The Käyser dolerite, a Mesoproterozoic alkaline dyke suite from Suriname

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Les dolérites Käyser, une série mésoprotérozoïque de dykes alcalins au Suriname

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Key words: Alkali basalt, Alkaline, Tholeiite, Rifting, Mesoproterozoic.

Abstract

The Käyser dolerite forms a NW-SE-trending dyke swarm in western and southwestern Suriname. Petrography and chemistry indicate that the dolerite has an alkaline composition, in contrast to the major dolerite suites in Suriname, i.e. the Avanavero and Apatoe suites, which are tholeiitic. The three dolerite types can be distinguished by their minor and trace elements. The Käyser dolerite is probably younger than the Avanavero Suite, but older than the Nickerie Metamorphic Episode, giving the time frame for its intrusion as between ca. *1800 Ma and 1200 ± 100 Ma. A first attempt at dating the dykes, using $^{40}Ar/^{39}Ar$ laser dating of biotite, yielded an age of around 1500 Ma. The Käyser dolerite dykes occur along conspicuous NW-SE-trending faults, some of which bound a graben. The relationship to the fault-system and graben structure indicates that the intrusion of the Käyser dolerite accompanied a major tensional event in the northern part of the Guiana Shield. Although no other tectonic or magmatic event at about 1500 Ma is known from this central part of the Guiana Shield, in the northwest of the Shield the huge anorogenic Parguaza granite pluton was intruded at about this time. It is possible that anorogenic granitoids of this age were intruded into the NW-SE-trending zone along with the Käyser dolerite dykes, but have not yet been noticed because of limited geochronological dating.*

Résumé

Au Suriname, l'essaim des dykes doléritiques de la suite Käyser est orienté NW-SE. Les données pétrographiques et géochimiques indiquent que ces dolérites ont une composition alcaline qui contraste avec celle des essaims doléritiques des Suites Avanavero et Apatoe, qui sont tholéitiques. Ces trois types de dolérites peuvent être distingués par leur composition en éléments mineurs et traces. Les dolérites Käyser sont vraisemblablement plus jeunes que celles de la Suite Avanavero mais plus anciennes que l'événement métamorphique Nickerie, ce qui situe leur mise en place entre 1 800 et 1 200 ± 100 Ma. Un premier essai de datation, utilisant la méthode $^{40}Ar/^{39}Ar$ par sonde laser sur biotite, a fourni un âge autour de 1 500 Ma. Les dolérites Käyser sont situées le long d'importants accidents orientés NW-SE. Quelques-unes de ces failles forment la bordure d'un graben. Les relations entre ce système d'accidents et la structure du graben indiquent que la mise en place des dolérites Käyser a accompagné un événement extensif majeur dans la partie septentrionale du Bouclier des Guyanes. Au centre du Bouclier, aucun autre événement tectonique ni magmatique n'a été reconnu autour de 1 500 Ma, en revanche, c'est à peu près à cette même époque que, dans la partie nord-ouest du Bouclier, se sont mis en place les granites anorogéniques de la suite Parguaza. Des granites anorogéniques de cet âge ont pu se mettre en place peut-être dans la même zone NW-SE que les dolérites Käyser mais ils n'ont pas été mis en évidence jusqu'ici à cause du faible nombre de données géochronologiques.

Introduction

The northern part of the Guiana Shield comprises vast areas of Trans-Amazonian basement locally overlain by

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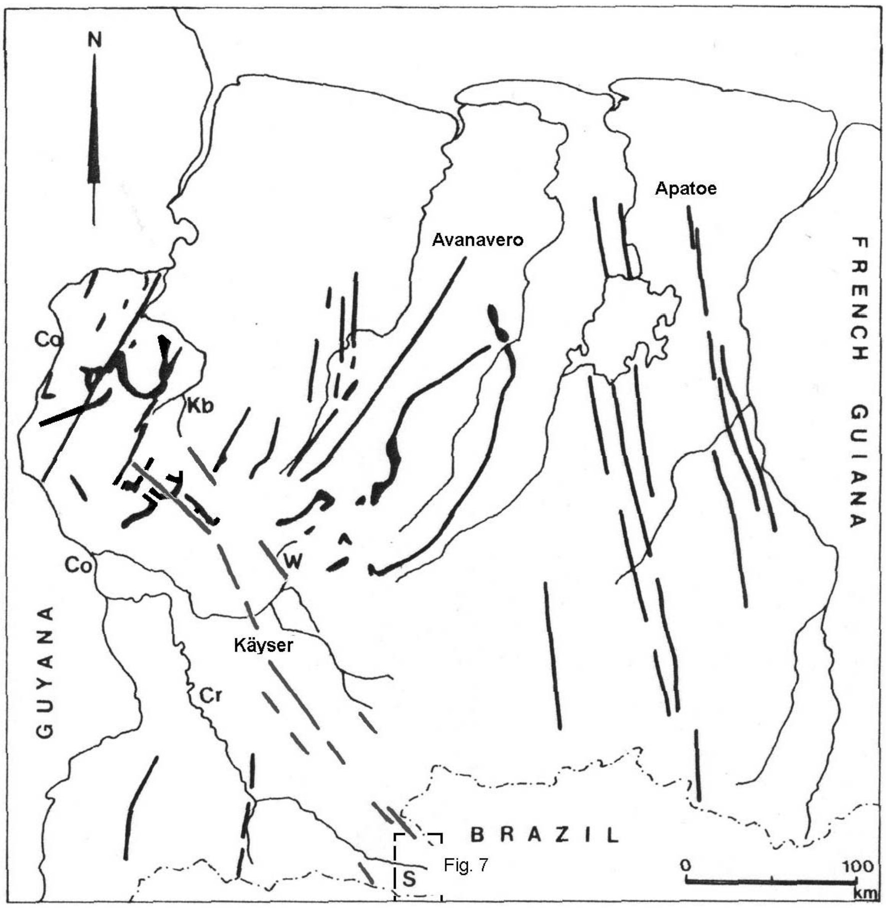

Fig. 1.- Dolerite suites in Suriname: NW-SE-trending Käyser dolerite dykes in the SW (grey/green, stippled); N-S-trending Apatoe Suite dykes in the E and W; NE-SW-trending Avanavero Suite dykes, sills and sheets in the centre and NW. Abbreviations: Käyser: Käyser Mountains; S: Sipaliwini river; W: Westrivier river; Kb: Kabalebo river; Cr: Coeroeni river; Co: Corantijn river. Insert near Sipaliwini river - Figure 7.

Fig. 1.- Champs filoniens du Suriname : dykes doléritiques Käyser de direction NW-SE (gris-vert) ; à l'est, dykes Apatoe de direction N-S ; dans le centre et au nord-ouest, dykes Avanavero de direction NW-SE. Abréviations : Käyser : Käyser Mountains; S : rivière Sipaliwini; W : rivière Westrivier; Kb : rivière Kabalebo; Cr : rivière Coeroeni; Co : rivière Corantijn. Insert près de la rivière Sipaliwini, cf. Fig. 7.

younger sedimentary Roraima Supergroup cover rocks. Two major dolerite suites, the Avanavero Suite and the Apatoe Suite, intrude both the basement and cover.

The Avanavero Suite forms a spectacular series of sills and sheets (up to 500 m thick), and associated feeder dykes, intruded in the Roraima Supergroup cover and underlying basement of southern Venezuela and adjacent parts of Guyana and Brazil (Roraima State). The dykes in this area may branch and change strike irregularly (Gibbs and Barron, 1993). In western and central Suriname (Fig. 1) this suite forms sills, inclined sheets, and large dykes that have a prevailing NE-SW strike, are up to 1 km wide, and reach lengths of 150 km. The Avanavero Suite was not known in French Guiana, but recently a NNE-trending dyke of this type was found near Cacao (Deckart, 1996). Rb-Sr dating of Avanavero dolerite in Suriname (recalculated from Hebeda *et al.*, 1973) gave an age of 1659 ± 27 Ma, but recent dating points to a considerably older age (see later).

The Apatoe Suite forms narrow dykes (rarely more than 50 m wide) that are abundant in eastern Suriname and French Guiana, where they occur in part as swarms of tens of dykes several hundred kilometres in length, and also in Guyana and Venezuela. The dykes are quite straight, suggesting a tectonic control for their intrusion. They have a prevailing N-S strike in Suriname, although tending more to NNE-SSW in the west, and more to NNW-SSE in the east. In western Suriname they occur amidst the Avanavero dolerite dykes and can be difficult to distinguish. K-Ar dating of the Suriname Apatoe dolerite yielded an age of 227 ± 10 Ma (Priem *et al.*, 1968).

Rather small dykes giving K-Ar whole-rock (WR) ages intermediate between those of the Avanavero and Apatoe suites have been found locally in Guyana (north and south of the Takutu Graben; Berrange, 1977) and northwestern Brazil (e.g. Taiano near Boa Vista; see Gibbs and Barron, 1993).

