclase is probably an ultramafic lava. Chemical data support this conclusion. The other specimen examined are non-porphyritic metabasalts.

Metasedimentary rocks

Metamorphosed sedimentary rocks are interbedded with the metabasalts in the upper part of the Tulu Dimitri complex and become abundant in the volcanosedimentary sequence to the west. They include clastics derived both from volcanic and continental source rocks.

The former include wackes of variable composition and para-amphibolite, and the latter consist mainly of arkose and quartzite. Metasedimentary rocks of mixed origin are also common.

Texturally the volcanic wackes vary from inequigranular and granoblastic to schistose, and they are compositionally similar to the mafic igneous source rocks. Opaque minerals, and both rare detrital and metamorphic hornblende occur in a few samples.

It is often difficult to determine whether the primary texture in some rocks from the mixed volcanic-sedimentary sequence is porphyritic or clastic. One specimen showed a concentration of yellowish to dark green hornblende in layers, and a variation in grain size between these and more felsic layers which contain plagioclase and quartz. The latter survive as megacrysts which are heavily altered in the case of plagioclase. Such amphibolites may represent basaltic crystal lithic tuffs. As will be seen in the following section they have the same chemical composition as the basalts from which they were derived.

Another sample of amphibolite probably largely derived from mafic tuffs but showing a more well defined sedimentary texture also consists of alternating felsic and mafic layers comprised respectively of sericitised plagioclase and quartz, and tremolite with some epidote, calcite and accessory sphene. Both relict and metamorphic hornblende are

represented. The latter is a dark olive brown variety the presence of which, together with fresh labradorite (An_{55}) is also thought to have a metamorphic rather than relict detrital origin, suggests fairly strong metamorphism in the amphibolite facies.

Pelites interbedded with the rocks described consist mainly of brown biotite, muscovite, chlorite, some tremolite, opaque minerals, and scattered quartz probably mainly of original detrital origin. They vary from calcareous to semi-pelitic. The former contain tremolite, calcite and in some cases hornblende in addition to the normal metapelitic assemblage. Banding on a scale of a few millimetres is commonly developed due to the alternation of quartz with or without plagioclase and pelitic layers. The felsic layers show a suggestion of graded bedding in rare instances although such structures are generally destroyed by metamorphism.

The meta-arkoses and quartzites contain no volcanic lithics. The former have an inequigranular blastic texture although in some instances schistosity is developed due to recrystallisation of quartz in a tabular form. In addition to quartz, they contain xenoblastic microcline locally showing perthitic texture, and sericitic plagioclase with minor amounts of epidote and biotite.

The impure quartzites have a metamorphic cataclastic-mosaic texture. Biotite is present in the matrix and they contain a minor amount of epidote and muscovite together with accessory opaque minerals, including haematite.

Magnetite quartzites with a strongly cataclased texture form a distinctive rock type within the sedimentary sequence. They are commonly banded due to alternation of coarse and fine grained layers of tabular quartz and are locally mylonitised. No original textures are preserved and they possibly represent ferruginous quartzites or cherts mylonitised in the vicinity of shear zones.

Geochemistry of the Tulu Dimitri suite

A batch of 17 samples representative of the main rock types were analysed for major, minor, and trace elements by Mather Laboratories in England using XRF techniques. A duplicate set of these samples was analysed for rare earth elements by one of the authors (W. K.).

Although the number of samples is too small to give a sound statistical basis for the determination of various trends, in most instances the results (with the exception of the REE analyses) confirm the petrological and field evidence suggesting that these rocks are members of an ophiolite suite of probable back-arc type.

Major element analyses reveal anomalously high SiO_2 values in some of the ultrabasic rocks such as serpentinised dunite. This is probably due to secondary silicification comparable to that recorded in other Late Precambrian ultramafic complexes within the region such as the Jabal al

Wask ophiolite (NEARY, 1974) and the Hamdah complex of Saudi Arabia (WARDEN, in press). In both instances the serpentinite units are permeated by secondary colloidal silicia.

Another feature is the high MgO content of 20–30 % in rocks thought to be metabasalts on field evidence but whose primary mineral composition could not be readily elucidated in thin section due to metamorphism. They resemble komatiites in this respect and may represent ultramafic flows of cumulate type, or sills. They are also compositionally similar to ankaramitic and picritic basalts formed by voiding of cumulates from high level magma chambers in island arcs (WARDEN, 1970 b). Ultrabasic lavas resembling those described have also been reported from the Troodos ophiolite complex (BEAR in COLEMAN, 1977). Another feature common to these various cumulate rock types is their high Ni and Cr content of the order of 1000–2000 ppm in the case of those from Tulu Dimitri, the high TiO_2 content of the latter is discussed later.

