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A comparative study on two trondhjemitic rock-series of different origin from the Mureş ophiolitic suture, Romania

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Abstract

The Mureş Ocean, where the two trondhjemitic rock-series occurred, evolved from the Liassic (ca. 180 Ma) up to the Lower Cretaceous (ca. 120 Ma). During its opening stage, through a spreading process, an ocean floor trondhjemitic rock-series, consisting of granophyres, plagiogranites and plagiaplites, associated with tonalites and quartz-diorites, was formed. These rocks form parallel dykes in a sheeted dyke complex and occur as dykes cutting the gabbro bodies. The closing of the ocean was determined by a bilateral subduction process acting along an Andean-type and a Mariana-type subduction planes. Within the Mariana-type subduction trench, extending from Drocea to the Trascău Mountains, island arc bimodal volcanism manifested itself, engendering a second trondhjemitic rock-series, represented by quartz-keratophyres, rhyolites, dacites and trachytes. The common geochemical features of the two different sources of the trondhjemitic rock-series consist in their high contents of SiO_2 and Na_2O, and low contents of K_2O, CaO and MgO.

Keywords: Mureş Ocean, ocean floor trondhjemites, island arc trondhjemites, geochemistry.

Introduction

The research conducted on the evolution of the Mureş Ocean toward its final stage, the Mureş Ophiolitic Suture (MOS), indicated that the former evolved through two intermediate stages (Savu, 1999, 2007), namely the opening stage and the closing stage. Throughout this long evolution, two trondhjemitic magma fractions, an ocean floor and an island arc magma fraction, have been engendered, from which two rock-series have derived. This fact raised an urgent question regarding the geotectonic and petrologic conditions that controlled the genesis of the two almost similar magma fractions which, despite their different sources, engendered the two trondhjemitic rock-series. The present study attempts to answer this question, to the extent that the available data allows it, and to indicate the common features of these two trondhjemitic magma fractions, as well as their origin.

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Occurrence of the ocean floor and island arc trondhjemitic rock-series

After a period of rifting (Late Triassic), which generated basic eruptions of within-plate basalts (Savu et al., 1986), at the beginning of the Liassic (ca. 180 Ma; Herz et al., 1974), the Mureş Ocean occurred along the rifting zone. This ocean was a branch of the large Alpine system of ocean zones from the Carpathian area. It was separated from the main Carpathian branch somewhere in the Transcarpathia area, and extended toward the southwest of the Southern Apuseni Mountains, where the MOS will be formed, stretching further away, through the Vardar zone, into Serbia. It joined the main Alpine branch of the Dinarides once again somewhere in the south of Serbia or in the west of Greece (see the model in Savu, 2007). It evolved during two genetic stages: the opening stage and the closing stage. If the spreading rate in the Mureş Ocean had been of only 5 cm/year, the width of this ocean would have reached about 400 km.

a. The opening of the Mureş Ocean. This stage lasted from the Liassic up to the Oxfordian, time span during which an ocean crust was engendered. This ocean crust of basic composition included two main tholeiitic rock complexes on top, namely a lower sheeted dyke complex and an upper pillowed, basalt complex (Savu, 1983, 2007). Each complex hosted gabbro bodies in which a layered structure occurred during the magma crystallization and differentiation (Cioflica and Savu, 1960); in the layered gabbro bodies, alternated strata of diopside gabbros, olivine gabbros, troctolites etc., and Ti-magnetite-rich gabbros were described. In addition, within the sheeted dyke complex, parallel dykes of trondhjemitic granophyres and plagiogranites, as well as of tonalites and quartz-diorites, were intruded between the basic dykes; similar rocks are cutting the gabbro bodies (Savu, 1962b).