A new type of dolerite was recognized in the 1970s, during the preparation of the current geological map of Suriname. For a better distinction between Avanavero and Apatoe dolerite, trace elements were determined for nearly 100 samples, as petrography and limited field data were often insufficient for this distinction. The trace-element analyses not only helped distinguish the two dolerite suites (see Appendix), but also revealed the presence of a third suite that appeared to differ in its petrography and in the strike of its dykes. It was thus that a suite of narrow olivine dolerite dykes was identified and mapped in western Suriname (Bosma *et al.*, 1978; see also Bosma *et al.*, 1984). Although the olivine dolerite had already been noted, it had been classified in some map sheets with the Apatoe Suite (Kroonenberg, 1976), and in others with the Avanavero Suite (Maas and van der Lingen, 1975). Nevertheless, they clearly represent a separate type for which the name Käyser dolerite was proposed, after the Käyser Mountains in southwestern Suriname.

One of the reasons for describing the Käyser dolerite in more detail is that it was overlooked in the Gibbs and Barron (1993) overview of the geology of the Guiana Shield. Here we describe the differences in petrography and chemistry of the Käyser, Apatoe and Avanavero dolerite suites, as well as a first attempt at dating these dykes and their relationship to the geology of western Suriname.

Occurrence

The olivine dolerite forms a set of dykes extending from the Sipaliwini area, near the Brazilian border in southwestern Suriname, through the Käyser Mountains to the upper Kabalebo River and probably the Corantijn River (see Bosma, 1971) to the northwest, a distance of more than 300 km. The dykes are narrow, probably not more than 50 m wide, have a NW-SE strike and coincide with conspicuous major faults that influence the drainage pattern (e.g. dykes along the NW-SE parts of the upper Kabalebo and Westrivier rivers; see Fig.1).

The Käyser dolerite dykes, like the Apatoe dykes, are quite straight compared to the more irregular Avanavero dykes. For the Apatoe Suite this would appear to result from marked tectonic control during intrusion (Choudhuri and Milner, 1971). The more irregular shape of Avanavero sills and dykes was interpreted by Gibbs and Barron (1983) as indicative of intrusion into a less rigid crust, shortly after the Trans-Amazonian orogeny. Thus the straight shape of the Käyser dolerite dykes, as compared to the Avanavero dykes, might point to a younger age for the Käyser dolerite with respect to the Avanavero Suite.

The 1:500,000-scale geological map of Suriname (Bosma *et al.*, 1978) shows that, near the Rechter Kabalebo River, two inclined Avanavero sheets or sills are cut by a 60-km-long Käyser dolerite dyke along a NW-SE fault. This would suggest that the Käyser dolerite is younger than the Avanavero sheets or sills. However, the relationships on the map were based on rather scarce rock samples combined with an aerial photographic interpretation, without detailed fieldwork.

Age constraints for the intrusion

The age of the Käyser dolerite is not known. K-Ar dating of an olivine dolerite from the Westrivier gave an age of 4940 ± 50 Ma (Priem, unpubl. data; sample *69Sur74* = VS 374), which only indicates a very high excess of argon. As mentioned earlier, the Käyser dolerite dykes are younger than the Trans-Amazonian granitoid-volcanic basement, which they transect, and are probably younger than the Avanavero dolerite. The Trans-Amazonian granites and metavolcanics were dated by Priem *et al.* (1971) at 1874 ± 40 Ma, but recent zircon Pb-Pb dating indicates a slightly older age of around 1950–2000 Ma (Lafon, pers. comm.). An age older than *ca.*1875 Ma is also suggested by recent zircon dating of Roraima cover rocks (Santos *et al.*, 2003; see later).

The Avanavero Suite has been dated in Suriname at 1659 ± 27 Ma (Rb-Sr isochron; recalculated from Hebeda *et al.*, 1973; see also Appendix, note 1) and a similar Rb-Sr WR age of 1695 ± 66 Ma was recorded by Snelling and McConnell (1969) in Guyana. At Tafelberg, in central Suriname, an Avanavero dyke cuts Roraima sediments. An ignimbritic horizon in the sediments was dated by Priem *et al.* (1973) at 1655 ± 18 Ma (Rb-Sr isochron), i.e. within the age range of the dolerite intrusion. However, recent U-Pb dating of single zircon and baddeleyite grains from an Avanavero dolerite dyke at the Omai Mine in central Guyana yielded a considerably older age of 1794 ± 4 Ma (Norcross *et al.*, 2000). A similar high age of 1782 ± 3 Ma was found by baddeleyite and zircon dating of two large Avanavero sills at Mt. Roraima (Santos *et al.*, 2001, 2002, 2003). A comparable age, 1798 ± 2 Ma, had previously been recorded by Ar/Ar dating of biotite from dykes in the Guaniamo swarm in Venezuela (Onstott *et al.*, 1984). Zircon dating of volcanic horizons in the Roraima Supergroup sediments below the Avanavero dolerite sills at Mt. Roraima yielded 1860 ± 15 Ma and 1875 ± 5 Ma for two horizons (Santos *et al.*, 2001, 2003), thus indicating that the Roraima Supergroup, deposited after the Trans-Amazonian orogeny, is substantially older than previously thought. This is consistent with the older age of the Avanavero Suite and also sets a minimum age for the end of the Trans-Amazonian orogeny. It is quite probable that the age of *ca.* 1780–1790 Ma also applies to the Avanavero dolerite in Suriname.

Excess argon is common in Avanavero-type dolerite from western Suriname, having been acquired during the Nickerie Metamorphic Episode at 1200 ± 100 Ma (Priem *et al.*, 1971). This episode caused low-grade metamorphism and mylonitization in western Suriname, as well as partial resetting of Rb-Sr and K-Ar mica ages in granites and gneisses. As the dated Käyser dolerite sample with its high argon excess comes from that part of Suriname afflicted by the Nickerie Metamorphic Episode, it is assumed that the excess argon was acquired during this episode; this would set a minimum age of 1200 ± 100 Ma for the Käyser dolerite. Younger dolerite of the Apatoe type does not show high excess argon, whether from eastern or western Suriname.

A maximum age of about 1950–2000 Ma, but probably considerably lower, around 1800 Ma, and a minimum age of around 1200 ± 100 Ma are therefore considered for the intrusion of the Käyser dolerite dykes.

As the Käyser dolerite is presumably younger than the Avanavero dolerite, but older than the Apatoe dolerite (i.e. PAPA = post Avanavero, pre Apatoe), one could look for Käyser dolerite occurrences outside Suriname by screening dolerite with PAPA ages. Such ages are indicated almost exclusively by K-Ar WR analyses and range from about 300 to 1300 Ma in Guyana (Berrange, 1977).

In Suriname, K-Ar dating of Apatoe dykes gave an age of 227 ± 10 Ma (Priem *et al*., 1968). Deckart (1996) showed that plagioclase from dykes of French Guiana and Suriname was affected by both excess argon and secondary alteration; however, $^{40}Ar/^{39}Ar$ laser dating of single biotite grains displayed mini-plateaux at intermediate temperature steps, with ages ranging from 188.7 ± 1.9 to 200.2 ± 2.4 Ma (Deckart, 1996; Deckart *et al*., 1997). Single amphibole grains from two dykes in western and eastern French Guiana displayed plateau ages of 196.0 ± 5.7 and 196.1 ± 7.5 Ma. Deckart therefore concluded that the main magmatic activity was restricted to a short time period in the Early Jurassic, between 200 and 195 Ma. A single biotite grain from a dyke in western Suriname gave a plateau age of 203.4 ± 1.8 Ma, which is nearly within this time frame (Deckart, 1996). A study of 30 sites of Apatoe dykes in French Guiana confirmed the age range of *ca*. 190–200 Ma, and the paleomagnetic data obtained even suggested the presence of at least two magmatic pulses within that period (Nomade *et al*., 2000).

The data given above indicate that not only Avanavero dolerite from western Suriname, but also Apatoe dolerite commonly shows excess argon. This clearly indicates that the K-Ar PAPA ages are unreliable. Avanavero dolerite from western Suriname gave a range of K-Ar WR ages from about 1250 to 2100 Ma (Hebeda *et al*., 1973), implying that 1200-1300 Ma K-Ar ages may simply refer to Avanavero dolerite. Younger K-Ar ages (>300 Ma) might refer to Apatoe dolerite with excess argon, as indicated by paleomagnetic data (for 675 Ma and 450 Ma dykes; Hargraves, *in* Gibbs and Barron, 1993) and similarities in minor and trace elements. Most PAPA ages may, therefore, just refer to Avanavero and Apatoe dolerites. In southwestern French Guiana, NNW-trending olivine-clinopyroxene dolerite dykes have been found with a PAPA age of 809 ± 29 Ma (K-Ar WR; Delor *et al*., 2003). They differ from the Apatoe dykes in their paleomagnetic data (Théveniaut *et al*., 2001; Théveniaut and Delor, 2003). Ar-Ar dating of the dolerite confirmed the age of around 800 Ma (Nomade, pers. comm., in Théveniaut and Delor, 2003), so these might represent dykes of true PAPA age.

Berrange (1977) found two dolerite dykes with abundant olivine in southern Guyana, one of which yielded a K-Ar WR age of around 900 Ma. They differ from the Käyser dolerite in a number of important aspects, including the K-Ar age (see Appendix, note 2).