As previously noted, the basaltic and gabbroic members of the suite are mostly affected by spilitization and metamorphism up to lower amphibolite facies. With the breakdowm of the primary minerals, MgO, FeO, and CaO are redistributed but probably remain relatively constant in terms of original content in representative specimen while the rocks are enriched in alkalis during spilitisation.

An AFM plot for the Tulu Dimitri suite (fig. 2) shows a concentration of points in the oceanic gabbro, metamorphic peridotite, and cumulate mafic and ultramafic fields. For comparison, rocks from the Bir Umq ophiolite in the Saudi Arabian portion of the shield are also plotted. Many of the metabasalts from both areas lie within field A for Coleman's ophiolitic pillow lavas. Displacement of many of the Bir Umq points towards the alkali corner probably reflects spilitization.

When plotted on a differentiation index diagram, the Tulu Dimitri rocks (fig. 3) show a short trend line suggestive of a consanguineous origin. However, this cannot be extended to include possible related intermediate rocks due to a lack of suitable samples. A Si + Al-Mg + Fe plot of the type used by PETRAKAKIS (1978) to demonstrate that amphibolites from the Stubachtal ultramafic complex in Austria are genetically related to the ultramafic members of the association was also used to test a similar affinity between basalts, amphibolites and the ultramafic rocks of the Tulu Dimitri complex (fig. 4). Despite a gap bridged by only one recording, a suggestion of a continuous trend is evident.

Although the foregoing evidence gives an indication of a possible ophiolitic origin, it is inconclusive. Attention therefore focusses on selected minor and trace elements including Ti, Zr, Y, Nb, Ce, Ga, Sc. These, particularly the first three elements listed, are inert during secondary alteration and metamorphism and thus help to fingerprint the original chemical character of the rocks (FLOYD and WINCHESTER, 1978;

PEARCE and CANN, 1973). Elements such as K, Rb, Sr, and to a certain extent P, on the other hand tend to be mobile under spilitic and metamorphic conditions and are therefore less useful for this purpose. Nevertheless, plots involving some of these elements gave a classification for the Tulu Dimitri rocks which was consistent with other methods employed.

The Tulu Dimitri rocks were plotted on a variety of discrimination diagrams involving combinations of, and ratios between, the minor and trace elements listed. On a Ti/Zr diagram of the type used by PEARCE and

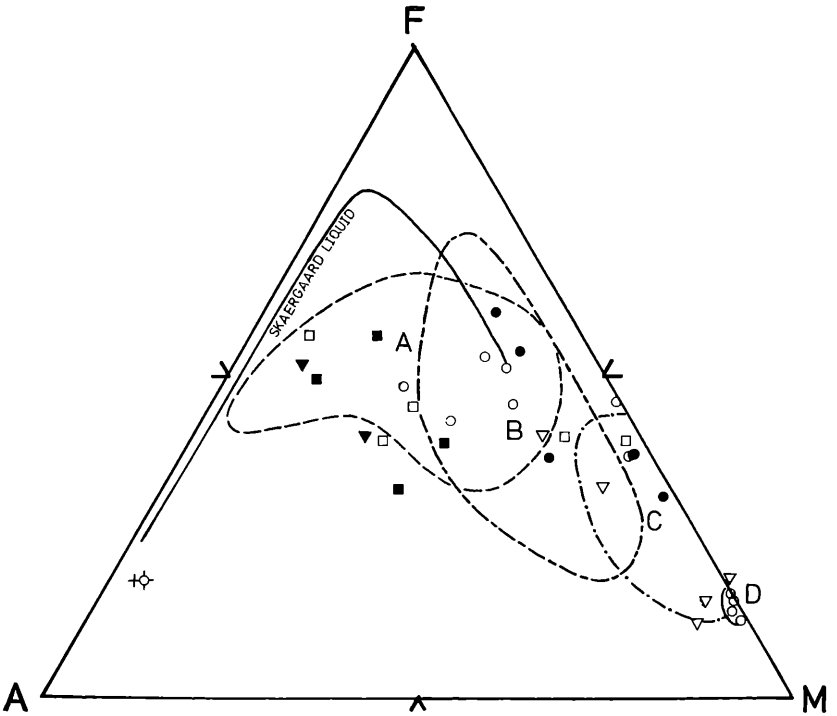

Fig. 2: AFM plot for Ethiopian and Saudi Arabian ultramafic complexes. Tulu Dimitri and Bir Umq show field characteristics of ophiolite which are lacking in the Hamdah Complex. Most of the rocks plot in the metamorphic peridotite, cumulate mafic and ultramafic, oceanic gabbro, and ophiolitic pillow lava fields. Displacement of some of the Bir Umq rocks towards the alkali corner may be due to spilitisation. A-approximate field for ophiolitic pillow lavas (COLEMAN 1977), B-oceanic gabbros (BAKOR 1976), C-mafic and ultramafic cumulate ophiolite rocks (COLEMAN 1977), D-metamorphic periodotites (COLEMAN 1977). Open circles = metagabbro and ultramafitite, open circles with cross = ortho-amphibolite, black dots = metabasalts from Tulu Dimitri; other signs for Bir Umq and Hamdah rocks.

