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Petrochemistry of Granitoids from the Mozambique Belt

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With 8 Figures and 4 Tables

1. General geology of the southern part of the Mozambique belt

The basement north of the Zambesi river is of old geological constitution (archean or proterozoic) and comprises the following structural units: Metil mobile belt, Lurio-Lugenda mobile belt, Nampula, Mueda, Marrupa, Lichinga and Fingoe blocks (Lächelt 1985, 1988, Figs. 1, 2, 1990, Fig. 1).

The Nampula, Marrupa and Fingoe blocks probably represent remains of an archean nucleus of granite-greenstone type. The mobile belts are relatively narrow zones (of graben or rift type) which were tectonically reactivated in different geological times. We still distinguish the Metil mobil belt and the Namama belt (Fig. 1) in the shape of a thrust, where numerous rare metal mineralizations occur.

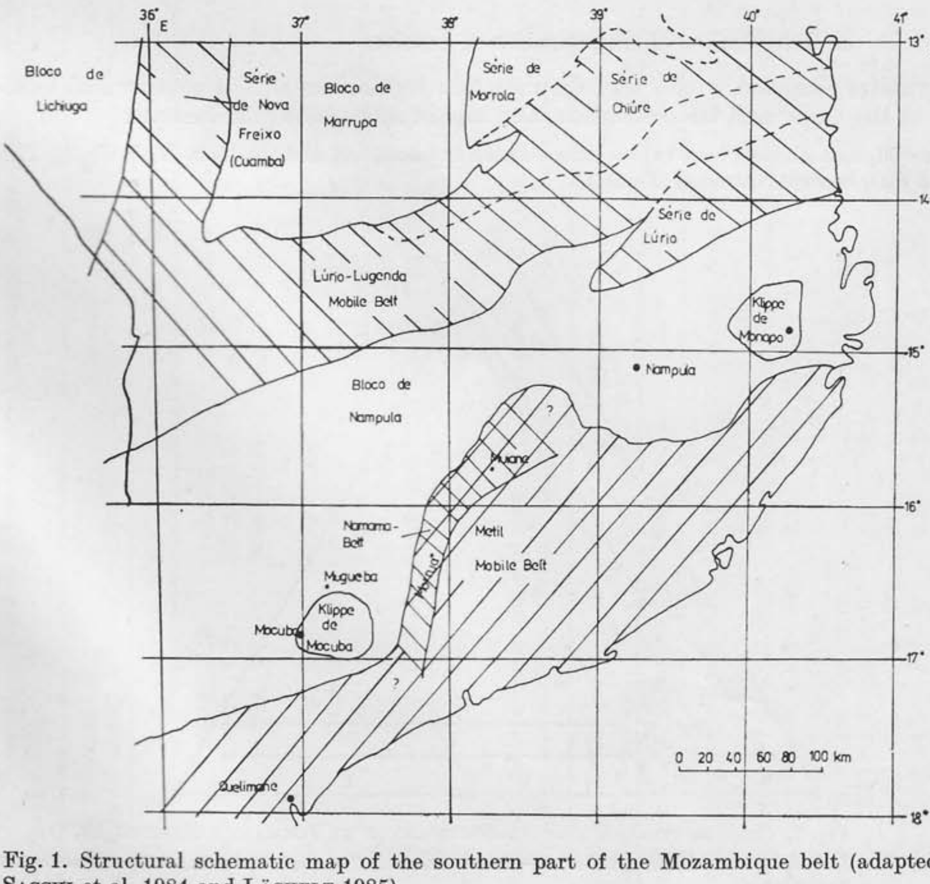

Fig. 1. Structural schematic map of the southern part of the Mozambique belt (adapted from Sacchi et al. 1984 and Lächelt 1985)

Petrographically, the southern part of the Mozambique belt is composed of leucogneisses, biotitic gneisses, micaschists, quartzites, basic to ultrabasic rocks, granitoids. The granitoids are pre-Kibaran (age older than 1000 m.y.), syn- and post-tectonic with Kibaran orogeny (about 1000 m.y.) or pan-African (about 500 m.y.) (SACCHI et al. 1984).