Petrography

The olivine dolerite is a fine- to medium-grained rock of greenish-grey colour due to the abundance of (commonly fresh) olivine. It contains about equal amounts of plagioclase (labradorite) and mafic minerals, olivine and clinopyroxene. Only one pyroxene is present; a purple, slightly or markedly pleochroic clinopyroxene with a small, or rather small, axial angle; it does not show exsolution. Microprobe analysis of the pyroxene from the K-Ar-dated sample (*69Sur74*) showed it to be a fairly Ca- and Mg-rich titaniferous augite. Microprobe analysis of the associated olivine showed considerable variation from grain to grain, as well as some zoning, from *ca*. $Fo_{63}Fa_{37}$ to *ca*. $Fo_{39}Fa_{61}$, the olivine being richer in Fe than the pyroxene.

The dolerite has a fairly large content of opaque matter, mainly ilmenite, generally overgrown with rims of deep reddish-brown biotite. A minor constituent is a kaersutite-like amphibole with the same reddish-brown colour as the biotite, and therefore easily overlooked in thin section. Alteration to chlorite, serpentine, actinolite and sericite occurs locally, to a small extent.

Hawkes (1966) distinguished six types of dolerite in differentiated dykes, sills and sheets of the Avanavero Suite in Guyana. They each had specific assemblages governed by the stage of fractionation, such as orthopyroxene dolerite, pigeonite dolerite, ferrodolerite and granophyric rock. The Avanavero dolerite in Suriname also has a varied composition (e.g. Bosma *et al*., 1984) but it consists mainly of strongly zoned labradorite and several types of pyroxene. Intergrowths of hypersthene and clinopyroxene represent inverted pigeonite. Uninverted pigeonite and subcalcic augite are also common, whereas olivine and primary hypersthene occur locally. Interstitial granophyric intergrowths are common. Minor components include some hornblende, biotite and opaque minerals.

The Apatoe dolerite is rather constant in composition and consists mainly of calcic plagioclase, pigeonite and subcalcic augite. Olivine and hypersthene occur locally as a core within clinopyroxene grains. Exsolution of pigeonite has not been observed. Interstitial granophyric intergrowths are common. Minor components include some hornblende, biotite, apatite and opaque minerals.

The dolerite of the Apatoe and Avanavero suites is a quartz-saturated tholeiite with a corresponding mineral composition: two pyroxenes (one Ca-rich, one Ca-poor), no or minor olivine (and, if present, pre-pyroxene), and micropegmatite/granophyric intergrowths. The Käyser dolerite, however, has only one pyroxene, accompanied by a large quantity of olivine, and lacks granophyric intergrowths. In these respects it shows an alkaline nature.

Chemical composition

The chemical composition was determined for six Käyser dolerite samples. For three of the samples, the major, minor and trace elements were determined by ICP-MS; for the other three, the major and minor elements were determined by XRF (Table 1).

The sum of alkalis, $Na_2O + K_2O$, was approx. 4½–6½ % at 43–50% SiO_2, so that the analysed samples fall in the field of alkaline rocks of, for example, MacDonald and Katsura (1964) (Fig. 2). This sum of the alkalis is nearly twice that of typical Avanavero dolerite (2½-3½ %; Hebeda *et al.*, 1973). Most of the analysed samples (5 out of 6) showed abundant normative olivine and diopside (without hypersthene) accompanied by minor normative nepheline, pointing to alkali olivine basalt with a mildly silica-undersaturated composition (Table 1). Both the chemical composition and the norm of the dolerite confirm the alkaline nature suggested by its mineralogical composition.

The trace- and minor-element levels also point largely to an alkali basaltic nature – for example, the high P_2O_5 content of 0.52-1.04% is typical of alkali basalt. In a P_2O_5 vs. Zr discrimination diagram (Fig. 3, after Winchester and Floyd, 1976) and TiO_2 vs. Zr/P_2O_5 discrimination diagram (not shown here; after Floyd and Winchester, 1975) the analysed Käyser dolerite samples plot within the alkali basalt field, contrary to samples of Apatoe and Avanavero dolerite (data from Hebeda *et al.*, 1973; Elliott, 1992; Deckart, 1996) which plot in the tholeiitic field.

A diagram of primitive-mantle-normalized incompatible elements shows a great similarity between Käyser dolerite and average oceanic alkali basalt (normalization data and OIB composition from Sun and McDonough, 1989), but it also indicates some substantial differences such as a marked negative Nb, Ta, Th and U anomaly, a marked positive Ba anomaly, and a slight negative Zr, Hf anomaly (Fig. 4). The Nb and Ta levels of the analysed Käyser dolerite samples are relatively low, and consequently their Nb/Y ratio falls in the range 0.4-0.5, slightly below the value of 0.6 taken by Floyd and Winchester (1975) as a boundary between subalkaline and alkaline basalt. The Nb/Ta ratio is 13-14 for the three samples, i.e. close to 17, which is the value generally assumed (e.g. Sun and McDonough, 1989). The low Nb, Ta, Th and U values are considered to be a characteristic, primitive aspect of the dolerite magma composition. Crustal contamination of the magma would have hardly changed the

	AH 2016	CS 763	JK 2444	CF 59	CF 60	SB 2164
SiO2	47.33	44.3	44.56	50.06	43.31	49.05
TiO2	2.6	3.95	2.86	2.34	4.02	2.60
Al2O3	15.24	14.89	17.39	18.19	14.13	19.07
Fe2O3*	16.9	19.4	17.51	12.24	21.81	12.44
MnO	0.19	0.22	0.17	0.16	0.24	0.15
MgO	5.18	4.51	5.6	2.72	6.31	2.94
CaO	7.55	7.57	7.93	8.07	7.07	8.66
Na2O	3.3	3.52	3.41	4.47	3.36	4.04
K2O	1.62	1.57	1.0	1.94	1.26	1.31
P2O5	0.61	0.82	0.52	1.04	0.93	0.62
Or	9.7	9.4	5.9	11.5	7.8	8.0
Ab	28.2	23.6	24.0	36.8	26.0	36.5
An	22.2	20.4	29.4	24.0	20.3	30.3
Ne	-	3.4	2.7	2.2	2.9	0.3
Di	9.8	10.8	5.7	8.0	7.6	7.2
Hy	2.3	-	-	-	-	-
Ol	18.7	19.7	22.4	10.2	24.4	10.8
Mt	2.9	3.3	3.3	2.0	3.4	2.0
Il	4.9	7.6	5.5	3.2	5.7	3.6
Ap	1.3	1.8	1.1	2.1	1.9	1.3

	AH 2016	CS 763	JK 2444		AH 2016	CS 763	JK 2444
La	29.1	32.0	19.1	Cs	1.72	0.76	1.42
Ce	64.1	71.2	42.2	Rb	32.3	27.1	14.5
Pr	8.59	9.48	5.73	Ba	782	822	597
Nd	36.8	42.9	25.5	Th	1.73	1.94	1.06
Sm	7.81	9.11	5.82	U	0.38	0.49	0.24
Eu	2.52	2.88	2.17	Nb	13.8	16.4	8.3
Gd	7.04	8.91	4.90	Ta	0.97	1.19	0.64
Tb	0.96	1.16	0.75	Pb	7.38	7.44	4.25
Dy	5.78	6.41	4.12	Sr	522	554	691
Ho	1.02	1.23	0.83	Zr	206	206	114
Er	2.72	3.21	2.13	Hf	4.99	5.39	9.11
Tm	0.418	0.490	0.308	Y	28.3	35.9	21.0
Yb	2.42	3.14	1.76				
Lu	0.415	0.520	0.268				

Table 1.- Chemical composition of typical Käyser dolerite samples, as determined by ICP-MS (samples AH2016, CS 763, JK2444) and XRF (samples CF 59, CF 60, SB 2164). Oxides in %, trace elements (determined by ICP-MS) in ppm. The asterisk refers to total iron oxide as Fe_2O_3. The CIPW norm was calculated assuming $Fe_2O_3/FeO = 0.15$.

Tabl. 1.- Composition chimique caractéristique des échantillons de dolérites Käyser, analyses par ICP-MS (échantillons AH2016, CS 763, JK2444) et fluorescence X (échantillons CF 59, CF 60, SB 2164). Oxydes en %, éléments en traces (déterminés par ICP-MS) en ppm. L'astérisque se rapporte au fer total sous forme de Fe_2O_3. *La norme CIPW a été calculée en supposant que* $Fe_2O_3/FeO = 0.15$.

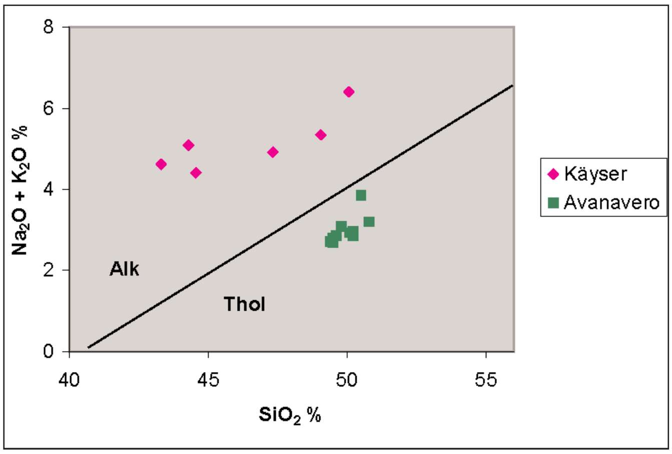

Fig. 2.- Alkalis vs. SiO_2 diagram (after MacDonald and Katsura, 1964), showing the alkaline nature of the Käyser dolerite.

