OCCURRENCE OF THE OCEAN AND ITS EVOLUTION TOWARD AN OPHIOLITIC SUTURE

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Abstract. The process leading to the occurrence of the ocean and to its evolution toward an ophiolitic suture can be separated into four stages. The first is the pre-ocean continental rifting stage, during which within-plate dyke swarm complexes are engendered. The rifting process is going into the spreading process of the second stage, which leads to the opening of the ocean, during the evolution of which an ocean crust is generated. This crust is formed of ocean floor N-Type and E-Type MORB rocks and of scarce oceanic sedimentary deposits. During the third stage, the closing of the ocean takes place, which is determined by processes of subduction, which lead to the consumption of the ocean crust and the occurrence of the island arcs, engendering calc-alkaline igneous rocks. The volcanic arcs usually are associated with important masses of sedimentary deposits. A regional and a load metamorphism often occur during this stage, too. This stage ends with the manifestation of the thrust phenomena. During the fourth, post-collision, stage a disjunctive tectonics is active. There occur the epicontinental sedimentary basins and the manifestation of a collateral continental magmatic activity.

Key words: rifting stage; ocean opening stage; ocean closing stage; post-collision stage.

INTRODUCTION

The ophiolitic sutures have a special significance in the history and structure of the continents, because they mark the zones where the old oceans evolved and preserve elements of their evolution. Usually, this couple ocean–ophiolitic suture is running through a complicated evolution, in which four main evolution stages are to be distinguished. These are as follows: the pre-ocean continental rifting stage, the ocean opening stage, the ocean closing stage and the post-collision stage, which represent, in fact, the evolution stages of a tectono-magmatic cycle. During the long evolution of the Earth, from the Archean up to Actual, several tectono-magmatic cycles with their oceans succeeded one another, but the most adequate for the purpose of this paper are the ophiolitic sutures of the Alpine cycle and, in part, those of the Variscan cycle, which preserve many elements of the evolution of their parental oceans.

Based on my experience got during the study of the ophiolitic sutures of different ages from the Romanian territory, I will tray to present in detail in this synthesis paper the four evolution stages of an ocean, based mostly on the ophiolitic sutures of the Alpine Oceans, the genetic elements of which are well represented, at the same time referring to the structure of the actual oceans.

THE PRE-OCEAN CONTINENTAL RIFTING STAGE

Usually, each tectono-magmatic cycle ends with a strong erosion period of the continents, which emerged from the seas, that leads to the peneplanization of their orogen structures. At the same time this period represents, in fact, the beginning of the first stage of the next tectono-magmatic cycle. Thus, by the end of the Variscan tectono-magmatic cycle, during the Permian and the beginning of Triassic, the continents, including the European one, were running through such a period of erosion. Under the arid conditions of this period the emerged old Variscan and Pre-Variscan orogen structures have been strongly eroded, getting into peneplane structures. Evidence of these processes is the presence of thick conglomerate and sandstone deposits from Romania and anywhere around the world (see Saulea, 1967), deposits like those of Buntsandstein from Germany.

At one time a thermo-tectonic process started in the mantle, which determined the occurrence of some swellings along the old peneplanized structures or parallel to them , along which the crust started cracking, a process which resulted in deep fault systems. It represents, in fact, the beginning of the pre-ocean continental rifting stage. Along this fault system basaltic magmas penetrated through the deep faults, there resulting dyke swarm systems, sometimes including multiple basic dykes, like those from the Carpathians and North Dobrogea, which took place in a triple junction structure (Savu, 1998), as shown in Figure 1.