2. Geochemical classification of the granites

The granites under investigation were ordered on the basis of EL BOUSEKEY & EL SOKKARY's (1975) ternary diagram Rb—Ba—Sr. From a total of 99 samples, they are distributed als follows (Fig. 2):

- 10 highly differentiated granites with high Rb contents and low Ba values
- 28 normal granites with high Ba, decreased Rb and uniform Sr contents
- 51 anomalous granites (metasomatizated or granitized) with lower Rb contents relative to those of normal granites but higher than those in granodiorites.
- 10 granodiorites with high Ba and Sr contents and low Rb ones.

This grouping has to do with a differentiation degree which corresponds, by decreasing order, to: highly differentiated granites > normal granites > anomalous > granodiorites. In the granodiorites to normal granites sequence, the factor governing the differentiation is the Ba/Sr ratio whereas in the normal to highly differentiated granite series the Ba/Rb ratio is more important.

3. Geochemical characterization of granites

The granites classified in this way show certain regularities in the geochemical behaviour of the major and trace elements, and also in ratios between elements.

- the SiO_2 and alkalies sum values increase with fractionation and the CaO, MgO, Fe_2O_3, TiO_2 and P_2O_5 contents decrease (Table 1).

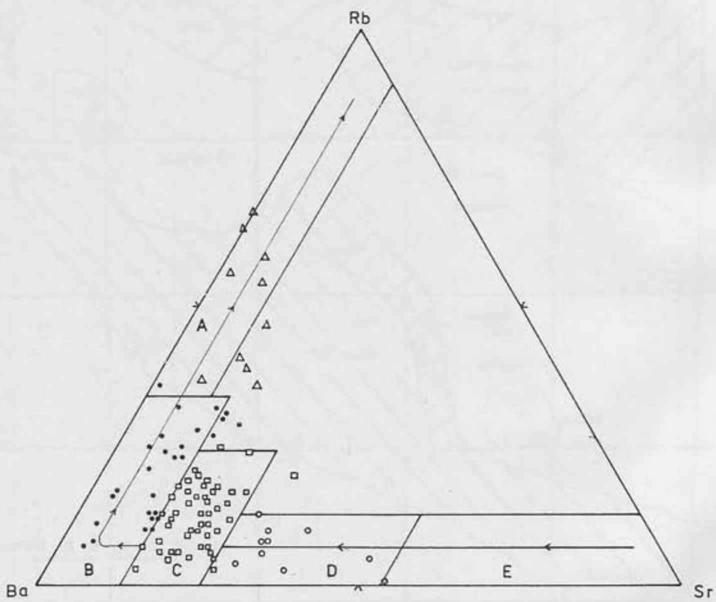

Fig. 2. Granites grouped after EL BOUSEILEY & EL SOKKARY's diagram (1975)

A — highly differentiated granites; B — normal granites; C — anomalous granites; D — granodiorites; E — diorites

Table 1. Chemical composition of granites in major elements ($\bar{x}$: mean values in %; s: standard-deviation; (v): variation range of the values; N: number of samples)

	Highly differentiated granites ($N = 10$)			Normal granites ($N = 28$)			Anomalous granites ($N = 51$)			Granodiorites ($N = 10$)		
	$\bar{x}$	s	v	$\bar{x}$	s	v	$\bar{x}$	s	v	$\bar{x}$	s	v
SiO_2	75.47	1.19	(73.5–77.0)	74.47	2.58	(69.3–78.8)	70.43	4.94	(56.7–76.5)	68.52	5.77	(58.5–77.7)
Al_2O_3	13.63	0.70	(12.3–14.9)	13.28	0.91	(11.6–15.4)	14.88	0.60	(13.3–16.0)	15.75	1.90	(13.2–19.5)
F_2O_3 (– total)	1.48	0.72	(0.66–2.83)	2.46	1.04	(0.68–5,05)	3.38	1.64	(1.05–10.0)	3.94	2.37	(0.85–9.60)
CaO	0.61	0.20	(0.32–0.82)	0.96	0.50	(0.30–2.55)	1.88	0.84	(0.80–5.48)	3.58	2.01	(1.68–7.41)
MgO	< 0.3	4×10^{-6}	(< 0.3)	0.26	0.17	(< 0.3–0.8)	0.67	0.49	(< 0.3–2.7)	0.88	0.90	(< 0.3–2.9)
Na_2O	3.04	0.80	(1.8–4.2)	2.53	0.62	(< 0.5–3.8)	2.49	0.73	(1.4–6.1)	3.12	0.95	(1.0–4.5)
K_2O	5.15	1.27	(3.58–8.23)	5.12	0.96	(3.76–8.87)	5.11	0.91	(1.22–6.47)	3.19	1.20	(1.32–5.26)
MnO	0.07	0,08	(0.02–0.27)	0.04	0.02	(0.01–0.09)	0.05	0.05	(0.01–0.36)	0.06	0.04	(0.02–0.12)
TiO_2	0.13	0.12	(0.01–0.40)	0.28	0.18	(0.05–1.01)	0.57	0.37	(0.01–1.99)	0.48	0.38	(0.10–1.41)
P_2O_5	0.05	0.05	(< 0.03–0.13)	0.08	0.05	(< 0.03–0.24)	0.19	0.16	(< 0.03–0.83)	0.15	0.16	(0.06–0.58)