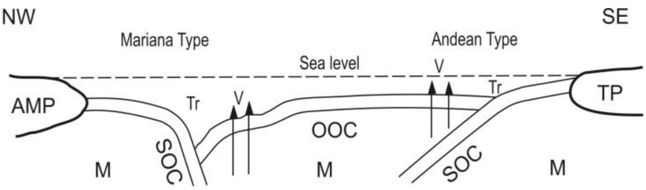
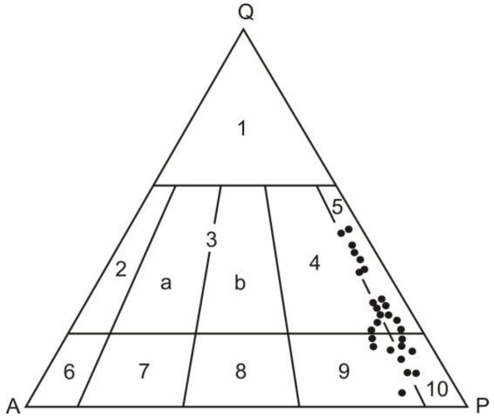


Fig. 1 Cross-section model between Slatina de Mureş and Căprioara, showing the subduction system of the Mureş Ocean (according to Savu, 2003). AMP-Apuseni Mountains Plate; TP-Transylvanian Plate; M-mantle; SOC-subducted ocean crust; OOC-obducted ocean crust; Tr-subduction trench; V-island arc volcanics.

b. The closing of the Mureş Ocean. The closing of the Mureş Ocean started in the Oxfordian and ended at the beginning of the Lower Cretaceous. At the beginning of this stage, an asymmetrical bilateral subduction of both marginal ocean crust zones under the ocean crust from the median zone of the ocean took place (Savu, 1983). Consequently, two marginal subduction trenches hosting island arc volcanism of different types occurred. The southern marginal trench of the Mureş Ocean developed a subduction of the Andean type, under a subduction angle of about 45°. The northern marginal subduction trench of the ocean occurred as the result of a Mariana-type subduction process, the subduction plane being almost vertical (Fig. 1). Within the southern subduction trench, normal island arc volcanism occurred, resulting in a volcanic association of the basalt-andesite-rhyolite type, accompanied by granitoid plutons, among which a shoshonitic granitoid pluton has also been noticed (Savu, 2008). In the subduction trench of the Mariana-type, island arc bimodal volcanism was active (Savu et al., 1986).

The bimodal volcanism produced two different groups of volcanic rocks, namely a basaltic to melabasaltic (high-Mg basaltic) group and an acidic (leucocratic) group. The latter consists of quartz-keratophyres (also see Uyeda, 1981), which are the equivalent volcanics of the plutonic trondhjemitic rocks (see Streckeisen, 1967), and other related leucocratic volcanics.



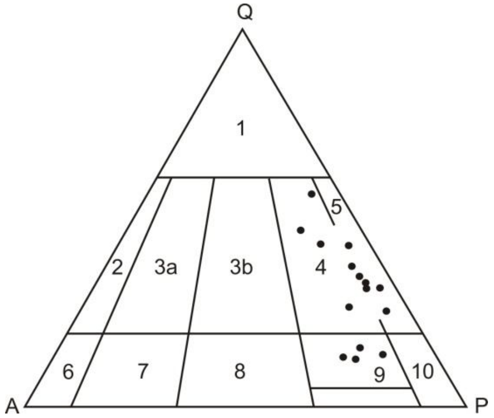


Fig. 2 (left) Plot of the ocean floor trondhjemitic and related quartz-bearing rocks on the QAP diagram (fields according to Streckeisen, 1967). 1-quartzitic rocks; 2-alkali granites; 3a,b-granites; 4-granodiorites; 5-trondhjemites + plagiogranites and tonalites; 6-alkali syenites; 7-syenites; 8-monzonites; 9-monzodiorites and monzogabbros; 10-diorites and gabbros. Data from Savu et al. (1970, 1982, 1985, 1987, 1992), Savu and Stoian (1988, 1991), and Saccani et al. (2001).

Fig. 3 (right) Plot of the quartz-keratophyres and related acidic (leucocratic) rocks on the QAP diagram (fields according to Streckeisen, 1967). 1-quartzitic rocks; 2-alkali rhyolites; 3a-rhyolites; 3b-rhyolites (quartz-latites); 4-dacites; 5-quartz-keratophyres and quartz-andesites; 6-alkali trachytes; 7-trachytes; 8-latites; 9-latite-andesite and latite-basalts; 10-andesite basalts. Data from Savu (1962), Savu et al. (1986; 1992), Nicolae and Bratosin (1980).