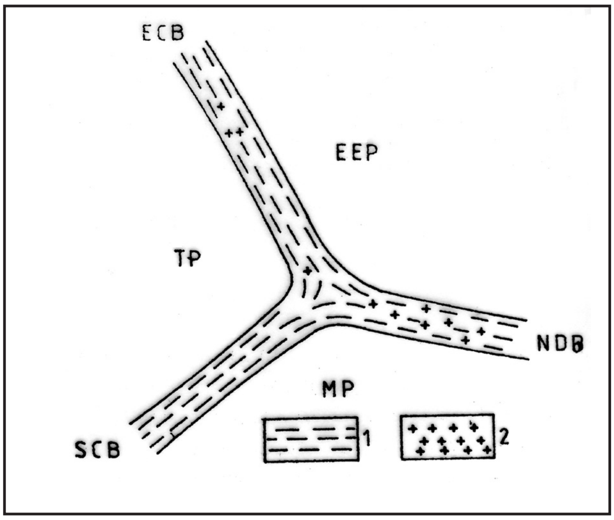

Fig. 1. Sketch showing the triple junction structure with dyke swarm of within-plate basaltic rocks from the Romanian Carpathians and North Dobrogea (data from Savu, 1998). **EEP**, East European Plate; **MP**, Moesian Plate; **TP**, Transylvanian Plate; **ECB**, East Carpathian branch of the triple junction; **SCB**, South Carpathian branch of the triple junction; **NDB**, North Dobrogea failed branch of the triple junction; **1**, basaltic dyke swarm system crossing the Pre-Alpine crystalline schists basement; **2**, remnants of basaltic and bimodal volcanics.

The within-plate magmatism got in some places into a bimodal volcanism, which generated basic and acid (quartzkeratophyric) dykes and volcanics. Sometimes the basaltic magmas erupting along the fault systems engendered flood basalt occurrences, which may extend over large areas, like those from Deccan that occupy one-third of the Indian territory (Hatch *et al*., 1961), or the Karroo basalt complex in South Africa, which extends over an area of up to 5,000 square miles (Walker and Poldervart, 1949). A small area of flood basalts was also preserved in North Dobrogea (Romania), where the thickness of flows reached about 200 meters (Savu, 1986).

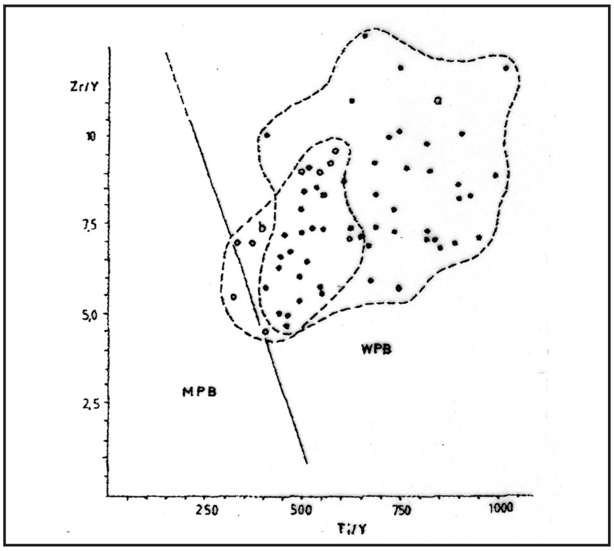

Fig. 2. Zr/Y vs. Ti/Y diagram showing the within-plate characteristics of the Triassic basic rocks related to the Mures ophiolitic suture and North Dobrogea, in Romania (data from Savu, 1999). Fields according to Pearce and Gale (1977): **MPB**, margin plate basalts; **WPB**, within-plate basalts; **a**, field of the North Dobrogea basalts; **b**, field of the Coştei basalts related to the Mureş ophiolitic suture.

The chemical characteristics of the rocks erupted during this stage show that they are within-plate rocks (Fig 2), as shown by Savu (1988).

THE OCEAN OPENING STAGE

At the beginning of the Liassic period (ca. 180 Ma) along some mobile belts of pre-ocean continental rifting the rifting process changed into a spreading one. This new process manifested itself along a spreading center or axis, which followed the trend of the rifting mobile belts, finally leading to the opening of the ocean zones *sensu stricto* (Fig. 3). Such a succession of geological processes was active in case of the Alpine (Tethysian) oceans and at some extent in case of some old oceans, as for instance, in case of the Appalachians and Ural oceans, where some elements of their evolution were preserved in their ophiolitic sutures, as I observed when visiting them in 1972 and 1978, respectively. It is noteworthy that these old ophiolitic sutures had a north–south position, which is perpendicular on the general east-west trend of the Tethysian ophiolitic suture.