Table 2. Chemical composition of granites in trace-elements ($\bar{x}$: mean value in ppm; s: standard deviation; (v): variation range of the values; N: number of samples; C: Clarke concentration — after Vinogradov, 1962 in Roesler & Lange 1972)

	Highly differentiated granites ($N = 10$)				Normal granites ($N = 28$)				Anomalous granites ($N = 51$)				Granodiorites ($N = 10$)			
	$\bar{x}$	s	v	C	$\bar{x}$	s	v	C	$\bar{x}$	s	v	C	$\bar{x}$	s	v	C
Rb	335.9	1.4	(168–529)	2.2	180.2	1.3	(112–376)	1.2	165.3	1.8	(< 10–286)	1.1	64.7	2.7	(< 10–153)	0.4
Sr	34.4	3.3	(< 10–164)	0.1	77.6	2.2	(27–208)	0.2	271.1	1.6	(28–629)	0.8	424.4	1.4	(270–828)	1.2
Ba	285.0	1.4	(200–500)	0.4	649.6	1.6	(330–1800)	1.0	1015.8	1.6	(160–3100)	1.6	688.4	1.4	(350–1000)	1.1
Sn	2.9	4.8	(< 1–22)	1.2	6.7	2.2	(< 1–15)	2.7	4.1	3.2	(< 1–41)	1.6	2.8	3.4	(< 1–10)	1.1
Be	5.5	1.7	(2–10)	1.4	2.8	1.6	(1–8)	0.7	2.5	1.8	(1–14)	0.7	1.8	1.5	(1–3)	0.5
Nb	39.9	1.9	(15–100)	2.0	22.0	1.4	(13–60)	1.1	22.7	1.8	(9–130)	1.1	12.9	1.4	(9–28)	0.6
Pb	66.7	1.9	(28–210)	4.2	23.0	1.7	(7–66)	1.4	27.6	1.9	(9–180)	1.7	18.8	1.4	(12–38)	1.2
V	4.7	2.0	(< 5–13)	0.05	8.2	3.0	(3–82)	0.09	35.7	2.0	(< 5–130)	0.4	51.5	2.3	(11–180)	0.6
Co	3.1	1.9	(< 3–6)	0.2	3.5	2.1	(< 3–12)	0.2	7.2	1.6	(< 3–27)	0.4	7.6	1.9	(4–22)	0.4
Cu	6.2	5.6	(1–150)	0.1	24.6	2.6	(3–100)	0.5	13.2	2.4	(2–100)	0.3	26.1	2.6	(9–130)	0.6
Ga	22.9	1.2	(17–31)	1.2	17.5	1.2	(13–29)	0.9	22.4	1.4	(11–110)	1.2	18.4	1.2	(13–25)	1.0
Zr	75.3	2.2	(16–170)	0.4	244.8	1.7	(74–670)	1.4	330.8	2.0	(45–820)	1.9	175.0	2.1	(57–410)	1.0
B	5.4	1.3	(4–9)	0.4	5.8	1.6	(3–14)	0.5	6.3	1.4	(3–15)	0.5	5.6	1.4	(3–9)	0.5

— the Rb, Be, Nb and Pb contents increase with differentiation while the Sr, V and Co ones decrease (Table 2, Fig. 3).
— Sn, Cu, Ga, Ba, Zr and B do not show a consequent relation with the differentiation trend.