Petrography and classification

The ocean floor dykes of quartz-rocks which form the trondhjemitic rock-series related to the ophiolites of the MOS vary in composition. Thus, they are represented by albite-quartz-bearing dolerites, even quartz monzo-gabbros, as the most basic terms of the series, followed by quartz-diorites and tonalites, trondhjemitic granophyres, plagiogranites and plagiaplites, as shown by the QAP diagram (Fig. 2).

The quartz-dioritic and tonalitic granophyres are rocks with a larger granulation than the related albite-quartz-bearing dolerites, both showing an almost similar divergent texture. They consist of long (up to 1 cm) crystals of albite, apart from quartz, green hornblende, magnetite, and, sometimes, ilmenite; their color is gray, presenting a variegated aspect. The trondhjemitic granophyres *sensu stricto* show almost the same features, but they are light in color because they contain pale green amphiboles; myrmekitic intergrowths between quartz and albite are specific to all these granophyres.

All granophyres are usually associated with the sheeted dyke complex of the MOS, where they also occur as parallel dykes, alternating with the basalt and dolerite dykes of the complex. On the contrary, the plagiogranites and plagiaplites occur either as parallel dykes or as irregular veins crossing both the sheeted dyke complex and the above-mentioned gabbro bodies; they are the most leucocratic of the quartz-rocks related to the ophiolites of the MOS. Moreover, they show a hypidiomorphic texture and consist of quartz, albite, a pale green hornblende and magnetite or ilmenite.

The quartz-keratophyres, together with the related leucocratic rocks and the basic rocks of the bimodal volcanism, are spatially associated with the flysch deposits formed during the Oxfordian-Valanginian (Savu et al., 1986). All these formations lie over the Pre-Oxfordian ocean floor rocks of the MOS. They are to be found in the Drocea-Trascău subduction trench of the Mariana-type, which extends from Pătârş, in the north of Banat, up to the Trascău Mountains, where these formations subsided into the Transylvanian Basin (Savu, 1990). This northern zone of the subduction formations was interrupted, in some places, by the Laramian formations and later tectonic faults.

The flysch deposits comprise two rock complexes, as follows: (1) the volcano-sedimentary lower complex, which is Upper Jurassic in age, and consists of jaspers (radiolarites), island arc volcanics and bands of manganese deposits; it is followed by (2) a Lower Cretaceous complex, which consists of marl deposits that alternate with limestone bands. Both complexes have been folded during the Austrian and Laramian movements.

The island arc volcanic activity was carried out mostly by volcanoes of the central type, under submarine conditions, generating pyroclastic rocks and, rarely, lava flows, formed of rocks that belong to the two members of the bimodal volcanism. The acid rocks are represented by quartz-keratophyres and the related leucocratic rocks, including rhyolites, dacites and trachytes. The quartz-keratophyres consist of numerous phenocrysts of quartz; rarely, K-feldspar, albite-oligoclase and biotite appear in a leucocratic groundmass. On the QAP diagram (Fig. 3), the island arc quartz-keratophyres and the related leucocratic rocks plot inside the same fields as the ocean floor trondhjemites and the related quartz-rocks.

The almost similar distribution of the ocean floor and island arc trondhjemites and the related quartz-rocks in the diagrams of Figures 2 and 3 represents a first common feature of these rocks. It shows that the two rock-series, although of different origin, contain close amounts of SiO_2, alkalies and CaO.

Geochemistry of the trondhjemitic rocks and their tectonic setting

The average chemical composition of the rocks from the two rock-series presented in Table 1 indicates that these rocks are rich in SiO_2 and Na_2O, which represents a second main characteristic.