The classical example of an old ocean was the Tethysian Ocean, which extended from the American continents eastward up to Himalaya. It occurred when the American continents were attached to the Gondwana. Branches of this ocean were the Carpathian and the Mureş Oceans, too, which evolved on the Romanian territory. The evolution of these oceans offered most of the data for the present paper.

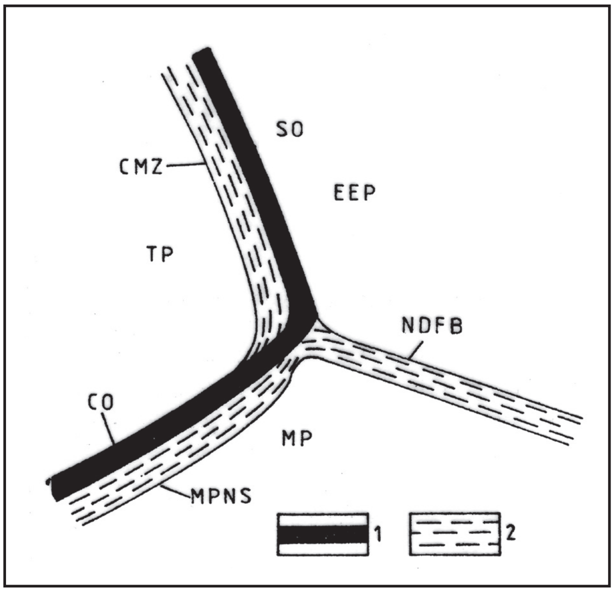

Fig. 3. Opening of the Carpathian ocean (CO) along the Triassic continental rifting mobile belt. CMZ, Crystalline-Mesozoic Zone of the East Carpathians; MP, Moesian Plate and its northern part (MPNS); NDFB Northern Dobrogea Failed Branch; EEP, East European Plate; TP, Transylvanian Plate; **1**, Carpathian Ocean; **2**, remnants of the basic dyke rocks from the previous continental pre-ocean rifting stage of the mobile belt.

The spreading rate was little differing from an ocean to another. For instance, in the Mureş Ocean the spreading rate was of about 5 cm a year, so that during its evolution, from the Liassic opening up to its closing in the Cretaceous, its width reached about 400 kilometers (Savu, 1983). The spreading rate of the actual oceans must have been so far almost similar. Thus, the Atlantic Ocean, the opening of which started in the Lower Cretaceous (130-135 Ma), to reach the width of about 7,000 kilometers, its spreading rate must have been of about 5 cm a year, too.

During its evolution the Alpine Ocean engendered an ocean crust, which was lying on the upper mantle. It consisted of three rock complexes: a lower complex formed of ultramafic rocks, over which a sheeted dyke complex was lying, followed by a third (upper) complex of pillowed basalts. Exceptionally, mantle plumes are intruding, as rheomorphic bodies, the upper mantle beneath the tectonic ocean plates, which can generate characteristic magmas from which within-plate volcanics derived, like those erupted in the Atlantic (see Weis *et al*., 1998) and the Pacific (see Haase and Devey, 1996)

Within the upper complex and especially over it, oceanic sedimentary deposits occured, which consisted of layers of jaspers, limestones or dolomites and sometimes of fine quartzites, the last usually occurring between the basaltic flows from the marginal zones of the oceans, which were contiguous with the continental plates (Fig. 4).

