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The Development of Croatian Geoscience as Reflected by the Study of Dinaridic Ophiolites

Jakob **PAMIĆ**

Key words: Dinaridic ophiolites, Genetically related sedimentary formations, Flysch period, Geosyncline period, Plate tectonics.

Ključne riječi: dinaridski ofioliti, genetski povezane sedimentne formacije, flišno razdoblje, geosinklinalno razdoblje, tektonika ploča.

Abstract

For approximately 120 years since the beginning of European geology up to the present day, Croatian geoscience has included intensive geological research of the Dinaride Ophiolite zone. Research results can be grouped into several periods depending on the basic predominant approaches of European and World geology. (1) During the flysch period, ophiolites were spatially connected with the flysch formations. (2) During the geosynclinal period ophiolites were classified into the "Diabas-Hornstein Formation". (3) During the transitional period, characterized by the elaboration of the Basic Geological Map, a voluminous data were collected which could not be incorporated in geosynclinal ideas. (4) The last period is characterized by modern geodynamic interpretations resulting from global tectonics.

Sažetak

Hrvatska je geoznanost, od samih početaka zagrebačke geologije sve do današnjih dana u intervalu od oko 120 godina, bila intenzivno uključena u geološko izučavanje Ofiolitne zone Dinarida. Rezultati tih istraživanja mogu se podijeliti u nekoliko razdoblja, u zavisnosti od osnovnih prevladavajućih pristupa europske, odnosno svjetske geologije. (1) Flišno razdoblje, koje je ofiolitne stijene vezalo za flišne tvorevine. (2) Geosinklinalno razdoblje, koje je ofiolitne stijene obuhvaćalo u tzv. dijabaz-rožnjačku formaciju. (3) Prijelazno razdoblje, koje se karakterizira izradom Osnovne geološke karte, odnosno prikupljanjem obimne faktografije koja se više nije mogla tumačiti geosinklinalnom koncepcijom. (4) Sadašnje razdoblje koje se karakterizira modernim geodinamskim interpretacijama proizišlim iz tektonike ploča.

1. INTRODUCTION

As carbonate rocks, limestones and dolomites characterize the external units of the orogenic belts, ophiolitic rocks (ultramafics, gabbro, diabase-basalt) and genetically related radiolarite and clastic formations represent a characteristic feature of the internal units of the Phanerozoic orogenic systems. The ophiolitic complexes of the orogenic belts represented one of the most complex problems of World geology until the appearance of the idea of plate tectonics. From the very beginning of European geology to the present day, Croatian geologists have been very active in the investigation of ophiolites.

Within the huge Mesozoic Alpine-Himalayan belt, the Dinaridic ophiolites occupy an important position, not only because of their large quantites but also by their typical geological and petrological development. The Dinaridic ophiolites stretch from the Hrvatsko Zagorje mountains in the northwest and continue a NW-SE direction through Banovina to Bosnia and further through Serbia to the Vardar zone and Mirdita zone of the North Hellenides (Fig. 1).

Croatian Academy of Sciences and Arts, Ante Kovačića 5, HR-10000 Zagreb, Croatia.

2. CHRONOLOGICAL PRESENTATION OF GEOLOGICAL IDEAS

2.1. FLYSCH PERIOD

Prior to inauguration of Croatian geoscience and the first systematic investigations of ophiolites, VUKOTINOVIĆ (1853) mentioned a finding of serpentinites in Mt. Kalnik.