The Rb/Sr, Rb/Ba ratios values as well as the agpaitic index are higher in the more differentiated granites; the K/Rb and Ba/Rb ratios decrease with the fractionation (Table 3).

Nearly all studied granites are peraluminous with an $Al_2O_3/(CaO + Na_2O + K_2O)$ ratio = 1 and show a predominantly potassic alkaline tendency.

The Fig. 4 shows the granite distribution in the $(Na_2O + K_2O)/SiO_2$ variation diagram (TISCHENDORF 1985).

In the highly differentiated granites SiO_2 ranges between 74 and 77% and the alkali content varies from 7 to 10%. These granites correspond to alkali feldspathic granites

Table 3. Some ratios between elements in granites

Ratio	Highly differentiated granites	Normal granites	Anomalous granites	Granodiorites
K/Rb	124.4	232,5	250.4	383.5
Rb/Sr	9.8	2.32	0.61	0.15
Ba/Rb	0.85	3.57	6.25	11.1
Ba/Sr	8.3	8.4	3.7	6.6
Ga/Al	3.17	2.50	2.85	2.22
Rb/Zr	4.5	0.74	0.50	0.37
K/Na	2.14	3.51	2.49	1.52
Na + K/Al	0.79	0,73	0.65	0.55

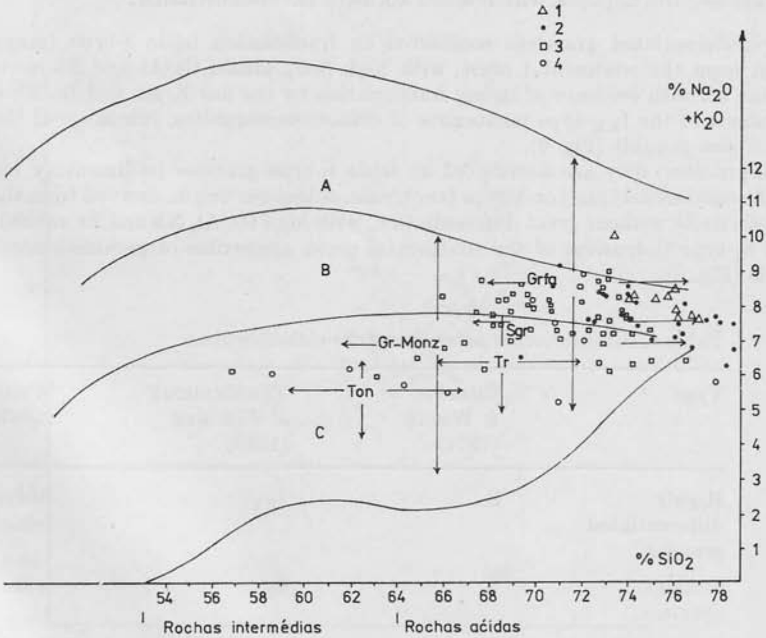

Fig. 4. $(Na_2O + K_2O)/SiO_2$ variation diagram for the considered granites
1, 2, 3, 4 see Fig. 3
A — alkaline rocks; B — subalkaline rocks; C — calcalkaline rocks; Grfa — alkali feldspathic granites; Sgr — syenogranite; Gr Monz — granodiorite/monzogranite; Ton — tonalite; Tr — trondhjemite

with characteristics of syenogranitic. The normal granites present SiO_2 values between 69 and 79% and the alkali sum varies form about 6.5 to 8.5%. These granites also follow an alkaline syenitic-granitic development. In the anomalous granites, one part is distributed in the same ways and other parts fall into the granodioritic field with alkali contents of about 6%.

The granodiorites show tonalitic-trondhjemitic tendencies, and they are characterized by lower SiO_2 (uptil 58.5%) and alkalies (uptil 5%) contents.

In the Tischendorf & Pälchen's (1985) Rb—Sr diagram, the highly differentiated, normal and anomalous granites follow the crust tendency (the Rb/Sr ratio varies in the range between 0.3 and 100 or more) while the granodiorites seem to be mantle-influenced.