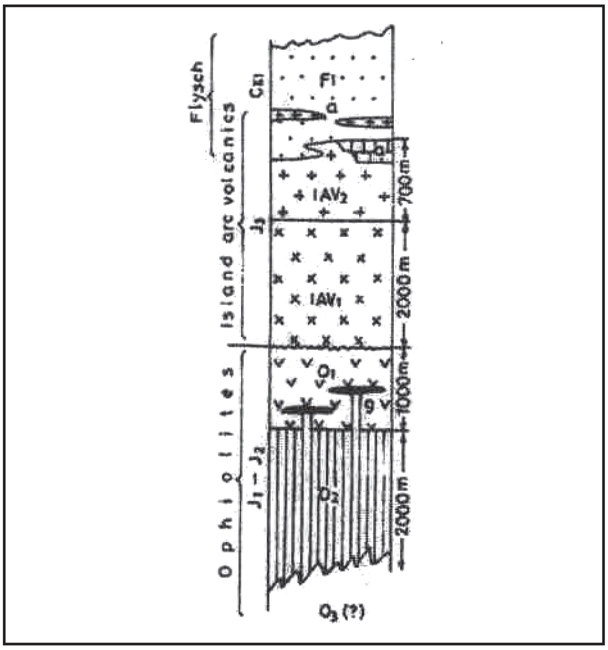

Fig. 4. Column showing the rock complexes from the obducted plate of the Mureş ophiolitic suture. **Fl**, flysch and island arc deposits; **a**, island arc volcanics; **IAV$_2$**, island arc leucocratic volcanics; **a**, Upper Jurassic–Lower Cretaceous reef limestones; **IAV$_1$**, island arc basalt-andesitic complex; unconformity; **O$_1$**, ocean floor pillowed basalt complex; **g**, small bodies of gabbros and cumulate ultramafic rocks intruded into the pillowed basalt complex; **O$_2$**, sheeted dyke complex; **O$_3$**, the place of the missing ultramafic rock complex from the obducted plate of the Mureş ophiolitic suture.

As shown in Figure 4 the lower ultramafic complex (O_3), which must have been formed of Alpine-type peridotites, is missing from the column of the Mureş ophiolitic complexes, but its rocks usually occur as olistoliths in the mélanges and olistostromes, which often accompany the obducted rocks from other ophiolitic sutures (Fig. 5).

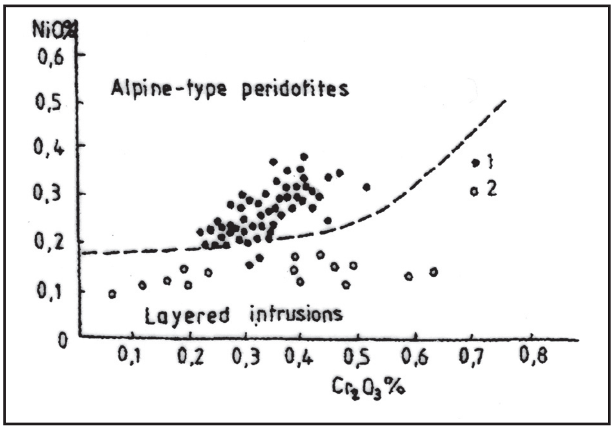

Fig. 5. Plot of ultramafic rock olistoliths from the Carpathian ophiolitic suture on the NiO vs. Cr_2O_3 diagram. Fields according to Malpas and Stevens (1977). **1**, ultramafic olistoliths from the Carpathian ophiolitic suture; **2**, cumulate peridotites from the layered intrusions of the Mureş ophiolitic suture. Data from Savu (2009).

Pyroxenite dykes are often crossing the obducted slabs of ultramafic rocks, as for instance, those from the old ophiolitic suture of the Polar Ural.

The median complex (O_2) of the ocean crust (Fig. 4) consists of sheeted dykes of basalts and dolerites along which dykelets of hyalobasalts also occur. Usually, the basic dykes present a chill margin of 1 to 5 cm thick. The presence of the chill margin on one side or on both sides of the dyke indicates that the spreading was either of one-sided type or of two-sided type (Savu *et al*., 1984a). The chemical composition of the basic dykes shows that they consist of tholeiitic rocks.

In some ophiolitic sutures like those from Oregon, Newfoundland, Corsica, Mureş (Romania), Turkey and Kamchatka dykes of trondhjemitic plagiogranites and granophyres were intruded between the basic sheeted dykes or into the gabbro bodies (Savu, 2002). Other dykes of quartz rocks like quartzdiorites and tonalites are associated with (Fig.6). The quartz rocks resulted from the acid magma fractions differentiated from the parental tholeiitic magma, which engendered the basic rocks of the ocean crust (Savu *et al*., 1984b).