Croatian geoscience started its development simultaneously with European geoscience. Đuro Pilar, the founder of Croatian geology, was included in the first investigation of the Dinaridic ophiolites at a time when the Dinarides had not been defined as a mountain system. He separated "Cretaceous flysch" in parts of the present Dinaride Ophiolite zone, and emphasized that

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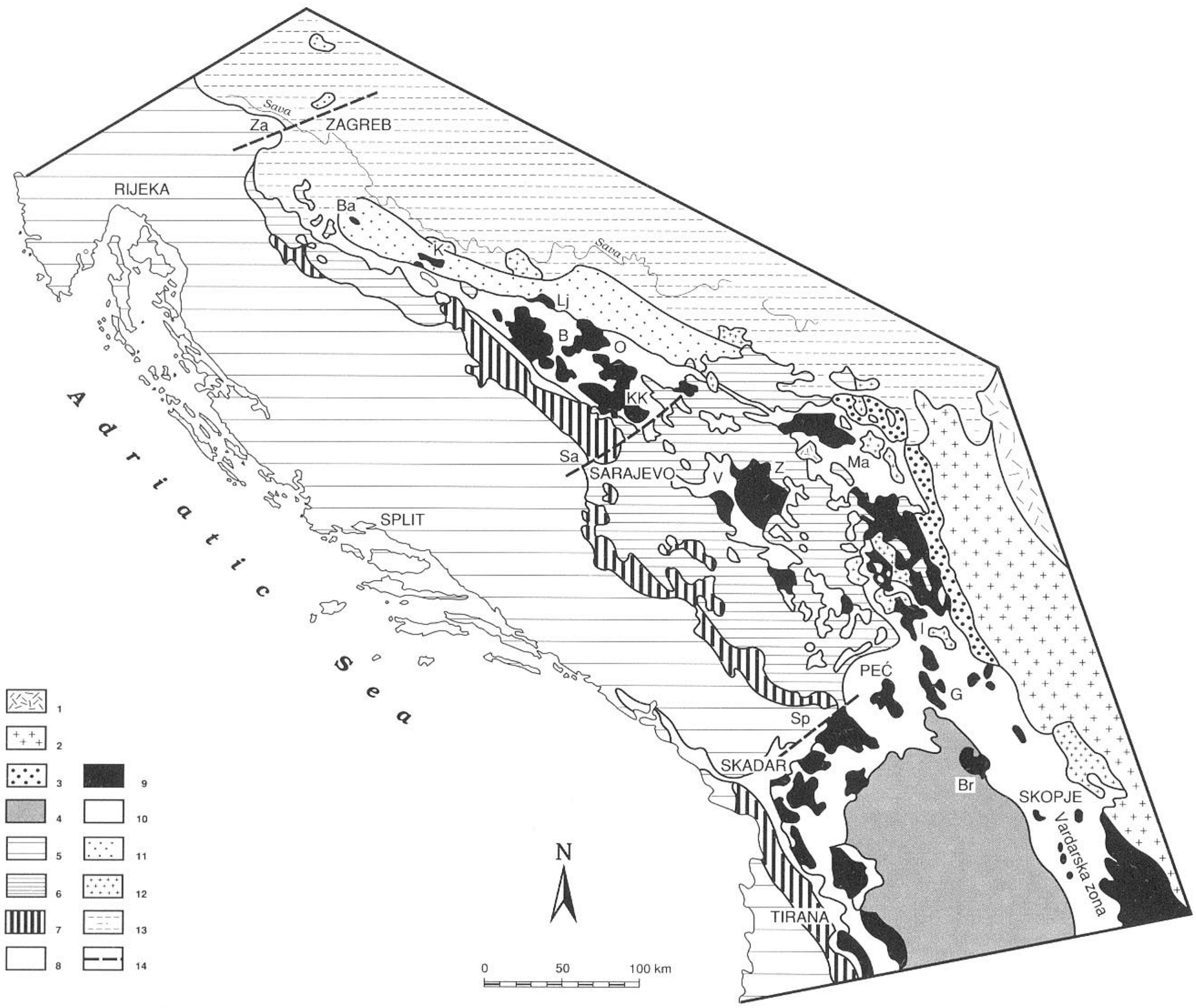