4. Application of other granitoid classification to granites

In recent publications, several classifications of granitic rocks can be found based on petrochemical, structural, formational and tectonic criteria (Chappel & White 1974 in Wimmenauer 1985; de la Roche et al. 1980; Didier et al. 1982 in Batchelor & Bowden 1985; Tischendorf & Pälchen 1985; Tischendorf 1986; Whalen et al. 1987).

The assignment of the granites under investigation to these different types is not often realistic, taking into account that the geologic setting in Mozambique may present characteristics which do not correspond to the other investigated regions of the world which served as a basis for the definition of these rock types.

So, we will try to establish an equivalence to some of the proposed types (Table 4), and to indicate the aspects which seem to have no concordance:

- highly differentiated granites: considered as fractionated felsic I-type (magmatic origin, derived from the continental crust, with high SiO_2, alkali, Ga/Al and Nb contents and low CaO und Sr, with evidence of strong fractionation by the low K/Rb and Ba/Rb values). Assignment to the I_{KK}-type (anatexites of orthometamorphites, intrusives of the continental crust) is also possible (Fig. 6).
- normal granites: they are distributed as felsic S-type granites (sedimentary origin, derived from the continental crust) or A-type (anorganic, of igneous origin, derived from the continental crust, normally without great differentiation, with high Ga/Al, Nb and Zr values). Assignment to the S_I-type (intrusives of the continental crust, anatexites of parametamorphites) is also possible (Fig. 6).

Table 4. Granite order after literature classifications

Type	Chappel & White (1974)	Tischendorf & Pälchen (1985)	Whalen et al. (1987)
Highly differentiated granites	S	I_{KK}	fractionated felsic I
Normal granites	S	S_I	felsic S A
Anomalous granites	S	S_S I_{OK}	S A
Granodiorites	I	I_{OK} I_{MT}	M

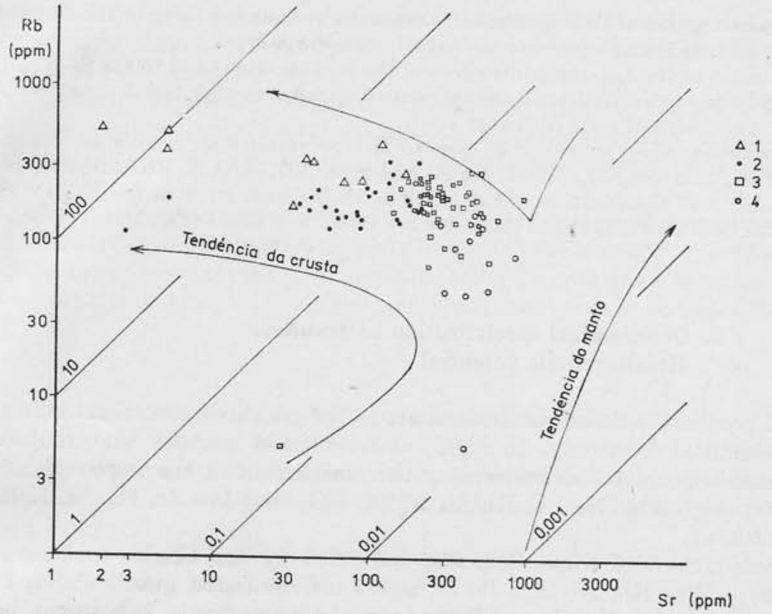

Fig. 5. Evolution tendencies of granitoids on the Rb/Sr diagram
1, 2, 3, 4 see Fig. 3