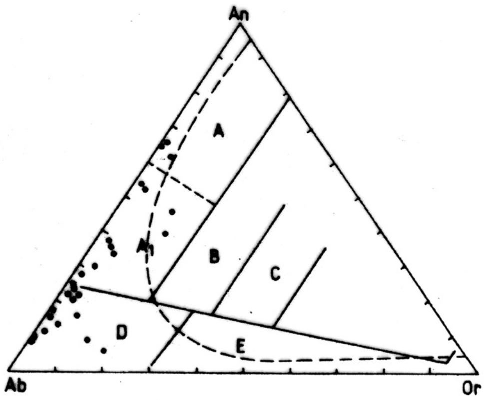

Fig. 6. Plot of the trondhjemitic and related quartz rock dykes from the Mureş ophiolitic suture on the Ab-An-Or diagram. Fields adapted after O'Connor (1965). **A**, melanocratic quartz rocks; **A_1**, quartzdiorites and tonalities; **B**, granodiorites; **C**, adamelites; **D**, throndhjemites; **E**, granites. Data from Savu (2002).

The upper complex (O_1) of the ocean crust usually consists of pillowed basalts, often associated with normal basaltic lavas and rarely basaltic pyroclastics or glassy tachilites and oceanic sediments.

The chemical composition of the rocks from the basaltic complex shows that they are tholeiitic rocks, like those from the sheeted dyke complex, the rocks of the basaltic complex representing, in fact, the results of the sheeted dyke basic magma, when flowing as lava on the ocean bottom. Therefore, all of the basic rocks from the ocean crust show an ocean floor (MORB) signature. It could have either a N-Type MORB or an E-Type MORB character (Savu, 1999), as shown in Figure 7.

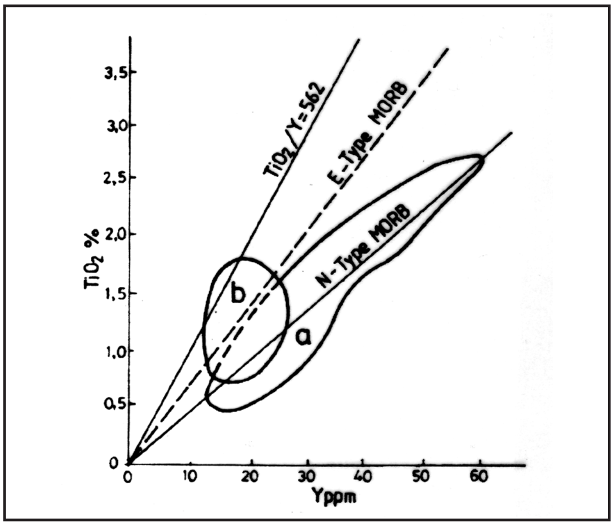

Fig. 7. TiO_2 vs. Y diagram, showing the N-Type MORB character of the ophiolites from the Mureş ophiolitic suture (field **a**) and the rather E-Type MORB character of the ophiolites from the Carpathian ofiolitic suture (field **b**). The values of the TiO_2/Y ratio are according to Perfit *et al. (*1980). Data from Savu (1996)

Sometimes, under special P/T conditions, on the ocean floor the basaltic lavas reacted with the ocean floor salty water at high temperatures, an ocean floor metamorphism manifesting itself there (see Savu, 1967; Coleman, 1977), which could determine the spilitization of a part of the ocean floor basalts (Fig.8). Usually the spilitic rocks show an amygdaloidal structure.

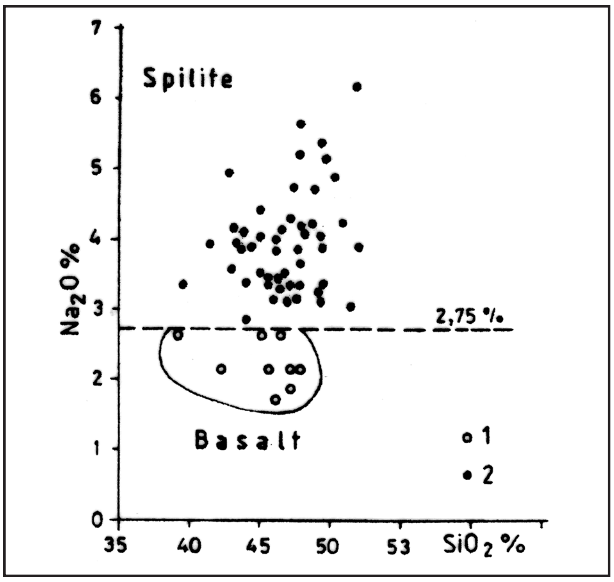

Fig. 8. Plot of the basaltic rocks from the pillowed basalt complex from the Mureş ophiolitic suture on the Na_2O vs. SiO_2 diagram. Fields according to Savu (2007). **1**, tholeiitic basalts; **2**, related spilitic rocks.