CANN (1973), (fig. 5), the few basalts and related intrusive rocks mostly plot just outside the field for the ocean floor basalts reflecting high Ti values. When these rocks are plotted on their triangular discrimination diagram for within plate basalts (fig. 6) based on adjusted ratios between Ti, Zr and Y, the same problem is encountered. The high Ti values place the majority in the field for oceanic or continental basalts and only two plot as ocean floor rocks. Although the Ti values are high, and it has been partly redistributed and concentrated within sphene formed during metamorphism, as noted later, these are not excessive because they fall within the limits established for the various rock types present.

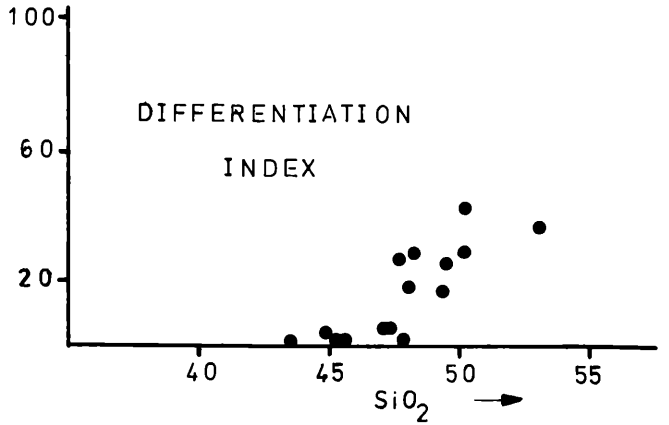

Fig. 3: Differentiation index diagram for all Tulu Dimitri rocks. Indication of a short trend line suggests a consanguineous origin.

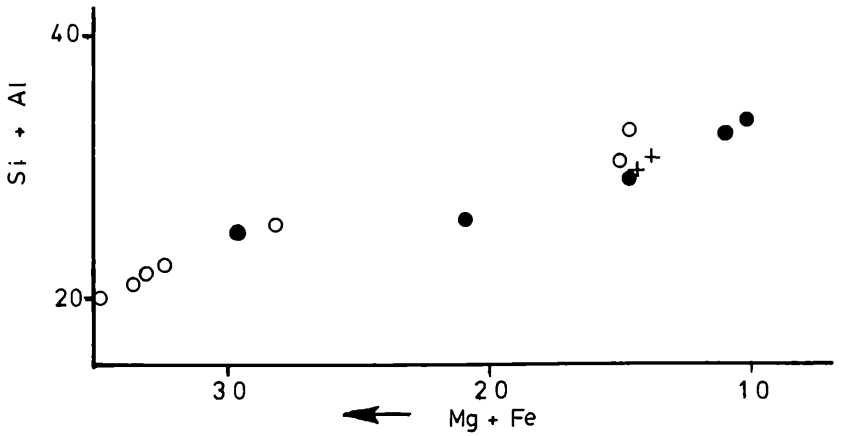

Fig. 4: A Si + Al – Mg + Fe plot. This suggests a genetic affinity between Tulu Dimitri ultramafic rocks, basalts and amphibolites although a gap exists which is bridged by only one sample. c. f. PETRAKAKIS (1978).

A TiO_2-K_2O-P_2O_5 ternary diagram (fig. 7) gives a clearer picture of the affinity of the Tulu Dimitri rocks. Most of the basalts and intrusive rocks plot within the oceanic field of PEARCE et al. (1975). The few basalts from the Bir Umq ophiolite in Saudi Arabia are also concentrated within this field.