Fig. 2.- Diagramme alcalins-silice (d'après MacDonald et Katsura, 1964) montrant l'affinité alcaline des dolérites Käyser.

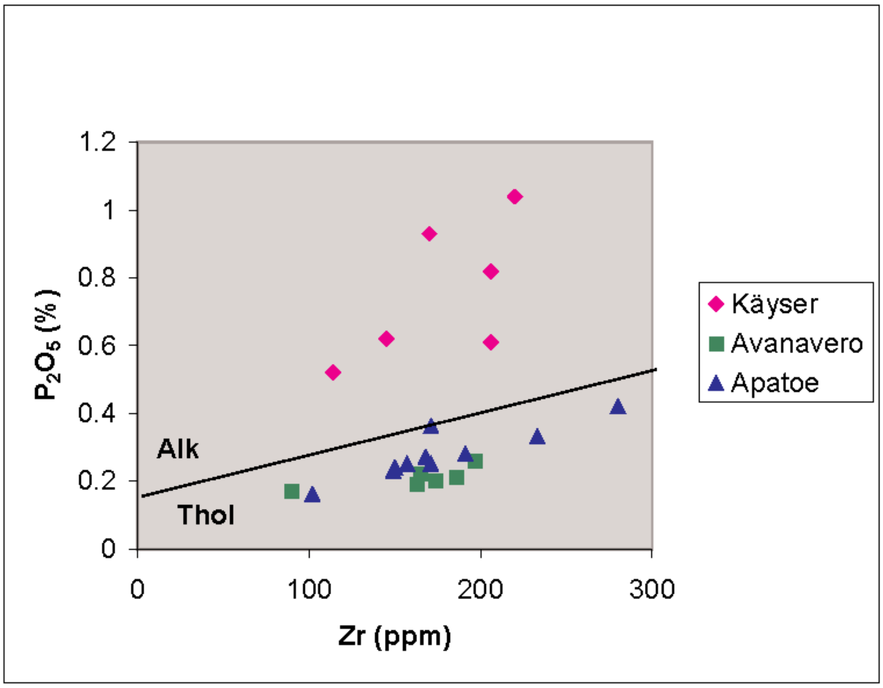

Fig. 3.- P_2O_5 vs. Zr discrimination diagram showing the alkaline nature of the Käyser dolerite (after Winchester and Floyd, 1976).

Fig. 3.- Diagramme P_2O_5 - Zr montrant l'affinité alcaline des dolérites Käyser (d'après Winchester et Floyd, 1976).

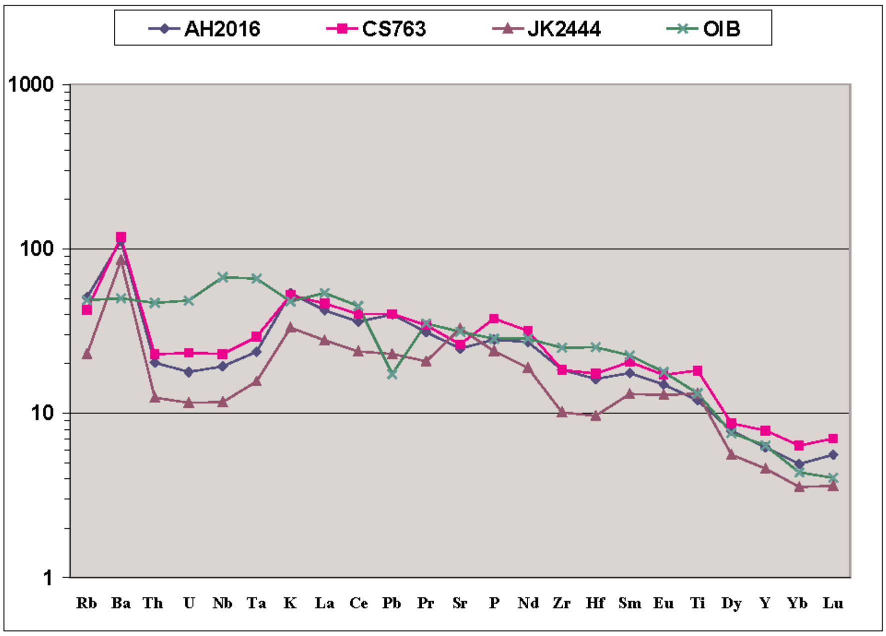

Fig. 4.- Comparison of mantle-normalized incompatible elements of three Käyser dolerite samples and average oceanic alkali basalt (OIB, after Sun and McDonough, 1989; the non-corrected normalization value of 0.185 ppm is used for Pb).

Fig. 4.- Comparaison des spectres d'éléments incompatibles, normalisés au manteau, de trois échantillons de dolérites Käyser avec la moyenne des basaltes alcalins océaniques (OIB, d'après Sun et McDonough, 1989; la valeur de normalisation non corrigée de 0,185 ppm est utilisée pour Pb).

Nb and Ta levels, and would have increased Th and U, leading to higher Th/Ta and lower La/Th ratios (see Taylor and MacLennan, 1985; Rudnick, 1995). The Käyser dolerite samples, however, show a low Th/Ta of <2 and a high La/Th of 16-18; this La/Th ratio is even higher than that of typical OIB, for which La/Th is 8-10.

The chondrite-normalized REE patterns of the three analysed samples show smooth subparallel trends essentially without any Eu anomaly for two samples and a positive Eu anomaly for the third one (Fig. 5). The patterns and La/Yb ratios are similar to those of average oceanic alkali basalt (OIB; after Sun and McDonough, 1989). They exhibit rather marked fractionation, with $LREE_N$ of 81-135 and $HREE_N$ of 11-20, giving La_N/Yb_N ratios of 6.9–8.2. Apatoe dolerite from French Guiana and Avanavero dolerite from Guyana and French Guiana (Elliott, 1992; Deckart, 1996) show less fractionation, with less elevated LREE and La_N/Yb_N ratios of 1.5-5.1 (Apatoe) and 3.5-4.8 (Avanavero).

In view of its alkaline nature, the Käyser dolerite can be distinguished rather easily from Apatoe and Avanavero dolerite by several major, minor and trace elements (see Appendix, note 3), as well as by its distinctive mineralogy.

$^{40}Ar/^{39}Ar$ experimental procedures

To determine the age of the Käyser dolerite, $^{40}Ar/^{39}Ar$ dating was carried out on biotite and hornblende from the sample that Priem had used for K-Ar WR dating. The amount of biotite and amphibole available for analysis was limited, because grains had to be separated from a small sample from a museum collection. Several amphibole and biotite grains were extracted and washed in distilled water and acetone prior to irradiation. The grains were then wrapped in aluminium packets and placed into an aluminium irradiation canister together with aliquots of the flux monitor GA1550 (Age = 98.8 Ma; Renne *et al.*, 1998). Packets containing degassed potassium glass were placed at either end of the canister to monitor the ^{40}Ar production from potassium. The irradiation canister was irradiated for 504 hours in position X34 of the HIFAR

Grain No.	Step No.	Cum ^{39}Ar	^{40}Ar/^{39}Ar	^{37}Ar/^{39}Ar	^{36}Ar/^{39}Ar	Vol. ^{39}Ar x10^{-15}mol	^{40}Ar* (%)	Ca/K	^{40}Ar*/^{39}Ar	Age (Ma)	± 1s.d. (Ma)
1	1	0.601	118.2	0.0320	0.0414	0.695	89.6	0.061	105.9	1496	4
	2	0.812	111.7	0.0863	0.0069	0.244	98.1	0.164	109.6	1532	4
	3	1.000	110.0	0.0160	0.0038	0.217	98.9	0.030	108.8	1524	6
2	1	0.612	115.8	0.0018	0.0347	0.346	91.1	0.004	105.5	1492	6
	2	0.826	107.3	0.0394	0.0106	0.121	97.1	0.075	104.1	1479	12
	3	1.000	105.6	0.0282	0.0043	0.098	98.8	0.054	104.3	1481	11
3	1	0.462	123.9	0.1472	0.0655	0.368	84.4	0.280	104.5	1483	6
	2	1.000	107.2	0.0243	0.0058	0.429	98.4	0.046	105.4	1492	5
4	1	0.417	123.9	0.0010	0.0638	0.654	84.8	0.002	105.0	1488	5
	2	1.000	108.5	0.0467	0.0040	0.916	98.9	0.089	107.3	1509	3
5	1	0.655	116.2	0.0708	0.0276	0.496	92.9	0.134	108.0	1516	5
	2	0.807	108.0	0.1448	0.0029	0.115	99.2	0.275	107.0	1507	9
	3	1.000	109.8	0.3264	0.0003	0.146	99.9	0.620	109.7	1533	12
69SUR74 (J = J = 0.012199 ± 0.000049)											
1.Isotopic ratios are corrected for mass spectrometer backgrounds, mass discrimination and radioactive decay.											
2. J-values are based on an age of 98.8 Ma for the GA1550 biotite monitor.											
3. Errors are 1s uncertainties and exclude the error in the J-value.											
4. Correction factors: (^{36}Ar/^{37}Ar)Ca = 3.5E-4; (^{39}Ar/^{37}Ar)Ca = 7.86E-4; (^{40}Ar/^{39}Ar)K = 0.025; I^{40}K = 5.543E-10.											