Sometimes, in the pillowed basalt complex layered bodies (2-5 km long) of gabbros, melagabbros and cumulate peridotites could occur, like in case of the Mureş ophiolitic suture

(Fig. 9). The intrusive bodies occur as big dykes, laccoliths and intrusive sheets (sills). Usually, they show a layered structure, resulted by the fractional crystallization of the magma and by the liquation process. Consequently, at their bottom layers of V-Ti-magnetite gabbros or cumulate peridotites could occur (Giuşcă, Cioflica, 1957; Savu, 1972) as shown in Figure 9. Basic hornfelses (beerbachites) may be formed at the contact of the intrusive basic bodies and the surrounding basaltic rocks, like those from the Mureş ophiolitic suture (Savu, 1962).

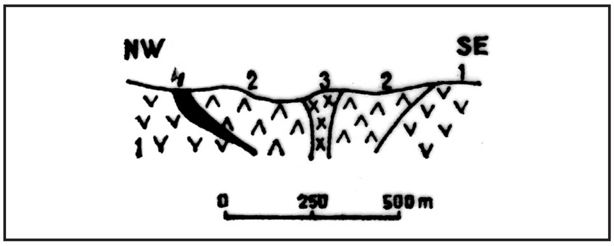

Fig. 9. Structure of the gabbro body of Almăşel (Savu, 1962). **1**, tholeiitic basalts; **2**, layered pyroxene gabbros; **3**, olivine gabbro; **4**, V-Ti – magnetite gabbro.

It is noteworthy that the gabbro bodies are sometimes crossed by dykes of trondhjemitic granophyres and plagiogranites like those from the sheeted dyke complex. It shows once again the origin of these quartz rocks in the extreme differentiation of the parental tholeiitic magma, the sheeted dykes and the gabbro bodies resulted from.

It is of note that the V/Cr ratio of the cumulate peridotites occurred at the bottom of the layered gabbro bodies, intruded into the basaltic complex from the Mureş ophiolitic suture (Savu, 2007), clearly differ from that of the mantle peridotites occurred as xenoliths in the young trachybasalts (Fig. 10). This relation is useful for the discrimination of the peridotitic exotic blocks from different mélanges, olistostromes and conglomerates, for instance.

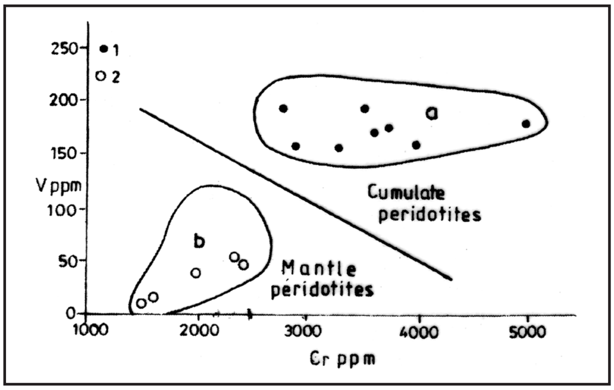

Fig 10. V vs. Cr discriminating diagram between cumulate and mantle peridotites. Fields according to Savu (2008): **a**, field of the cumulate peridotites from the Mureş ophiolitic suture; **b**, field of the mantle plume peridotite xenoliths from the young trachybasalts of the Perşani Mountains.

There must be added that, in some basalt complexes, like that of the Carpathian ophiolitic suture, Cyprus-type copper deposits are associated with.

As for the scarce occurring sedimentary deposits associated with the ocean floor basalts complex, it is known that they consist of jaspers and argillites, rarely of limestones and dolomites. As a rule, the first two types of sedimentary rocks are red rocks, coloured by the iron hydroxides resulted by the spilitization of basalts.