In the ocean floor trondhjemitic rocks, the average SiO_2 content is 69.24%, while the related quartz-rocks display an average of 64.80% SiO_2. On the other hand, the average SiO_2 content is 75.71% in quartz-keratophyres, and 71.87% in the related leucocratic rocks. The average Na_2O content is higher in the ocean floor trondhjemitic granophyres than in the equivalent island arc volcanics. In the trondhjemitic granophyres and plagiogranites it is 5.98%, and in the related quartz-rocks it is 4.69% Na_2O. In the equivalent volcanic rocks it is a little higher (i.e. 6.66% Na_2O in quartz-keratophyres), than in the ocean floor rocks, but it is only 2.01% in the related leucocratic volcanic rocks. On the contrary, due to the slightly higher K_2O content of the latter, the average values of (Na_2O+K_2O) are higher in the island arc volcanics than in the ocean floor rocks. For instance, the sum of alkalies is 6.08% in the ocean floor granophyres and plagiogranites, and 4.99% in the related quartz-rocks; in comparison, the quartz-keratophyres display values of alkalies of 7.65%, while in the related leucocratic rocks the average sum of alkalies is 7.25%.

The total iron components (such as FeO*) are higher in the ocean floor trondhjemitic rocks than in the related island arc equivalent rocks. The average FeO* content is 4.63% in the trondhjemitic granophyres, and higher in the related quartz rocks (up to 8.06%). In the island arc volcanics, the average FeO* content is 2.44% (quartz-keratophyres), and only 1.62% in the related leucocratic rocks. These data support the conclusion reached by Fenner (1929), according to whom, through differentiation, the tholeiitic magmas concentrate iron. MgO is very low in both rock-series, as is the CaO content (Tab. 1).

Tab. 1 Average chemical composition of the ocean floor and island arc trondhjemitic and related quartz-rocks*.

Rock-series	Ocean floor rocks	Related quartz-rocks	Island arc rocks	Related quartz-rocks
Melanocratic mineral	Green hornblende		Biotite	
SiO_2	69.24	64.80	75.71	71.87
Al_2O_3	13.52	14.63	13.68	14.41
FeO*	4.63	8.06	2.49	1.62
MgO	0.86	2.62	0.60	0.68
CaO	3.23	6.36	1.68	1.10
Na_2O	5.98	4.69	6.66	2.91
K_2O	0.10	0.30	0.99	4.34
TiO_2	0.72	1.28	0.36	0.24
V ppm	3.06	117.9	46.3	5.57
Co	6.26	17.20	4.60	4.46
Sr	88.3	133.2	163.3	227.4
Ba	17.6	30.3	60.1	302.1
Y	107.9	78.3	28.26	21.7
Zr	441	293.1	162.4	220.7
Nb	12.5	18.0	10.4	16.5
Rb	4.75	2.47	-	-
Na_2O/K_2O	6.08	4.99	7.65	7.25
Mg#	38.6		46.1	
Eu/Eu*	10.5		8.74	

* The average values based on 24 analyses of ocean floor rocks and 18 analyses of island arc rocks (see the authors quoted in the captions of Figures 2 and 3).

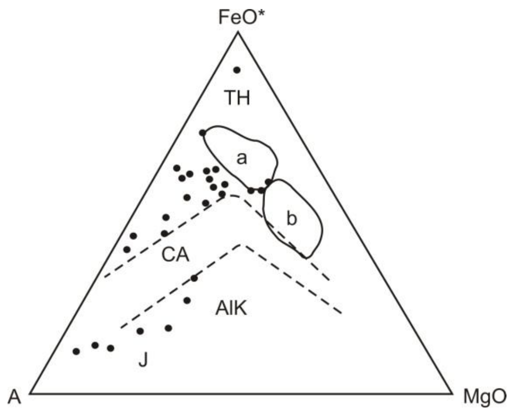
The high differentiation of the trondhjemitic magma fractions from the tholeiitic parental magma determined a dispersion of the chemical elements in relation to the original set. Thus, the amount of elements such as SiO_2, TiO_2, Fe_2O_3, and Na_2O increases, while that of CaO, MgO and K_2O decreases. At the same time, the trace elements related to the major elements underwent the same dispersion. Therefore, sometimes, most of these elements cannot be taken into account when using diagrams that deal with the tectonic setting.