Table 2.- Analytical ^{40}Ar/^{39}Ar laser probe data for single biotite grains from dolerite sample *69Sur74*.

Table 2.- Résultats analytiques ^{40}Ar/^{39}Ar obtenus à la sonde laser sur les monograins de biotite de l'échantillon 69Sur74.

reactor (Lucas Heights, New South Wales, Australia). The canister, which was lined with 0.2 mm Cd to absorb thermal neutrons, was inverted three times during the irradiation, which reduced neutron flux gradients to <2% along the length of the canister.

After irradiation, the samples were removed from their packaging and grains were loaded into a copper sample holder. The samples were then individually step-heated or fused with an argon-ion laser. ^{40}Ar/^{39}Ar step-heating analyses were carried out on a VG3600 mass spectrometer using a Daly photomultiplier detector. Mass discrimination was monitored by analyses of standard air volumes. Correction factors for interfering reactions are as follows: $(^{36}Ar/^{37}Ar)_{Ca}$ = 3.50 (± 0.02) x 10^{-4}; $(^{39}Ar/^{37}Ar)_{Ca}$ = 7.9 (± 0.5) x 10^{-4} (Tetley *et al.*, 1980; McDougall and Harrison, 1999); $(^{40}Ar/^{39}Ar)_K$ = 0.035 (± 0.005). K/Ca ratios were determined from the ANU laboratory hornblende standard 77-600.

The reported data have been corrected for system backgrounds, mass discrimination, fluence gradients and atmospheric contamination. Errors associated with the age determinations are one sigma uncertainties and exclude errors in the J-value estimates (± 0.35%) and the age of the fluence monitor GA1550 (± 1%). Decay constants are those of Steiger and Jager (1977). The ^{40}Ar/^{39}Ar dating technique is described in detail by McDougall and Harrison (1999).

Geochronology

^{40}Ar/^{39}Ar laser probe step heating of single biotite grains from the olivine dolerite sample (*69Sur74*) yielded apparent ages ranging from 1479 ± 12 Ma to 1533 ± 12 Ma (Table 2). Due to the small size of the biotite grains, only two to three heating steps were obtained from each grain. A plateau age is defined here as a minimum of two adjacent heating steps comprising >50% of the total ^{39}Ar released, with ages within 2σ of the mean. Under this definition, grains 2 and 5 display age plateaux, with mean ages of 1487 ± 7 Ma and 1518 ± 8 Ma, respectively (Fig. 6). These ages are just outside the 2s uncertainties of one another. The mean age of all biotite analyses is 1505 ± 5 Ma, indistinguishable from the average of the two plateaux results (1503 ± 6 Ma). Although a number of ages are close to this mean result, several steps are clearly older. The

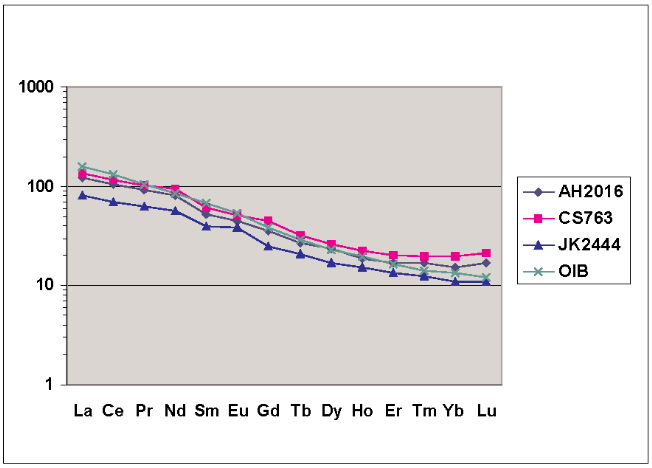

Fig. 5.- Comparison of chondrite-normalized REE data for three Käyser dolerite samples and average oceanic alkali basalt (OIB, after Sun and McDonough, 1989).

Fig. 5.- Comparaison des spectres de Terres Rares, normalisés aux chondrites, de trois échantillons de dolérites Käyser avec la moyenne des basaltes alcalins océaniques (OIB, d'après Sun et McDonough, 1989).

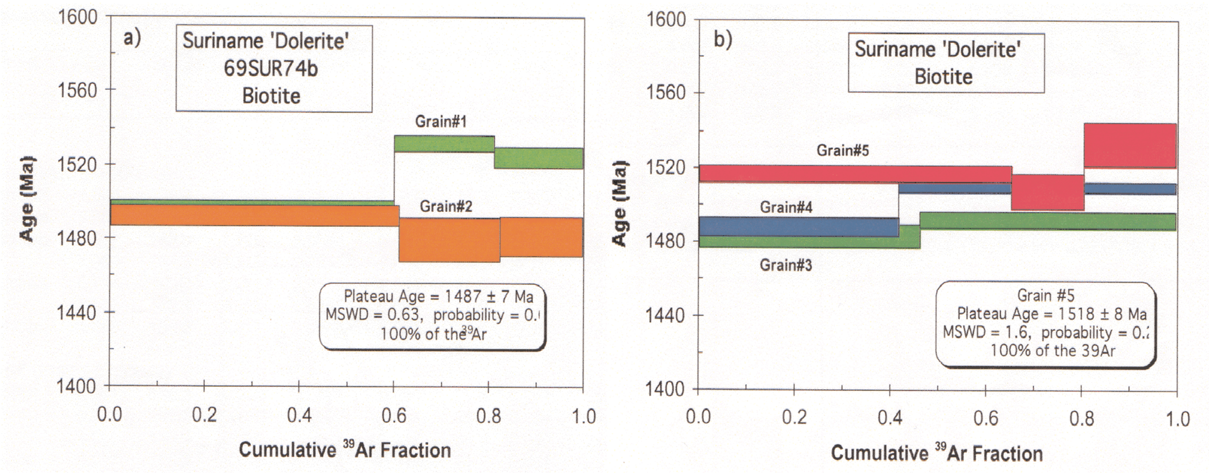

Fig. 6.- Results of $^{40}Ar/^{39}Ar$ laser probe dating by step heating of single biotite grains from the olivine dolerite sample *69Sur74* dated by K-Ar WR at 4940 ± 50 Ma.

Fig. 6.- Résultats des datations $^{40}Ar/^{39}Ar$, par sonde laser et chauffage par paliers de température sur monograins de biotite, de l'échantillon 69Sur74 *de dolérite à olivine daté à 4 950 ± 50 Ma par K-Ar sur roche totale.*

highest temperature steps (excluding grain 2) are similarly discordant, with a slightly older mean age of 1511 ± 6 Ma. It is unclear whether the discordance in the apparent ages is due to minor alteration or whether the results reflect slightly different cooling ages.

Laser probe dating of single amphibole grains from the same sample produced only small volumes of argon and highly discordant results. Consequently, these results are not discussed further.

The average age for the biotite grains (1505 ± 5 Ma) could represent a cooling age after a metamorphic event or a cooling age after intrusion. This interpretation is supported by the coarse grain-size of the sample, suggesting crystallization at depth. In this case, the age would be a minimum estimate for the time of dyke intrusion. However, there is little evidence in the surrounding rocks for a metamorphic 'event' in the time interval 1.2 to 1.9 Ga. Also, the dated sample comes from a narrow dyke (50 m or less), intruded in an already cooled crust. Therefore, it is assumed that the biotite age approximates the time of dyke emplacement. The average age of *ca*. 1500 Ma falls within the expected time frame discussed in a previous section.

Tectonic significance of the Käyser dolerite intrusions

The Apatoe dykes and accompanying faults along the Atlantic Coast in the northern part of the Guiana Shield, follow a tensional pattern imposed upon the continental crust prior to the onset of North Atlantic sea-floor spreading (May, 1971; Berrange and Dearnley, 1975). Using $^{40}Ar/^{39}Ar$ dating, Deckart (1996; see also Nomade *et al*., 2000) showed that the Apatoe dolerite belongs to the JACT (Jurassic Atlantic Continental Tholeiites) association, occurring in an area of nearly 4500 km in length, from Iberia to Liberia, and also in North America, e.g. the Palisades sill. Extensive flood basalts in northern and central Brazil also form part of the association (Marzoli *et al*., 1999; they use the name Central Atlantic Magmatic Province). The magmatism accompanied the initial stage of continental rifting in the Central and South Atlantic, leading to the break-up of Pangea around 200 Ma. The dykes were probably not due to active rifting at a hot spot, but to discontinuities along the cratonic margin (Deckart, 1996). The magmatism would have coincided with a major mass extinction at the Triassic-Jurassic boundary (Marzoli *et al*., 1999). The relatively mild tensional phase at 190-200 Ma was followed by a more profound tensional event that resulted in the fault-bounded subsidence of the North Savannas/Takutu graben and extrusion of the Apoteri basalt outflows in the graben at 180-150 Ma, synchronous with the opening of the southern North Atlantic (Berrange and Dearnley, 1975).