Fig. 1 Geological sketch-map of the Dinarides and North Hellenides showing the position of the ophiolite complexes (PAMIĆ, 1982). Legend: 1) Carpathians; 2) Serbo-Macedonian Mass; 3) Šumadija flysch; 4) Pelagonides and Korab; 5) Mesozoic-Palaeogene carbonate platform; 6) allochthonous Palaeozoic-Triassic complexes; 7) Mesozoic clastics of the passive continental margin; 8) Ophiolite zone; 9) ultramafic massifs; 10) radiolarites; 11) Late Cretaceous-Palaeogene flysch of the active continental margin; 12) Alpine granites and andesites; 13) Neogene-Quaternary sedimentary rocks; 14) transversal faults. Ultramafic massifs: Z) Zlatibor; V) Varda; Ba) Banija; K) Kozara; Lj) Ljubić; B) Borje; O) Ozren; KK) Krivaja-Konjuh; Ma) Maljen; I) Ibar; G) Goleš. Transversal faults: Za) Zagreb - Zemplen; Sa) Sarajevo; Sp) Skadar-Peć.

"the Late Cretaceous terminates in Bosnia as in adjacent countries by the flysch which includes large quantities of igneous rocks" (PILAR, 1882, p. 17), i.e., the ophiolites. He included sedimentary rocks surrounding ophiolites into the Jurassic and Cretaceous and was of the opinion that "the zone of igneous rocks represents only a facies within the flysch formations" (PILAR, 1882, p. 51). He also emphasized the regional, geological occurrence of ophiolites claiming that they stretched from Bosnia northwestward into Hrvatsko Zagorje in Croatia.

KIŠPATIĆ (1897, 1899) continued Pilar's work on the Bosnian ophiolites. His monograph "Crystalline rocks from the Bosnian Serpentinite zone" includes mainly petrographic data, but some were used for geodynamic considerations. At that time Kišpatić clearly noticed that lherzolites, (predominant ultramafic rocks), were characterized by typical metamorphic fabrics. He recognized that these rocks have "aligned" structure and that "the alignment does not represent an exception but a characteristic feature of the Bosnian lherzolites" (KIŠPATIĆ, 1897, p. 226).

Based on these data KIŠPATIĆ (1897, p. 230) drew the heretical conclusion that "crystalline rocks from the Bosnian serpentinite zone, except melaphyres and diabases, should be classified as crystalline schists and that they belong to Archean formations". Characteristic parallel structures in lherzolites clearly indicate that these rocks originated in the same way as in associated amphibolites and both of them represent primordial rocks.

If one bears in mind that the fundamental ideas concerning the upper mantle, Mohorovičić discontinuity, asthenosphere etc., were unknown in the late 19th century then it can be said that Kišpatić's ideas were nearly ingenious. First of all, he noticed consanguinity of ophiolite rocks which represent, indeed implay that they were, primeval rocks that came from the "Earth interior". Due to the fact that these primordial rocks lie beneath Triassic and Palaeozoic formations, they could only have been considered to be only of an Archean age according to ideas of that time.

Kišpatić emphasized that the Bosnian ophiolitic rocks have regional signatures continuing northwestward into Croatia to Mt. Medvednica. Although he was not a geologist *sensu stricto* he was persistent in his incorrect opinion of the Archean age of the Bosnian ophiolites (KIŠPATIĆ, 1917) and he argued with KATZER (1919) who correctly claimed that a gabbro occurring in the area of Doboj was of Mesozoic age. In the same way Kišpatić disputed the age of the Mt. Fruška Gora serpentinites with KOCH (1882) who classified these rocks as belonging to the Late Cretaceous.

Following Pilar's idea, GORJANOVIĆ-KRAMBERGER (1908) separated serpentinites on the first map of Mt. Medvednica. The serpentinite occurrence has a very important position because it is located along the boundary between the "Oriental land" and "Eastern Alpine branch". He was of the opinion that gabbro, diabase and melaphyre association, together with Upper Cretaceous sedimentary country rocks, stretched from Mt. Medvednica northeastward to Mt. Kalnik. KOCH (1904) and POLJAK (1914) published similar conceptually based idea on the Mts. Kalnik and Medvenica.