THE OCEAN CLOSING STAGE

At a moment, when the ocean reached its maturity, it starts closing owing to the subduction process. As a consequence, different phenomena get into life in the ocean area, like the consumption of the ocean crust, the manifestation of an island arc volcanism associated with base metal mineralizations and the deposition of arc sedimentary formations. In some special conditions a regional metamorphism and rarely a load metamorphism could manifest themselves.

The subduction process is of two types: the Andean-type and the Mariana-type. These two subduction types are manifesting themselves either as an ocean plate under a continental plate, or as an ocean plate under an ocean plate. In the Mureş Ocean, for instance, both types of subduction manifested themselves, at the same time, as ocean plate under ocean plate, like a bilateral phenomenon (Fig. 11). The subduction process usually acts as an unilateral process. In the classical Andean–type of subduction the ocean plate was subducted under the American continents. Its subduction plane plunged under an angle of about 40° and engendered a continental arc volcanism, which extended from Alaska down to Chili, producing large quantities of calc-alkaline volcanics and big granitoid plutons. It generated also an important olistostrome like the Franciscan formation from the Coast Ranges, USA, which was studied, among others, by Page (1966). As I observed when visiting it in 1972, south of Menlo Park, in the company of dr. Eberline, it contained olistoliths of basalts, serpentinites, glaucophane schists and eclogites. Such an olistostrome also occurs in the Severin Nappe from the Mehedinţi Plateau, Romania, but it contains olistoliths of basalts and serpentinites, only (Savu, 2009; Savu *et al.*, 1985).

On the contrary, the Mariana-type subduction manifested itself in the Pacific Ocean as oceanic plate under oceanic plate, and under an almost vertical subduction plane, generating an intra-oceanic arc volcanism with quartzkeratophires (see Uyeda, 1981).

The arc volcanics engendered by the two types of subduction differ from one another, although they are all calc-alkaline rocks. As for instance, in the Mureş Ocean, where both types of subduction manifested themselves (Fig. 11), the volcanics determined by the Andean–type subduction, which manifested itself on the southern margin of the ocean, engendered arc volcanics of the following calc-alkaline assemblage: basalt-andesite-rhyolite (Savu, 2007). The island arc volcanism engendered by the Mariana-type subduction, which took place on the northern margin of the ocean, was a bimodal arc volcanism, which engendered the following volcanic rock assemblage: basalt-quartzkeratophyre (Savu *et al*., 1986).

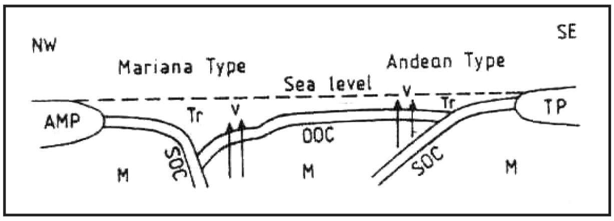

Fig. 11. Model (not to scale) showing the closing of the Mureş Ocean due to a bilateral subduction and of the obduction of the median ocean crust as a large obducted plate. According to Savu (1983, revised, 2007). **AMP**, Apuseni Mountains Plate; **TP**, Transylvanian Plate; **SOC**, subducted ocean crust; **OOC**, obducted ocean crust; **M**, mantle; **Tr**, subduction trench; **V**, island volcanoes.

While the chemical characteristics of the rocks from the Andean-type volcanism show a normal calc-alkaline magmatic series, the rocks engendered by the Mariana-type volcanism are plotting on the diagram in Figure 12 within two separate fields – the basic rocks field in the center of the diagram and the acid (qurtzkeratophyric) rock field near the alkali corner, the last rocks showing a trondhjemitic signature (Savu, 2003).

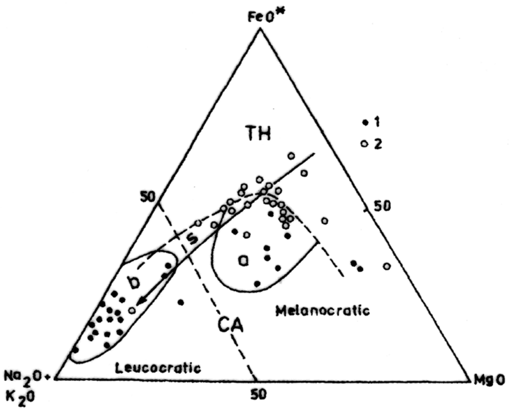

Fig. 12. Plot of the bimodal volcanics from the Mureş ophiolitic suture on the FeOtot – Na_2O+K_2O – MgO diagram. Fields according to Irvine and Baragar (1971): **TH**, tholeiitic; **CA**, calc-alkaline; **Alk**, alkaline. Data from Savu *et al.* (1986). **1**, island arc bimodal volcanics: **a**, basic rock field; b, acid rock field; **2**, normal calc-alkaline volcanics; **S**, differentiation trend of the island arc volcanics.