The Avanavero dolerite, which marks the 'rigidization' of the Guiana Shield after the Trans-Amazonian Orogeny, also indicates a major tectonic event. In Suriname the Avanavero dolerite was thought to be associated with block-faulting along NW-SE and NE-SW directions. Since the NW-SE-trending dykes have now been proven to represent a different type, with a different age, the Avanavero dolerite dykes in Suriname are associated with a unidirectional fault pattern, which might be related to a tensional event (similar to the Apatoe dykes). A comparable preferential direction (NNE-SSW) is indicated for Avanavero-type dolerite dykes in central French Guiana (Delor *et al*., 2001). However, Avanavero feeder dykes in the Guyana–Venezuela–Brazil border area, associated with sheets and sills, lack a clear preferential direction (e.g. Gibbs and Barron, 1993). This might be due to the higher crustal level exposed, comprising a huge area of Roraima Supergroup sediments overlying the Trans-Amazonian basement. Possibly a preferential dyke direction is present at deeper levels, within the basement, as in Suriname. Therefore, the intrusion of the huge volumes of Avanavero dolerite is assumed to be related to a tensional event at the scale of the Shield (and continuing in the Guapore Shield; Santos *et al*., 2001). Choudhuri *et al*. (1990) associated the voluminous intrusions with an abortive attempt at continental rifting.

The Käyser dolerite dykes are associated with a pattern of major NW-SE faults that dominates part of the course of the Westrivier, Zandkreek, and Kabalebo rivers, and apparently also parts of the Corantijn and Coeroeni rivers. The dykes occur in a zone that extends for over 300 km from the Brazilian border in the southwest up to northwestern Suriname. The fault pattern and associated dykes may also extend into Brazil, but have not yet been found there. In the Sipaliwini area near the Brazilian border in southwestern Suriname, the NW-SE faults (with locally associated Käyser dolerite dykes) define a large graben structure filled with poorly recrystallized acid volcanics (Fig. 7; from Maas and van der Lingen, 1975). The graben structure probably continues into Brazil.

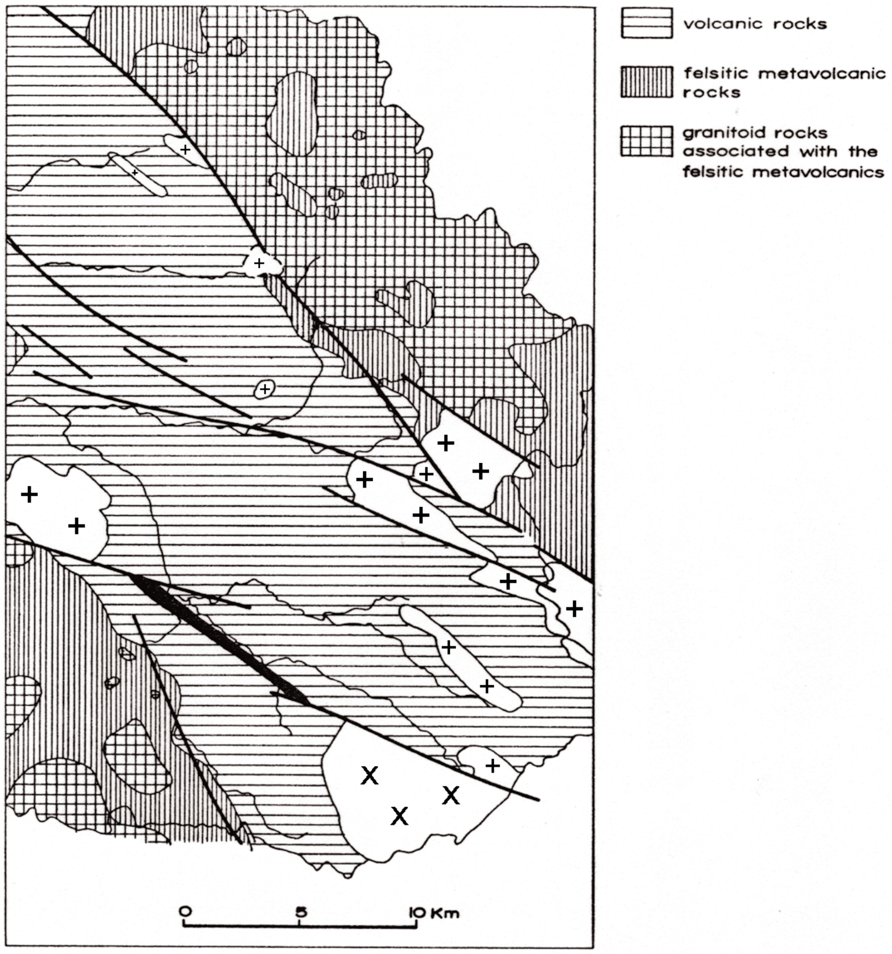

Fig. 7.- Geology of the Sipaliwini area along the Brazilian border in SW Suriname (after Maas and van der Lingen, 1975). The area is situated near the letter S in Figure 1. Thick black lines: faults visible in the field. Long NW-SE downthrow faults border a graben of poorly recrystallized acid volcanics between felsitic metavolcanic rocks and granite ("older granites"). Thick black zone: quartzite dyke with porphyritic subvolcanics. Areas with ++: leucogranite ("younger granites"); area with xx: biotite granite.

Fig. 7.- Géologie de la région de Sipaliwini le long de la frontière entre le Brésil et le Suriname (d'après Maas et van der Lingen, 1975). La position de ce secteur est située sur la fig. 1 à proximité de la lettre S. Traits noirs épais : failles observables sur le terrain. Failles normales NW-SE bordant un graben de volcanites acides peu recristallisées entre des métavolcanites felsitiques et des granitoïdes «Older granites». Zone noire épaisse : filon de quartz avec des roches subvolcaniques porphyriques. + : leucogranites («Younger granites») ; x : granites à biotite.

The intrusion of the Käyser dolerite dykes may represent another major tectonic event on the scale of the Guiana Shield. The event would not have been merely a mild tensional phase, as for the Apatoe (and Avanavero?) dolerite dykes. The association with a graben structure in southwestern Suriname indicates a stronger tensional event related to rifting. No other major event around 1500 Ma, the supposed age of intrusion, is known in this central part of the Guiana Shield. However, the huge (anorogenic) Parguaza rapakivi granite pluton was intruded at approximately the same time, at about 1.55 Ga, in the northwest of the Guiana Shield. Dolerite dykes are known to be temporally and spatially associated with large anorogenic rapakivi granite plutons elsewhere in the world, such as in Finland (e.g. Heeremans, 1997). Indeed, olivine dolerite dykes have been described from within the Parguaza pluton (Bangeter, 1981, *in* Gibbs and Barron, 1993). Smaller granitic plutons of around 1500 Ma have been found in the southwest of the Shield, in Roraima State (Surucucus), and somewhat older plutons, near Pitinga, 250 km north of Manaos; they comprise rapakivi granite and are Sn-rich (see Appendix, note 4). However, the large distances involved do not favour a relationship with the Käyser dolerite dykes.

Anorogenic granitic magmatism at *ca*. 1.5 Ga is also known from the Guapore Shield and surroundings south of the Amazon, and linked to the Guiana Shield. Alkali

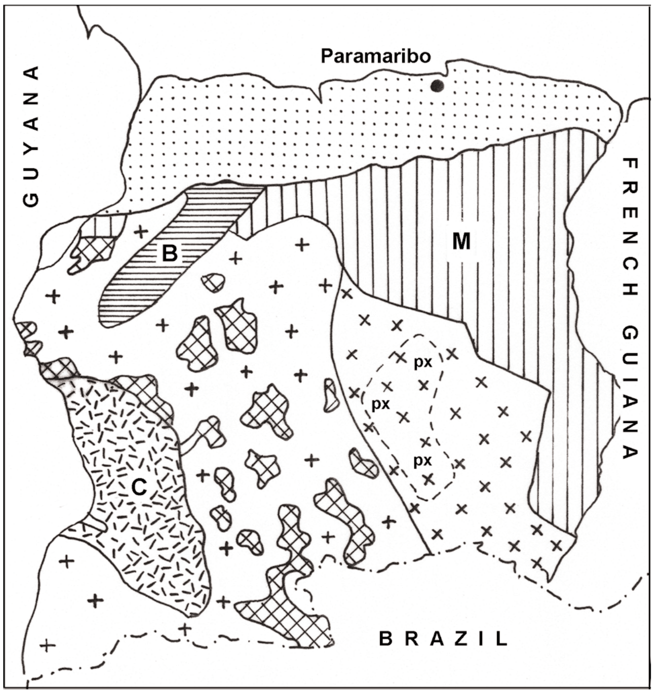

Fig. 8.- Simplified geology of Suriname, based on the map of the Guiana Shield by Delor *et al*. (2001, this volume). Distribution of acid metavolcanics after Bosma *et al*. (1984). Legend: *stippled*: Cenozoic sedimentary cover; +++: biotite granite and hypabyssal granite, and *diagonally blocked* acid metavolcanics, of the Uatuma plutonovolcanic complex; C, *random dashes*: granulite and migmatite of the Coeroeni area; B, *horizontal lines*: late-Trans-Amazonian granulite of the Bakhuis horst; M, *vertical lines*: volcano-sedimentary sequences of the greenstone belt and tonalitic plutons; xxx: granitic rocks south of the greenstone belt (including px = pyroxene granite).