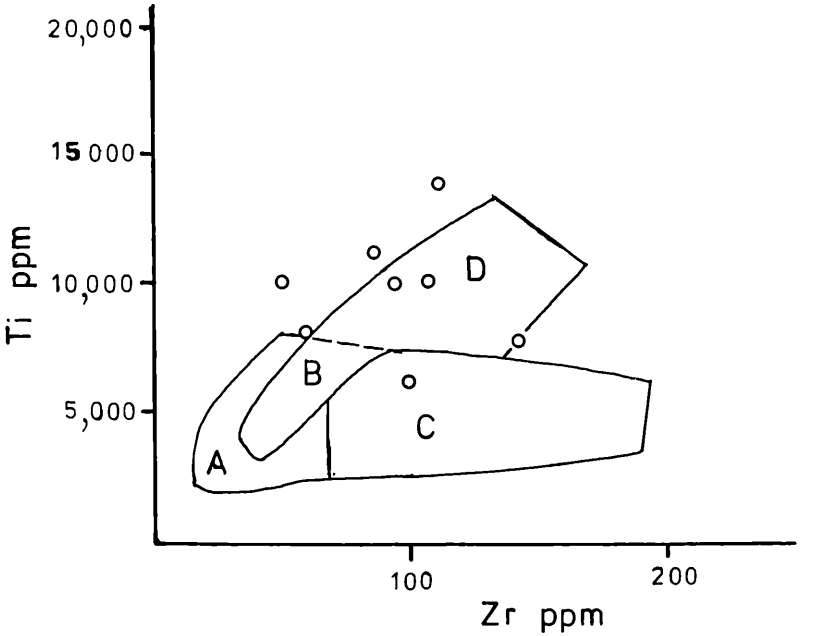

Fig. 5: Diagram of discrimination of basalts in terms of tectonic setting using Ti and Zr, after PEARCE and CANN (1973). Ocean floor basalts plot in fields D and B, low K tholeiites in field A and B, and calc-alkaline basalts in fields C and B. Tulu Dimitri basalts and related intrusive rocks plot outside the field of ocean floor basalts reflecting high Ti values. As pointed out by COLEMAN (1977) the shortcoming of this diagram is the considerable overlap between the fields. Also different Ti and Zr values from different parts of an ophiolite sequence vary according to degree of differentiation and describe a trend through fields A, B and C.

Significantly, in the diagrams advocated by FLOYD and WINCHESTER (1975, 1978) for discrimination of metavolcanic rocks, nearly all the Tulu Dimitri basalts and intrusives fall within the appropriate fields.

These diagrams (fig. 8–12) use ratios of various minor and trace elements against single elements or ratios of other elements; Zr/TiO_2 is one of the parameters in most cases. In all diagrams, the rocks plot in the basalt field, and in the sub-alkaline field where this is shown. In fig. 10 the Tulu Dimitri rocks are clearly grouped in the oceanic tholeiitic basalt field. However, this presentation is partly unsatisfactory as the respective fields lack the clearly defined boundaries which characterise the other diagrams (E. F. STUMPFL, pers. comm.).

Clearly one of the problems with the methods used by PEARCE and CANN (op. cit.) is the high Ti values. Although a high Ti content is a characteristic trait of the alkali basalts, tholeiitic basalts can also have large TiO_2 values as high as 1.74 %, for example in the MAR rift valley (HERKINIAN et al., 1976) while olivine tholeiite basalts show maxima of 2–2.2 % TiO_2 (WEDEPOHL, 1978). The latter also cites values for ultramafic rocks ranging from 0.81 % in peridotites to 2.88 % in

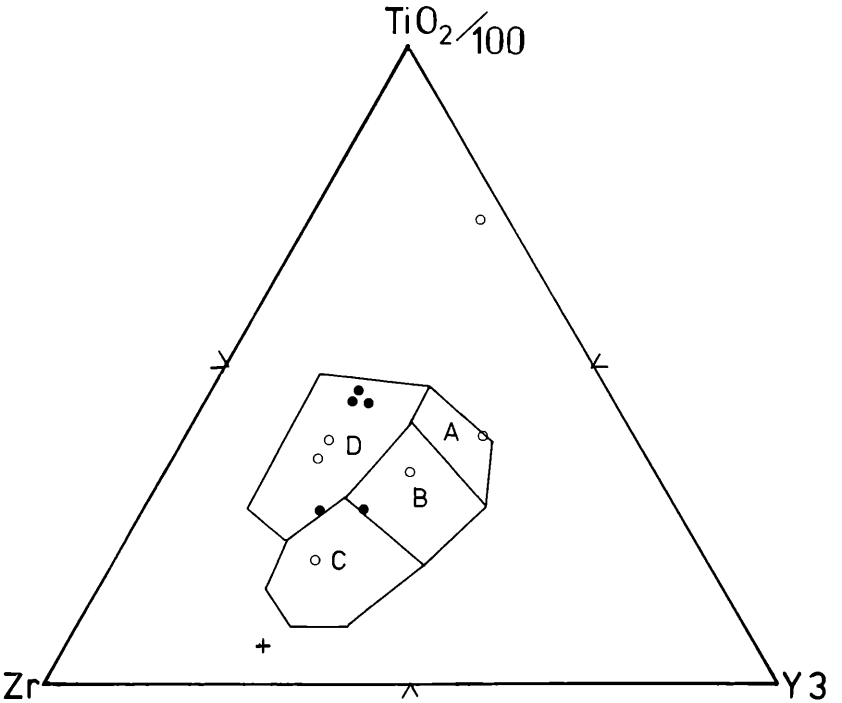

Fig. 6: Discrimination diagram using Ti, Zr and Y for "within plate" basalts. Based on PEARCE and CANN (1973). Ocean island or continental basalts plot in field D, ocean floor basalts in field B, low K tholeiites in fields A and B, and calc-alkali basalts in fields C and B. High Ti values place most of Tulu Dimitri rocks in field for oceanic or continental basalts. Only 2 plot as ocean floor rocks.

hornblendites. Even allowing for some local concentration of Ti by secondary redistribution into sphene the Tulu Dimitri suite still falls within acceptable limits of TiO_2 values for the various rock types. A point which should be remembered when using the TiO_2 content as a parameter to establish the identity of various rock types is the fact that because of its considerable variability it is difficult to derive a meaningful average for rocks of a particular composition (FISHER et al., in WEDEPOHL, op. cit.).