The ocean floor trondhjemitic granophyres and related quartz-rocks inherit from their parental magma the character of the tholeiitic rocks, as results from the diagram in Figure 4. On this diagram, most of the ocean floor rocks plot in the TH field. The surprising plot of the quartz-rock dykes that cut the Juliţa gabbro body, in the alkaline field, leads to the assumption that the alkaline character was acquired through the extreme differentiation of the residual trondhjemitic magma.

As shown in Figure 5, the island arc quartz-keratophyres and the related leucocratic rocks are of the calc-alkaline type; the diagram in Figure 6 leads to the same conclusion. Moreover, the last diagram shows that these rocks are clearly of the arc type (Sajona, 1995), and that they are not adakitic rocks, as old trondhjemitic rocks usually are (see Martin, 1999).

Because of the lack of adequate data, the identification of the tectonic setting of the trondhjemitic granophyres and the related quartz-rocks is difficult to accomplish.

However, a sample from the sheeted dyke complex of the Juliţa area, analysed by Saccani et al. (2001), revealed the following results: 57% SiO_2, 2 ppm Rb, and 122 ppm (Y+Nb). These values would situate the rock in the ocean ridge granite domain established by Pearce et al. (1984), which sheds favorable light over the tectonic setting of all the ocean floor trondhjemitic dykes from the MOS.



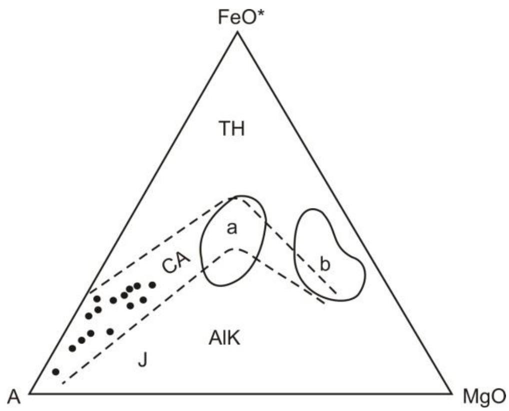


Fig. 4 (left) Plot of the ocean floor granophyres and related quartz-rocks on the FeO*–(Na_2O+K_2O)–MgO diagram (fields according to Irvine and Baragar, 1971; Hutchinson, 1982). TH-tholeiitic; CA-calc-alkaline; Alk-alkaline. a-field of the normal basalt and gabbro rocks; b-field of the Ti-magnetite-gabbro, basalt and dolerite rocks; J-plots of the Juliţa quartz-rocks. Data sources as in Figure 2.

Fig. 5 (right) Plot of the island arc quartz-keratophyres and related leucocratic rocks on the FeO*–(Na_2O+K_2O)–MgO diagram (fields as in Figure 4). a-field of the normal bimodal basalts; b-field of the high-Mg basalts. Data sources as in Figure 3.

As shown above, the behaviour of the trace elements is in agreement with that of the major elements they are related to. For instance, the average contents of V and Co, which represent the trace elements related to the sideritic major elements, are higher in the ocean floor rocks than in the island arc volcanics. This relation between the trace elements of the two rock-series is also obvious in the case of the related major elements (Tab. 1). On the contrary, Sr and Ba display higher contents in the island arc quartz-keratophyres and related leucocratic rocks than in the ocean floor rocks. By contrast, Y is higher in the ocean floor granophyres and related quartz-rocks. It is notable that Zr presents high contents in both the ocean floor and island arc rock-series, but its amounts are lower in the latter.

The average REE contents of the ocean floor, island trondhjemites and the related rocks are shown in Table 2. According to this table, in both rock-series the contents of LREE are higher than those of the HREE. Moreover, the amounts of La, Ce, Tb, and Yb are higher in the island arc quartz-keratophyres and the related rocks than in the ocean floor rocks. On the contrary, Sm and Eu are higher in the ocean floor granophyres and related rocks.