Fig. 8.- Carte géologique simplifiée du Suriname, d'après la carte du Bouclier des Guyanes (Delor et al*., 2001, ce volume). Distribution des métavolcanites acides d'après Bosma* et al*. (1984). Légende,* barré *: couverture sédimentaire cénozoïque; +++ : granite à biotite et granites hypabyssaux, et* figurés diagonaux *: métavolcanites acides, du complexe Uatuma;* C *:* points irréguliers*, granulites et migmatites de la région de Coeroeni;* B *:* lignes horizontales*, granulites tardi-transamazoniennes du horst des Bakhuis;* M *:* lignes verticales*, séquences volcano-sedimentaires de ceintures vertes et plutons tonalitiques;* xxx *: roches granitiques au Sud de la ceinture verte (incluant* px *= granite à pyroxène).*

syenite at Peixe (Tocantins, central Brazil, between the Guapore Shield and São Francisco Craton) has been dated at 1478 ± 8 Ma (Rossi *et al*, 1996). The magmatism was possibly connected with rifting. Anorogenic magmatism associated with extensional tectonism and possible rifting occurred probably for a long period beforehand: U-Pb dating of alkali-rich tin-bearing granite in Goias State has revealed two distinct episodes of magmatism at approximately 1600 and 1770 Ma (Pimentel *et al*., 1991).

The Käyser dolerite dykes are situated in a large NW-SE zone of acid metavolcanics, with associated hypabyssal (and biotite) granite, which runs from northwestern Suriname to the southern border near Sipaliwini (Fig. 8), and continues across the Shield to the Amazon River. The NW-SE zone is bordered to the west by the large Coeroeni Gneiss area and to the east by the biotite granite and associated pyroxene granite of central Suriname. The NW-SE zone of acid metavolcanics runs parallel to the Käyser dolerite dykes and associated faults, suggesting a possible relationship. However, the acid metavolcanics, as well as the hypabyssal granite and biotite granite from the zone plus other granite from central Suriname, have been dated at 1874 ± 40 Ma (Priem *et al.*, 1971; Rb-Sr isochron based on >40 samples scattered over western and central Suriname), i.e. much older than the Käyser dolerite intrusion. Perhaps the NW-SE zone also contains younger granite or acid volcanics that have not been noticed because of poor exposure in the dense jungle and/or their similarity to the Trans-Amazonian granitoid rocks and acid metavolcanics. Also the anorogenic Parguaza pluton and the granite intrusions in Roraima occur amidst these acid metavolcanics and associated hypabyssal granite. Verhofstad (1970) described rapakivi granite from the Wilhelmina Mountains in western Suriname. Their rapakivi structure might possibly point to younger anorogenic magmatism. Two Rb-Sr dated samples of rapakivi granite partially fitted the Priem *et al.* (1971) Trans-Amazonian Rb-Sr isochron (one sample fitted, the other one did not). In the Sipaliwini area in southwestern Suriname, Maas distinguished older and younger granite (Maas and Van der Lingen, 1975). The younger granite, mainly leucogranite and granophyric alkali-granite, forms small bodies partly bounded by the NW-SE faults and by slightly oblique WNW-ESE faults that offset the NW faults (see Fig. 7). The bodies appear to be related to the fault systems and are "best considered as late- to post-orogenic intrusions" (Maas and van der Lingen, op. cit.). The WNW faults are accompanied by quartzitic dykes and albite-rich porphyritic subvolcanics. A leucogranite sample from Sipaliwini was also dated by Rb-Sr, but did not fit the Priem *et al*. (1971) isochron mentioned above, either because of weathering or because of a younger age. Zircon Pb dating might provide solid evidence for the presence of younger, anorogenic magmatism.

Western and southwestern Suriname show a zone of marked NW-SE faults associated with a graben structure, and with alkaline dolerite dykes along part of the faults. The zone runs through the heart of the Guiana Shield and may continue into Brazil. Although solid evidence of spatially associated acid magmatism is still lacking, the dolerite appears to be contemporaneous with acid anorogenic magmatism elsewhere in the Guiana Shield.

Acknowledgments

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Appendix

Note 1. Gibbs and Barron (1993; p 138, Table 9-3) refer to 1800 K-Ar ages for biotite from two Avanavero dolerite samples from Suriname (Priem *et al*., 1970) as a possible indication for two intrusion ages of the dolerite, around 1800 and around 1650 Ma. However, as was discovered during the preparation of the geological map of Suriname (see Bosma and de Roever, 1975), the two dated samples were derived from De Goeje-type gabbroic bodies.

Note 2. The olivine dolerite samples were taken from narrow NE-SW-trending dykes. One sample, JPB 341, contained abundant olivine, titanaugite, pigeonite and plagioclase (An_{50}), with accessory quartz (but without micrographic intergrowths). The other sample also contained two pyroxenes (Berrange, 1977). Their K-Ar WR age of 907 Ma is quite different from the high K-Ar age of 4940 ± 50 Ma of the dated Käyser dolerite sample.

Note 3. Much effort was put into distinguishing the dolerite types by their mineralogy and chemistry, as an aid to mapping poorly exposed and deeply weathered areas with thick jungle, little relief and few outcrops. Although microscopical study could distinguish between Avanavero and Apatoe dolerite in some cases, minor and trace elements were also used during the preparation of the geological map of Suriname (Bosma *et al.*, 1978) for distinction. They were determined by XRF on powdered rock at the Suriname Geological and Mining Service. This approach not only helped to partly distinguish between Avanavero and Apatoe dolerite, but also led to the discovery of the Käyser dolerite.

The mineralogy of Käyser dolerite is rather striking and, in most cases, distinguishes it from the other dolerite types. Nevertheless, the minor and trace elements are still useful. Apart from the sum of alkalis, the high P_2O_5 level of the Käyser dolerite provides a good distinction, the more so if plotted against Zr (Fig. 3) or against TiO_2. Also the high Sr levels are quite different, *ca*. 400-1000 ppm Sr compared to *ca*. 150-300 ppm Sr for Apatoe and Avanavero dolerite (data from Priem *et al*., 1968; Hebeda *et al.*, 1973; Elliott, 1992; and Deckart, 1996). The difference is even more marked if Sr is plotted against K (Fig. 9) or against Rb. Many major tholeiite dyke suites, e.g. from Tasmania, eastern North America and Antarctica, show a fractionation trend in which Sr is rapidly depleted relative to Rb and K, as compared to a slow depletion trend exhibited by alkaline and many tholeiitic basalts (Condie *et al.*, 1969). The Avanavero dolerite and Apatoe dolerite follow a fast Sr depletion trend and the Käyser dolerite a slow Sr depletion trend.

Regarding the distinction between Avanavero and Apatoe dolerite by minor and trace elements (using XRF) for the Suriname mapping campaign, Ti levels were found to differ considerably, despite partial overlap, and K and Zr levels showed partial difference. Plotting Ti versus K provided a reasonable distinction (based on less precise XRF data for powders). Using more precise data from Hebeda *et al.* (1973), Elliott (1992) and Deckart (1996), a good distinction was found between Avanavero dolerite from Guyana, Suriname and French Guiana and Apatoe dolerite from Suriname and French Guiana (Fig. 10).

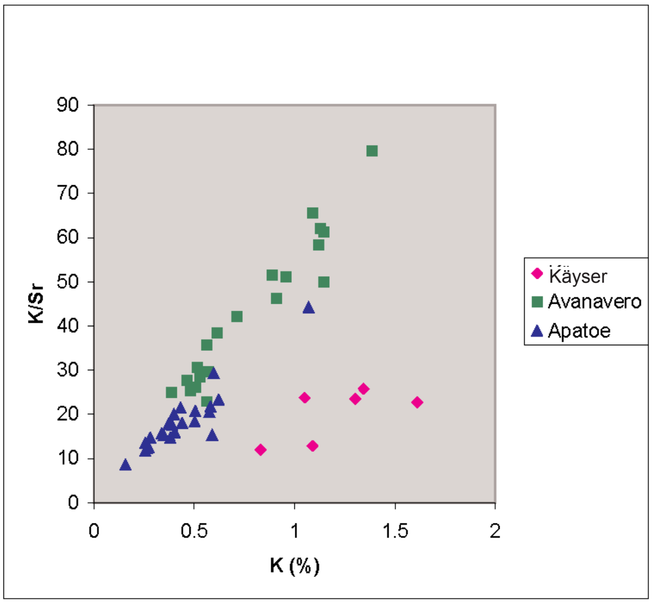

Fig. 9.- Plot of K/Sr vs. K (which serves as index of differentiation) for the different dolerite types. Avanavero dolerite and Apatoe dolerite follow a steep Sr depletion trend, whereas the alkaline Käyser dolerite follows a shallow Sr trend, like alkali basalts and many tholeiitic basalts.