The critical factor for discrimination between rock types is the ratio between selected minor and trace elements rather than their absolute

values. Although the methods of PEARCE and CANN are effective for fresh and spilitized rocks, and also for those metamorphosed in the lower greenschist facies, the techniques of FLOYD and WINCHESTER appear to be more effective for discrimination of rock types metamorphosed at higher grades. The Tulu Dimitri rocks are identified as ophiolites on the basis of their methods.

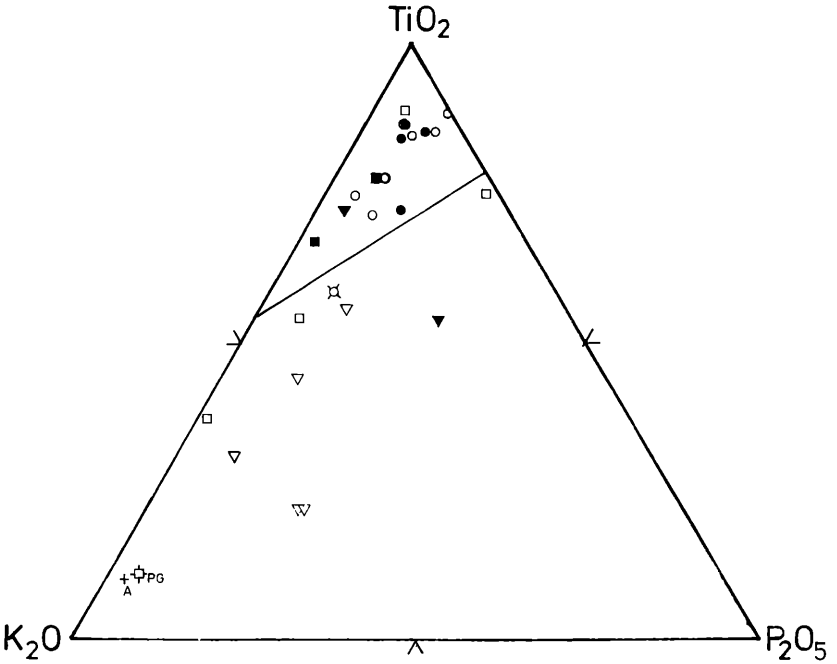

Fig. 7: Proposed ternary discrimination diagram of PEARCE and CANN using TiO_2-K_2O-P_2O_5 Most of the Tulu Dimitri rocks plot in the oceanic basalt field near the TiO_2 corner as do many of those from the Bir Umq ophiolite. It is notable that most of the rocks from the Hamdah Complex plot in the non-oceanic field.

Some 17 samples were analysed for selected trace and REE. These were normalised in relation to REE in chondrites. It was thought that the 7 REE analysed out of a total of 12 would be sufficient to produce curves for comparison with established patterns for various members of the ophiolite suite, the ultramafic members of which give a characteristic inverted bell shaped curve for depleted REE (COLEMAN, 1977, fig. 3; EL AGEED and STUMPFL, 1980). However, REE values for the Tulu Dimitri rocks give curves which differ from, and do not simulate, the typical curves for the various members of the ophiolite suite (fig. 13). A few similarities are, however, evident. The serpentinised peridotite and dunite show depletion in incompatible REE relative to chondrites, but not to the same degree as in metamorphic peridotite from more modern ophiolites. Some features of the typical curve are reproduced. These include a rise in

the proportion of europium in one instance, and a slight rise in the proportion of heavy elements such as lutetium. However, the typical inverted bell shape is not reproduced.

One gabbro roughly approximates to the curve of the upper level gabbros and the MAR averages although containing a much higher proportion of all REE than the former. However, the others show a downward, instead of upward trend from La to Nd, although showing in some cases the positive europium anomaly, and a slight drop in heavy REE from Yb to Lu.