In this way, the Croatian geoscientists laid the foundations of the knowledge of the Dinaridic ophiolites in the earliest way of European geoscience. The work of MOHOROVIČIĆ (1909) who was a geophysicist not undertaking research on ophiolites should also be recognized from this period. His study of the Pokupsko earthquake resulted in his discovery of the layered structure of the Earth, and the boundary between the crust and upper mantle was named the Mohorovičić discontinuity in his honour. According to modern geodynamic ideas, rocks of the Ophiolite association are generated close to this discontinuity. Therefore, this was a contribution to global geological knowledge of great importance by Croatian geoscience.

2.2. GEOSYNCLINE PERIOD

After this first successful period during the historical investigation of the Dinaridic ophiolites, the mineralogical-petrological school of Zagreb University (under the leadership of Tućan), was very active in the investigation of crystalline rocks from the Vardar zone. TAJDER (1938) studied the Dren Boula ophiolites in Mazedonia, which form the largest fragment of Mesozoic oceanic crust in Europe. MARIĆ (1933) produced first complex geological-petrological study of ophiolites from the southeasternmost parts of Serbia, including the first analytical data for sedimentary rocks surrounding the ophiolites.

This period of the research activity on ophiolites was preceded by very important papers published by foreign geologists: AMPFERER & HAMMER (1917, 1918), HAMMER (1921) and PILGER (1939, 1941, 1942), who strongly influenced our subsequent investigations of the Dinaridic ophiolites. These authors introduced the term "Diabas-Hornstein Formation" comprising ophiolites and genetically related sedimentary rocks. This term was used for the next fifty years.

MAJER (1956) was the first of our geoscientistis who studied ophiolites from Mt. Šara, positioned in the area of the southeasternmost Dinarides adjoining the Vardar zone. Besides the first modern petrological data, he produced the first detailed geological map, and discovered that these ophiolites, as distinguished from the Bosnian ones, occur in metamorphic rocks of the Kačanik-Veleš Formation. He did not use at that time the prevailing ophilite hypothesis in his geodynamic interpretation.

Afterwards attention was focused on the Bosnian ophiolites. Geoscientists were greatly interested in the age of the Diabas-Hornstein Formation as shown in numerous and bitter discussions. However, the absurdity was the fact that basic stratigraphic data for these discussions had been misinterpreted. The Dinaridic ophiolites including the surrounding genetically related sedimentary rocks, are in many areas spatially accompanied by smaller or larger masses of Triassic and Palaeozoic carbonate and clastic rocks, in which are also included Middle Triassic volcanics. The age of the Diabas-Hornstein Formation as a whole was determined on the basis of fossil findings in these actually allochthonous Triassic and Palaeozoic formations. Based on this criterion, the age of the Diabas-Hornstein Formation varied from one area to another from the Permian up to the Late Triassic, rarely up to the Jurassic, depending on available palaeontological data from the allochthonous formations. Such an approach gave rise to additional misconceptions, and to the Middle Triassic volcanic-sedimentary formations positioned outside the Ophiolite zone were also given the name Diabas-Hornstein Formation (e.g. JOVANOVIĆ, 1957, 1960; PAMIĆ, 1961).

Step by step, during mapping over a comparatively short period of time, new data were collected which proved that two magmatic-sedimentary formations existed: the Middle Triassic formation, genetically related to the carbonate platform, and a second formation genetically related to the ophiolites (PAMIĆ, 1963).

At that time the supposed Jurassic age of the ophiolites was based mainly on data on the geological map of Bosnia and Hercegovina carried out by KATZER (1906 and others). Over several map sheets he included ophiolites in his "it" unit to which Jurassic to Lower Cretaceous ages were assigned.