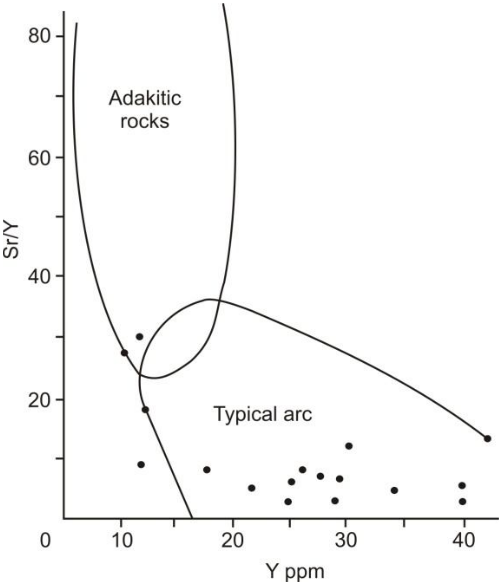


Fig. 6 Plot of the island arc quartz-keratophyres and related rocks on the Sr/Y vs. Y diagram (fields according to Sajona, 1995). Data sources as in Figure 3.

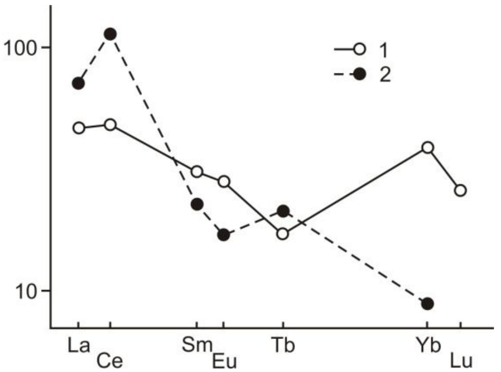


Fig. 7 The chondrite-normalized REE patterns of the ocean floor granophyres and island arc quartz-keratophyres. 1-pattern of the ocean floor granophyres; 2-pattern of the island arc quartz-keratophyres. Data from Table 2.

The diagram in Figure 7 shows the chondrite-normalized patterns of the two rock-series. It reveals certain differences between the two patterns; for instance, the pattern of the ocean floor granophyres and related quartz-rocks shows an almost uniform decrease from the LREE towards the HREE, with a slight Tb negative anomaly and a strong Yb positive anomaly.

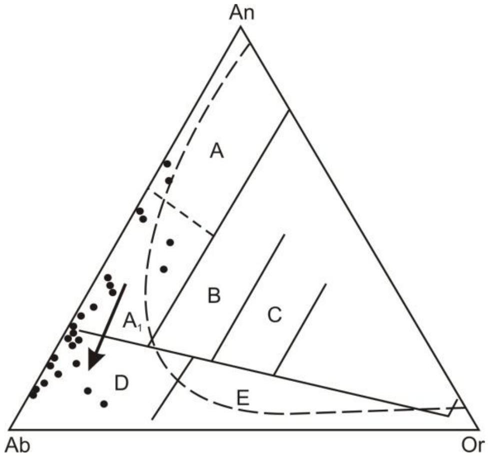
The pattern of the island arc quartz-keratophyres and related leucocratic rocks presents positive anomalies of Ce and Tb, and a strong Eu negative anomaly. All anomalies are the result of the differentiation of the parental magmas, which affects the two rock-series (see Philpotts and Schnetzler, 1968).

As shown above, the ocean floor and island arc trondhjemites and related rocks are highly rich in SiO_2 and Na_2O, and poor in K_2O, CaO and MgO. These features are the most important ones in the definition of the trondhjemitic rocks and parental magmas they have derived from. The ocean floor trondhjemitic magma occurred through the differentiation of the tholeiitic parental magma, to form the sheeted dyke complex and the gabbro bodies.