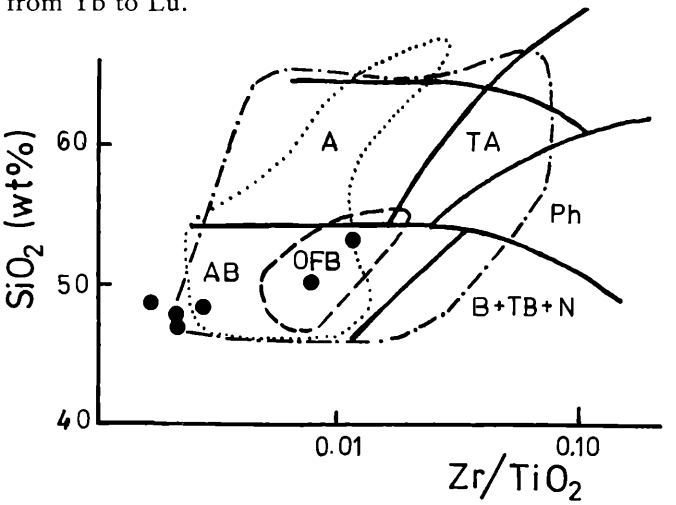

Fig. 8: Proposed SiO_2-Zr/TiO_2 diagram of FLOYD and WINCHESTERS (1978) for discrimination of metabasalts. Field A – andesites; TA-trachyandesites; Ph-phonolites; B + Tb+ N-basanites, trachybasanites, nephelinites; AB-subalkaline basalts; OFB-ocean floor basalts. The dotted line indicates field for Noranda greenstones. Tulu Dimitri metabasalts plot in the subalkaline basalt field, and in two instances in the ocean floor basalt field.

The basalts show an irregular trend with a high Eu value in one instance, probably due to substitution for Ca in the plagioclase phenocrysts. Some samples are abnormally enriched in REE.

An orthoamphibolite sample from Tulu Dimitri has comparable REE values and when plotted shows a similar trend to garnet amphibolite from the Hochgrössen ultramafic complex in Austria (EL AGEED et al., 1980 b). These rocks have similar REE values to the basalts of the Troodos complex. Like the gneiss amphibolite from the Hochgrössen two metagabbros show a steady drop in REE values from La to Lu although the gradient is less steep than in the case of the former and the Ethiopian rocks show a slight positive instead of negative Eu anomaly. The Hochgrössen gneiss-amphibolite has similar REE values to diorites of the Troodos complex. One of the Tulu Dimitri samples was classified petrologically as diorite although chemically gabbroic on the basis of major element analyses.

Although the Tulu Dimitri ultramafic suite shows ophiolitic characteristics in terms of petrological criteria and major, minor and trace element geochemistry, evidence from the REE is inconclusive. This is probably because the REE are less stable under conditions of intermediate metamorphism, particularly where shearing has occurred (for example DOSTAL et al. 1980) than was formerly suspected. The enrichment patterns noted for some of the upper members of the Tulu Dimitri suite (various gabbros and lavas in fig. 13) show overall REE enrichment and selective light REE enrichment comparable to the Type 1 REE mobility of HELLMAN et al. (1979). The contrasted very strong LREE enrichment and apparent HREE depletion evident in the ultramafic and lower intrusive members of the Tulu Dimitri suite do not correspond well with the mobility types of HELLMAN and co-workers. They are, however, similar to patterns observed by DOSTAL et al. (fig. 1., op. cit).

Conclusions

Field relations, petrographic investigations and limited chemical data with the exception of the ambiguous REE results confirm the ophiolitic identity of the Tulu Dimitri complex. Due to mineralogical and chemical

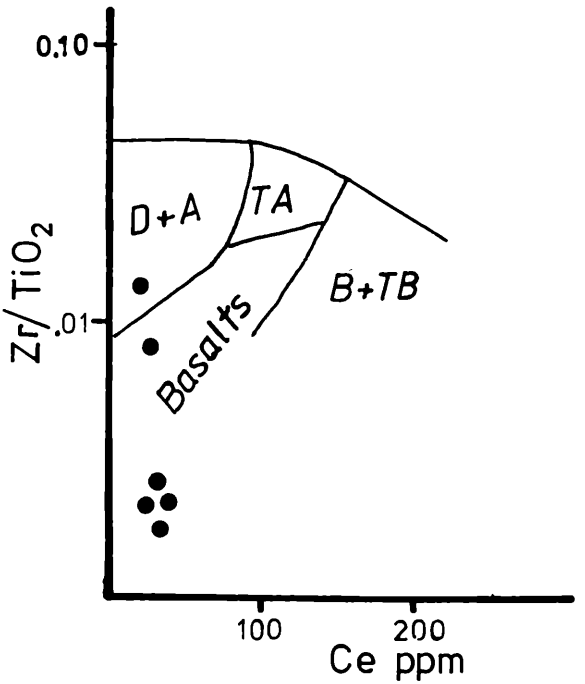

Fig. 9: A Zr/TiO_2-Ce variation diagram for metavolcanic suites. Based on FLOYD and WINCHESTER (1978). Fields as for figure 8 except for D + A = dacites and andesites. Tulu Dimitri rocks plot mainly in the basalt field.

changes during metamorphism this is established mainly on the basis of ratios between diagnostic minor and trace elements.