Fig. 9.- Diagramme K/Sr - K (servant d'indice de différenciation) des différents types de dolérites. Les dolérites Avanavero et Apatoe suivent une tendance évolutive montrant un fort appauvrissement du Sr tandis que les dolérites alcalines Käyser suivent une tendance évolutive présentant une faible variation de Sr, comme les basaltes alcalins et la plupart des basaltes tholéitiques.

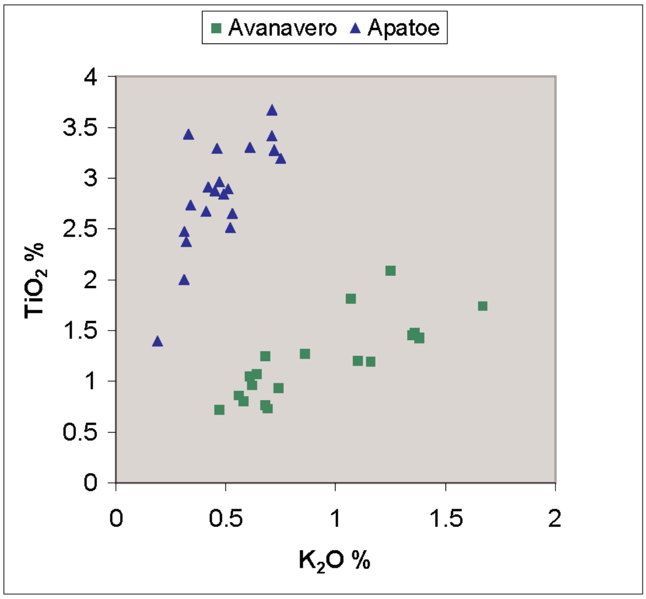

Fig. 10.- TiO_2 vs. K_2O diagram for Avanavero and Apatoe dolerites. The diagram provides a good distinction between the two dolerite types.

Fig. 10.- Diagramme TiO_2-K_2O des dolérites Avanavero et Apatoe. Le diagramme fournit une bonne distinction entre les deux types de dolérite.

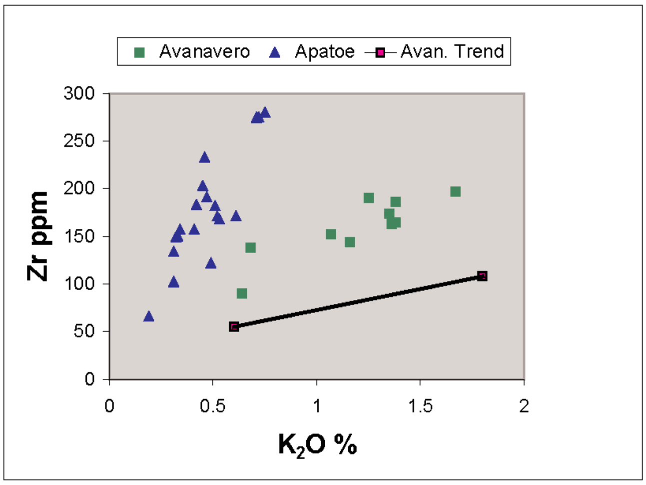

Fig. 11-. Zr –K_2O levels for Avanavero and Apatoe dolerite. Note that Käyser dolerite (not shown) follows the trend of the Avanavero samples, which differs from the Avanavero Trend suggested by Choudhuri *et al*. (1991).

Fig. 11.- Diagramme Zr-K_2O des dolérites Avanavero et Apatoe. Noter que les dolérites Käyser (non représentées) suivent la tendance des échantillons de dolérites Avanavero. Cette tendance est différente de la tendance Avanavero suggérée par Choudhuri et al. *(1991).*

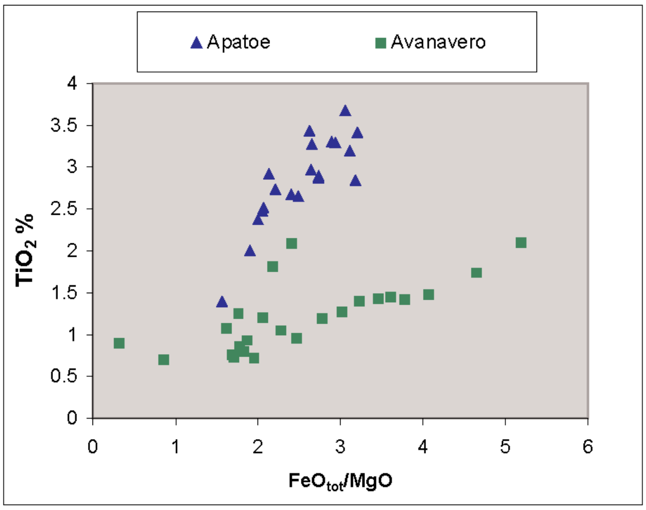

Fig. 12.- TiO_2 vs. FeO_{tot}/MgO diagram (proposed by Deckart, 1996) for Avanavero and Apatoe dolerite. Most Avavanero dolerite samples follow a shallow differentiation trend coinciding with the average low-TiO_2 CFB trend (Albarede, 1992); Apatoe dolerite follows a steep differentiation trend coinciding with that of the average high-TiO_2 CFB (Albarede, op. cit.).

Fig. 12-. Diagramme TiO_2-FeO_{tot}/MgO (proposé par Deckart, 1996) pour les dolérites Avanavero et Apatoe. Les dolérites Avavanero suivent principalement une tendance évolutive modérée qui coïncide avec la tendance moyenne des basaltes CFB pauvres en TiO_2 (Albarede, 1992); les dolérites Apatoe montrent une forte tendance de différenciation qui coïncide avec la tendance moyenne des basaltes CFB riches en TiO_2 (Albarede, op. cit.).

Others have also tried to distinguish between Avanavero and Apatoe dolerite using minor- and trace-element chemistry. Sial *et al*. (1987) used a P_2O_5-TiO_2 diagram, but Avanavero and Apatoe dolerite showed considerable overlap. Choudhuri *et al*. (1991) found a good distinction on the basis of a Zr-K_2O diagram, with a steep trend for Apatoe dolerite and a shallow trend for Avanavero dolerite. Zr-K_2O data for Avanavero dolerite from Elliott (1992) and Deckart (1996) define a less shallow trend (Fig. 11) than that found by Choudhuri *et al*. (1991). Apatoe dolerite from Suriname and French Guiana (data from Deckart, 1996) indeed follow a steep trend that is largely separated from Avanavero dolerite. Elliott (1992) argued that the diagram is less useful because Apatoe-like dolerite from southern Guyana (see Table 9.7 in Gibbs and Barron, 1993) follows the rather shallow Avanavero-like trend (also in the TiO_2-K_2O diagram, Fig. 10). However, this dolerite is of PAPA age and as yet poorly known.

Deckart (1996) used two diagrams - TiO_2 versus FeO_{tot}/MgO, and Th/Yb versus K/Nb. In the latter diagram, Apatoe dolerite from French Guiana and Suriname (12 samples) and two samples of Avanavero dolerite from French Guiana are clearly separated, because the Avanavero samples show a) considerable enrichment in some incompatible elements, Rb, Ba, Th and U (also Choudhuri *et al*., 1990), and b) a reduction in Nb and Ta; they therefore had high Th/Yb and K/Nb ratios (Deckart, 1996). Data for three Avanavero dolerite samples from Guyana (Elliott, 1992) confirmed the distinction. Based on the limited amount of data, the higher Th and U (and to a lesser extent Rb) appear to be distinctive in themselves. In the TiO_2 versus FeO_{tot}/MgO diagram the latter ratio serves as a differentiation index. The trend of Apatoe dolerite (20 samples from French Guiana and Suriname) in the diagram coincided with the trend of the average high-Ti Continental Flood Basalts of Albarede (1992), whereas two Avanavero dolerite samples from French Guiana showed a parallel, but separate trend (Deckart, 1996). However, Avanavero dolerite data from Guyana and Suriname (Hawkes, 1966; Elliott, 1992; Hebeda *et al*., 1973) follow a completely different, shallow trend in the diagram (Fig. 12), which coincides with the trend of the average low-Ti CFB of Albarede (1992). This marked difference in differentiation trend for Apatoe dolerite from French Guiana + Suriname and Avanavero dolerite from Guyana + Suriname explains their difference in TiO_2 level and the usefulness of TiO_2 levels for their distinction. The two Avanavero dolerite samples from French Guiana follow a high-Ti CFB trend rather than a low-Ti one, but are close to the Avanavero trend in the TiO_2-K_2O diagram (Fig. 10).

Note 4. Dykes of alkali diabase have been found in the Pitinga region (Veiga *et al*., 1978, *in* Gibbs and Barron, 1993). On geological evidence they were ranged with the Avanavero dolerite, which also occurs as sills and dykes in the region (see Gibbs and Barron, 1993). However, an analysed alkali diabase sample showed 4.4% alkalis and 3.8% TiO_2 (Veiga *et al*., 1978, in Tables 9.4 and 9.6 of Gibbs and Barron, 1993), completely different from Avanavero dolerite, but rather similar to Käyser dolerite.