On the diagram in Figure 8, the plots of the ocean floor granophyres and the related quartz-rocks are distributed along its An–Ab side, occupying the quartz-diorite, tonalite and trondhjemite fields and suggesting a strong process of differentiation. The trend of the differentiation processes is from the albite-quartz-dolerites (situated near the An corner of the diagram), through the quartz-diorite and tonalite domains, toward the trondhjemite field D, as the arrow in the diagram shows. This type of differentiation undergone by the tholeiitic parental magma that eventually leads to a trondhjemitic magma fraction, from which the ocean floor trondhjemites and the related quartz-rocks have resulted, is specific to both the ophiolitic series of the MOS and to similar series.

Tab. 2 Average REE contents from the ocean floor and island arc rocks and their related quartz-rocks (data from Savu and Stoian, 1988, 1992).

Element	La	Ce	Sm	Eu	Tb	Yb	Lu
Ocean floor rocks	13.3	40	6.7	2.24	0.93	0.1	1.10
Island arc rocks	23.5	88	4.75	1.08	1.01	1.8	-



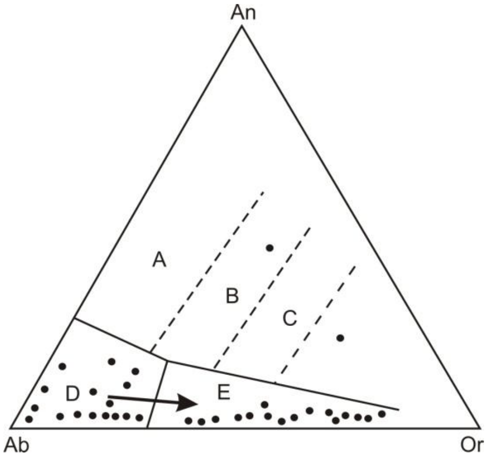


Fig. 8 (left) Plot of the trondhjemitic granophyres and related quartz-rocks on the An–Ab–Or diagram (fields according to O'Connor, 1965). A-albite-quartz-dolerites; A_1-tonalites and quartz-diorites; B-granodiorites; C-adamelites; D-trondhjemites; E-granites. The dashed line separates, to the left, the low pressure (> 5 kbar) feldspar field (according to Coleman, 1977; Coleman and Donato, 1979). The arrow shows the differentiation trend of the tholeiitic Si-rich magma to get to a trondhjemitic magma fraction. Data sources as in Figure 2.

Fig. 10 (right) Plot of the acid rocks of the bimodal volcanism from the Drocea-Trascău trench on the An–Ab–Or diagram (fields according to O'Connor, 1965; Streckeisen, 1967) A-tonalites (dacites); B-granodiorites and adamelites (rhyolites and delenites); C-adamelites (delenites); D-trondhjemites (quartz-keratophyres). The dashed line separates, to the left, the low pressure (> 5 kbar) feldspar field (according to Coleman, 1977; Coleman and Donato, 1979). The arrow shows the trend of the parental acidic magma differentiation. Data sources as in Figure 3.

The separation of the tholeiitic parental magma into Fe-rich and Si-rich magma fractions begins when SiO_2 reaches a concentration of about 50% in the tholeiitic parental magma. This differentiation process was carried out according to the model in Figure 9 (see also the diagram in Figure 4).

This model relies on the supposition that, in the upper mantle, a melting wedge occurred beneath the spreading zone of the Mureş Ocean, so that pyrolite was formed through partial melting processes. From this pyrolite, tholeiitic parental magma differentiated itself and started its own evolution. At some point, from this parental magma, basic iron-rich magma was separated (Fenner, 1929), from which the Ti-magnetite-gabbros have formed, through differentiation. These rocks now occur as strata in the layered gabbro bodies. As a consequence, the remaining tholeiitic magma was enriched with SiO_2, thus becoming the parental magma of the quartz-rocks from the ophiolitic complexes. Through further differentiation of this magma, a Si- and Na-rich trondhjemitic magma fraction occurred, leading to the formation of the trondhjemitic granophyres, plagiogranites and plagiaplites.

During the closing stage of the Mureş Ocean, bimodal volcanism occurred and triggered the process that controlled the genesis of the island arc trondhjemitic (quartz-keratophyric) magma fraction.