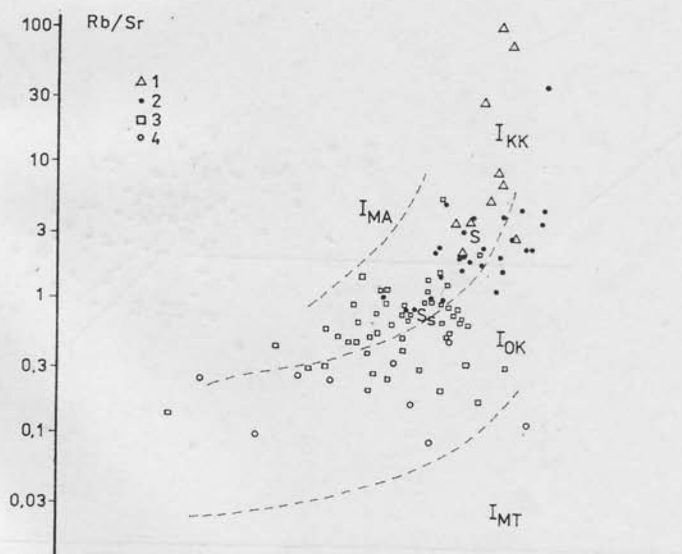

Fig. 6. Granite distribution on the Rb/Sr-SiO_2 diagram with indication of the genetic types after TISCHENDORF & PÄLCHEN (1985)
1, 2, 3, 4 see Fig. 3

- Anomalous granites: their geochemical characteristics assign them to the S-type (sedimentary origin, derived from the continental crust) or to the A-type.
  Assignment to the I_{OK}-type (intrusives of the oceanic crust) and to the S_S-type (in situ granitoids of the continental crust, anatexites of parametamorphites) is not probable from the geotectonic point of view (SCHMIDT 1986).
- Granodiorites: their behaviour is close to M-type granites (intrusives associated to a mantle evolution, with low SiO_2, Rb/Sr, Rb/Ba and high CaO, MgO, K/Rb contents).
  For a tectonic classification of the granites, their distribution in the $Na_2O \times Zr$ – Rb/MgO diagram (BEUGE 1987) shows that they are collision granites (Fig. 7).

5. Geochemical specialization of granites. Metallogenetic potential

It is not possible to make conclusions about the granitoid specialization on the basis of the geochemical data only. In highly differentiated granites we can observe, in some cases, certain peculiarities concerning the enrichment or the impoverishment of some indicators (high Nb, Rb, Pb, Rb/Zr, K/Na, SiO_2, and low Zr, Ba, Sr, K/Rb, MgO and CaO contents).

The enrichment of some elements, indicated by the Clarke concentrations values (Table 2) – Pb, Rb, Nb and Be in highly differentiated granites; Sn, Pb and Zr in normal granites; Zr, Pb, Sn and Ba in anomalous granites – is however, not as high as compared to the limits normally defined for a specialization (TISCHENDORF 1977; BARSUKOV 1967 in GOVETT 1983).