This study, and evidence from other recent investigations on comparably metamorphosed mafic-ultramafic suites, indicates the equivocal nature of the REE signature as a determinative criterion for an ophiolitic origin, where these have been deformed. In establishing the identity of such complexes equal weight must be given to the other lines of evidence which suggest their ophiolitic character.

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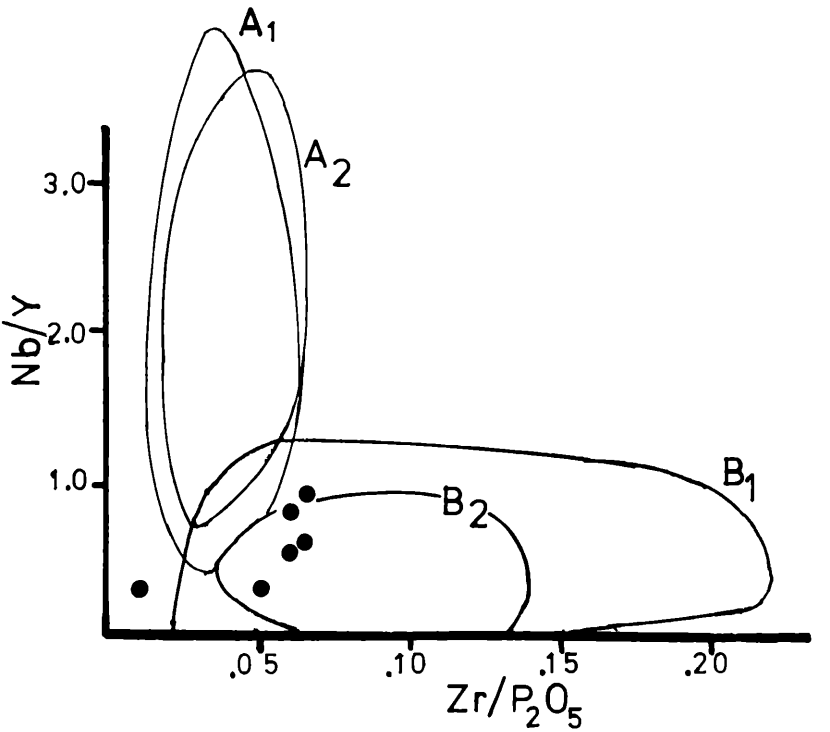

Fig. 10: Nb/Y-Zr/P_2O discrimination diagram of FLOYD and WINCHESTER (1975). Field A1 = continental alkali basalts; A2 = oceanic alkali basalts; B1 = continental tholeiitic basalts; B2 = oceanic tholeiitic basalts. Most of Tulu Dimitri basalts plot in latter field.

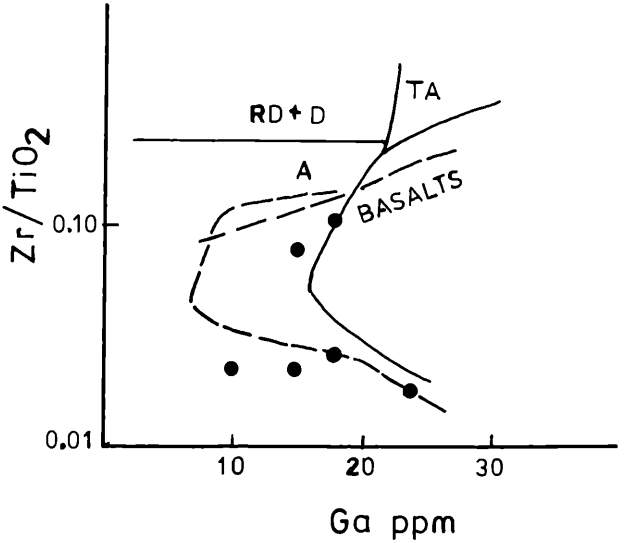

Fig. 11: Zr/TiO_2-Ga diagram for greenstones based on FLOYD and WINCHESTER (1978). Fields as for figure 9; RD and D = rhyodacite and dacite. The Tulu Dimitri metabasalts all plot within the appropriate field, mostly within the field of the yellowknife Archaean greenstone.