The process through which the acid and the basic magma fractions of the bimodal volcanism occurred is not properly known. In contrast with the tholeiitic magma differentiation during the spreading stage of the ocean, bimodal volcanism has no intermediate terms like quartz-diorites and tonalites or their volcanic correspondents (andesites). The fact is that the trondhjemitic calc-alkaline magma fraction occurred from the beginning as parental magma, from which the trondhjemitic rocks and then the granites resulted, as shown in Figure 10.

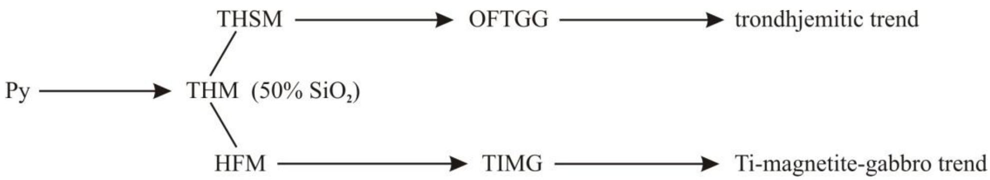


Fig. 9 Model showing the differentiation of the tholeiitic parental magma. Py-initial pyrolite; THM-tholeiitic parental magma (MORB); THSM-tholeiitic Si-rich magma; OFTGG-ocean floor trondhjemitic granophyres and plagiogranites; HFM-iron-rich magma; TIMG-Ti-magnetite-gabbro.

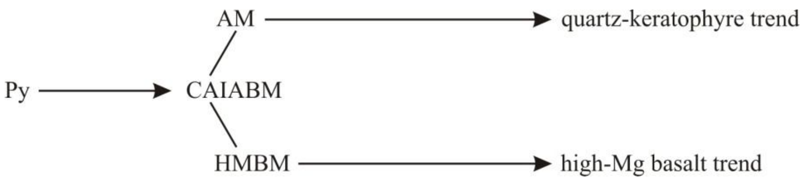


Fig. 11 Model showing the bimodal differentiation of the Mariana-type initial pyrolite. Py-pyrolite; CAIABM-parental calc-alkaline island arc basaltic magma; HMBM-high-Mg basaltic magma; AM-acid magma.

The initial pyrolite from which the calc-alkaline magma derived occurred in the somatic mantle wedge situated over the Mariana-type subduction plane (Fig. 1); it evolved according to the model in Figure 11 (see also the diagram in Figure 5).

This model shows that, from an initial pyrolite, a calc-alkaline island arc basaltic magma probably occurred under the conditions of an almost vertical subduction plane of the Mariana-type. This magma underwent a bimodal differentiation process, which engendered, on one hand, magnesium-rich magma, from which the high-Mg island arc basalts resulted (Savu, 1999), and, on the other hand, acid magma, from which the quartz-keratophyres and the related leucocratic rocks occurred through further differentiation (Savu, 2003).

Conclusions

The present study reveals the fact that, during the different stages of the evolution of the Mureş Ocean, the differentiation of two separate parental magmas occurred and two trondhjemitic rock-series were formed.

During the opening stage, under spreading conditions, an ocean floor trondhjemitic rock-series occurred, along with its related quartz-rocks, such as quartz-diorites and tonalites. The parental magma of this rock-series separated from the initial tholeiitic basaltic magma when its SiO_2 content reached values of about 50%, as a result of the iron extraction, to form the Ti-magnetite-gabbros.

The closing stage of the Mureş Ocean unfolded through a bilateral subduction process, acting as Mariana- and Andean-type subductions. In the Mariana-type subduction trench, island arc bimodal volcanism occurred; it engendered two magma fractions from which a basic and an acid rock-series resulted. The latter was formed of quartz-keratophyres (as trondhjemitic rocks) and the related leucocratic acid rocks, such as rhyolites, dacites and trachytes.

The similarity between the ocean floor and island arc trondhjemitic rock-series consists in their high content of SiO_2 and Na_2O, as well as the low content of K_2O, CaO and MgO, caused by the long-term differentiation process undergone by their ocean floor and island arc parental magmas.

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