By the differentiation of the island arc calc-alkaline magma sometimes there results on the one hand high-Mg melabasalts and on the other hand acid magmas, from which quartzdiorite, granodiorite and granite plutons occur, which cross the rocks of the ophiolitic sutures (Savu, 1999), altering them into basic hornfelses. Usually, mineralizations of base metals and of other elements more often occur during the manifestation of the island arc volcanism, especially of the continental one.

The island arc basaltic lavas and pyroclastics react, at high temperature, with the ocean salty water, so that there result spilitic rocks like those occurring during the manifestation of the ocean floor metamorphism presented in a previous chapter (Savu, 2002). Owing to the manganese and iron hydroxides resulted from the chloritization of clinopyroxenes, deposits of manganese and red jaspers and argillites occur in association with the island arc sedimentary deposit, represented by marls and limestones. Meanwhile processes of regional and load metamorphism affect all of the ocean floor and the island arc formations.

The subduction process continues its manifestation up to the Upper Cretaceous collision of the convergent plates, when the ocean is definitely closed and the nappes are thrusting over the structures of the ophiolitic suture, which finally resulted there.

Examples of island arc volcanics erupted during this later period of the closing stage of the Carpathian Ocean occur for instance, in the Tithonian-Berriasian flisch from the Bratocea Unit of the Carpathian ophiolitic suture (Savu *et a*l., 1994) and in the Upper Cretaceous wildflysch occurring onto the outer margin of the Danubian Autochthone of the same ophiolitic suture (Savu *et al*., 1987).

THE POST - COLLISION STAGE

After the collision moment there follows a distension period accompanied by disjunctive tectonics, during which important fault systems could be very active and epicontinental sedimentary basins occur as well. The motion of the subducted plate is sometime still active or reactivated, so that a continental arc volcanism could be present on the obducted plate. In the Carpathian area, for instance, which had a very complex post-collision hystory, for the elucidation of which more profound studies would be necessary, and especially comparative studies based upon modern chemical analyses. For instance, there occurred some syn-collision and post-collision Banatitic intrusions and later on the calc-alkaline continental arc volcanism manifestations, which determined the Neogene continental arc magmatic activity in the obducted plate. It is of note that the episodes of the last, alternated with withinplate volcanic episodes of plume-source origin, engendering the Paleogene alkali basalts from the Poiana Ruscă Mountains and the Pliocene-Quaternary hotspot trachybasalts originating in the Transylvania mantle plume (see Savu, 2005). These geological processes are not directly related to the ocean. They are rather collateral effects of the evolution of the ocean, as they occur during and after the collision process, which ended the ocean evolution.

CONCLUSIONS

The occurrence of an ocean and its ending into an ophiolitic suture take place as a result of a complex evolution, which could be divided into four evolution stages: pre-ocean continental rifting, ocean opening, ocean closing and the post-collision stages. During the first stage there occurs a rifting process with deep faults, along which dykes of within-plate rocks occur and volcanic rocks erupt. At a moment this process get into a spreading process, which leads to the opening of an ocean, which generates an ocean crust formed of ocean floor N-Type MORB or E-Type MORB rocks. The closing of the ocean is determined by subduction, which could be of ocean plate under ocean plate or ocean plate under a continental plate types. Usually, it determines the occurrence of the island arcs, which generate island arc volcanics and granitoid plutons, sedimentary deposits being associated with. Regional and load metamorphism processes are manifesting themselves, too. During the post-collision stage a disjunctive tectonics is active. There occur epicontinental sedimentary basins and the manifestation of the calc-alkaline continental arc volcanism, the episodes of which are alternating with the episodes of a withinplate volcanism of plume-source origin.

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