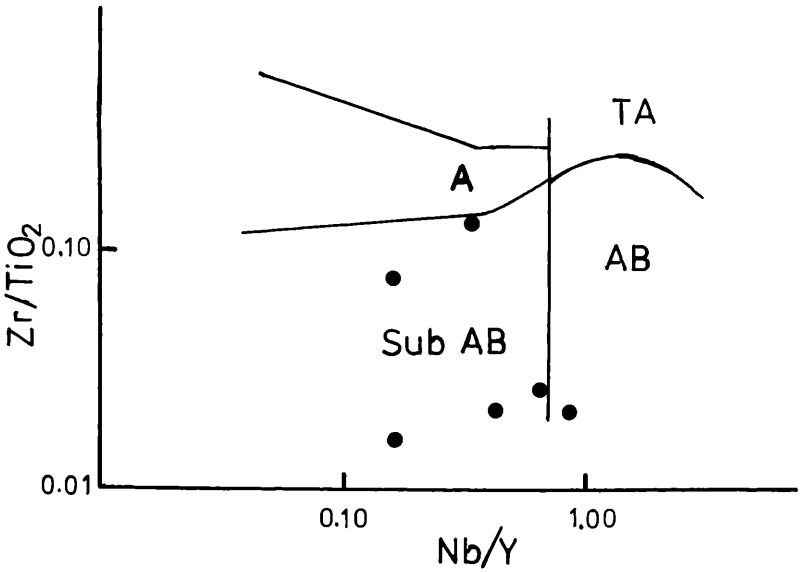

Fig. 12: Zr/TiO_2-Nb/Y diagram for discrimination of metavolcanic rocks. After FLOYD and WINCHESTER (1978). Fields as for figure 8 Tulu Dimitri basalts plot mainly within the sub-alkaline basalt field.

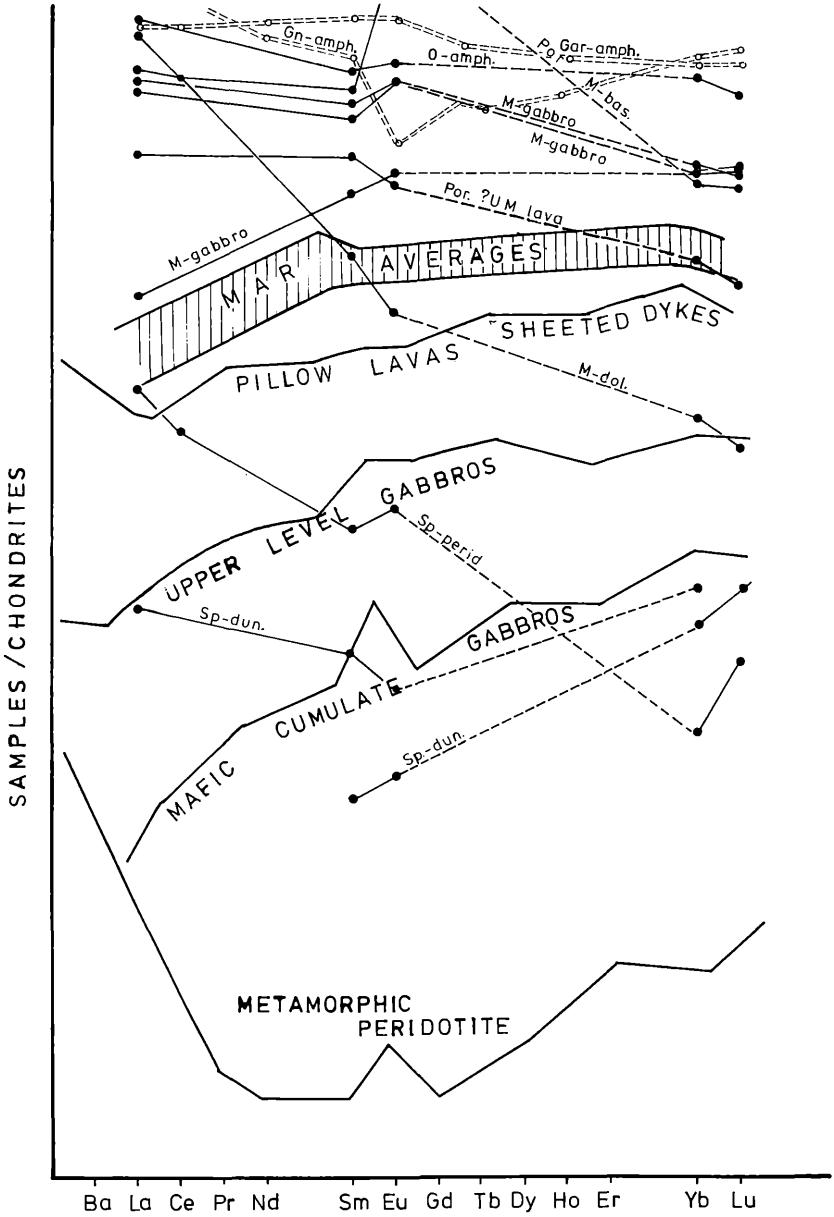

Fig. 13: REE distribution in Tulu Dimitri ultramafites and associated rocks compared with typical curves for members of established ophiolite suites (after COLEMAN, 1977). Double dashed lines are for REE in amphibolites from the Hochgrössen ultramafic complex (after EL AGEED et al., 1980). Analyses by W KIESL, Chemistry Dept. University of Vienna.

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