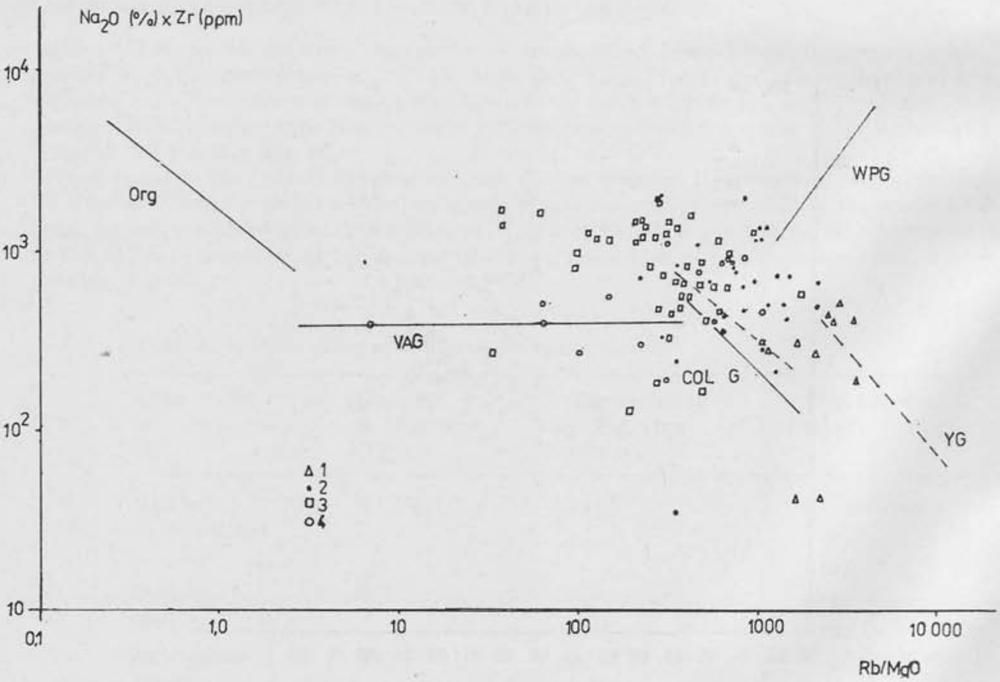

Fig. 7. Correlation between $Na_2O \cdot Zr$ and Rb/MgO in granites

MPG – within plate granite; COLG – collision granite; VAG – volcanic arc granite; ORG – ocean rift granite; YG – younger granite; OG – older granite; 1, 2, 3, 4 see Fig. 3

From its analysis (see also the structural map of Fig. 1) we deduce the following:

(1) It seems that there is a link between the structural units of the region and the granite types, since
  - the anomalous granites are preferentially located in the Nampula block and in the border regions of the Lurio-Lugenda mobile belt (only subordinately in the Metil mobile belt).
  - the highly differentiated granites, normal granites and granodiorites occur in the Metil mobile belt, including the granulitic complex of Mugeba.

(2) We observe a relation between the represented tectonics and the granite type:
  - the normal granites occur in two spots (Alto-Ligonha and Mocuba regions) which, as in the known pegmatitic fields, are located at the crossing of linear structures of great dimension.
  - the granodiorites are found in a zone between the two spots mentioned above following the NNE–SSW tectonic direction and in the southern part the Namama belt direction.
  - the highly differentiated granites occur in a southeast zone of the region under investigation and also in the Mocuba spot; these granites seem to be associated with NE–SW and NW to SE lineaments.
  - the anomalous granites do not show a relation with the main tectonic directions concerning the granites-pegmatites relation, has not yet been clearly defined a genetic connection between the two formation types.

The pan-African granites have often been related to the rare metal pegmatites, but only in temporal and spatial aspect (Aquater 1983).

From the results obtained we can conclude:

- the highly differentiated and the anomalous granites are not, as a rule, spatially connected to zones where useful mineralizations are known.
- the normal granites occur in zones where great pegmatitic fields are found, at the crossing of old Kibaran and pre-Kibaran lineaments of NW–SE orientation with younger, Pan-African aged lineaments of NE–SW orientation.
- the granodiorites are located in areas of economically important mineral occurrences of the Namama belt.

Summary

The studied granites are classified on the basis of their relative Rb, Ba and Sr contents. Four groups resulted from this classification — highly differentiated granites, normal granites, anomalous granites and granodiorites — which are distinguished by their differentiation degree and by some characteristics in the geochemical behaviour of major elements, trace-elements and values of the ratio between elements. The tectonic control of the granites reveals a connection between the granite type and the geotectonics of the considered region as well as a relation between the granite type and the localization of economically important ore deposit areas.

Zusammenfassung: Die untersuchten Granite können auf der Grundlage ihrer relativen Gehalte an Rb, Ba und Sr geordnet werden. Daraus ergeben sich vier Gruppen von Granitoiden — hochdifferenzierte Granite, anomale Granite, Normalgranite und Granodiorite. Sie unterscheiden sich durch ihren Differentiationsgrad und durch einige Charakteristika in der Geochemie von Haupt- und Spurenelementen sowie Elementverhältnissen. Es existiert eine Beziehung zwischen dem Granittyp und der geotektonischen Situation der betrachteten Region einerseits sowie dem Auftreten ökonomisch wichtiger Erzlagerstätten andererseits.

Резюме: Классификация исследованных нами гранитоидов на основании относительного содержания в них элементов Rb, Ba и Sr возможно. Таким путем возможно выделение четырех групп гранитоидов:

Высокодифференцированных гранитов, аномальных гранитов, нормальных гранитов и гранодиоритов.

Они различаются друг от друга по степени дифференциации и по некоторым характерным признакам геохимии главных элементов и элементов-примесей, а отличаются также по элементным отношениям.

Существует связь, с одной стороны, между типом гранита и геотектонической ситуацией рассматриваемого района, с другой стороны, между типом гранита и появлением экономически важных рудных месторождений.

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