At approximately the same time, interest was generated in ophiolites from the Hrvatsko Zagorje area of the northwestern Dinarides. Initial results further complicated the "ophiolite problem". In the Ivanščica and Samoborska Gora Mts., HERAK (1956, 1960) discov-

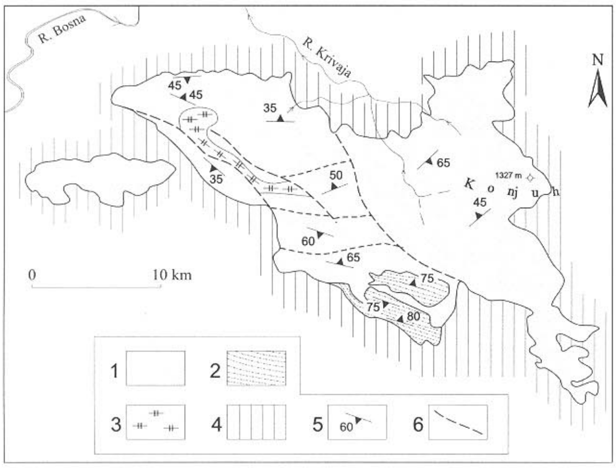

Fig. 2 Structural-geological map of the Krivaja-Konjuh ultramafic massif (PAMIĆ et al., 1977). Geographical position of the Krivaja-Konjuh massif is marked on the geological sketch-map of the Dinarides (Fig. 1). Legend: 1) ultramafics; 2) amphibolites; 3) gabbros; 4) country rocks, mainly Jurassic/Early Cretaceous graywackes and shales-ophiolite melange; 5) statistical dip of foliation; 6) fault.

ered a close spatial connection between the typical Upper Cretaceous flysch, and the formation composed of sandstone with ophiolites, which is correlative in facies with analogous formations of the Dinaride Ophiolite Zone. He cautiously included the ophiolites in the Upper Cretaceous which had a great influence on the ensuing geological mapping of the ophiolite terrenes of north Croatia. HERAK (1960, p. 117) concluded that: "New data obtained represent evidence that the Dinaridic Ophiolite zone continues northwestward more further than it was presumed", obviously bearing in mind the then time prevailing geotectonic schemes of KOBER (1929) and PETKOVIĆ (1958).

Also in this period KRANJEC (1969) described conformable diabase bodies in the palaeontologically documented Upper Cretaceous flysch of Mt. Majevica, in northeast Bosnia which overlie the Dinaride Ophiolite complex.

2.3. TRANSITIONAL PERIOD

The geosyncline period preceded the elaboration of the Basic Geological Map in which the Dinaride Ophiolite Zone was also included. In late 1950's and early 1960's, the mapping of the middle parts of the Dinaride Ophiolite Zone in Bosnia began. During this period some ideas were clarified and very important results obtained.

1) It was quite clear that ophiolite bodies were included in the Diabas-Hornstein Formation which was identified with KATZER's (1906) "it" unit composed mainly of sandstone and shale.

2) A unit was mapped which was composed mostly of radiolarite interlayered with shale and micrite with synsedimentary basalt. The unit had a large stratigraphic span from the Middle/Late Triassic to the Early Cretaceous. In spite of the fact that radiolarites are characteristically associated with ophiolites (STEINMANN, 1926) this radiolarite formation had not been connected with ophiolites at this time.

3) Under the influence of Aubouin's students (BLANCHET, 1975 and others) the allochtonous character of the Triassic rocks was discovered. Those are also very common as olistoliths in the Diabas-Hornstein Formation. It than became quite clear how the previous idea that these Triassic formations were normal members of the the Diabas-Hornstein Formation was incorrect.

4) Mapping also included structural analyses of large ultramafic bodies. Identifying Kišpatić's "allignment", i.e. the foliation, it was discovered that internal structures of the ultramafic bodies were not comformable with the structures of the surrounding genetically related sediments. Based on their obvious tectonic contact it was concluded that the ultramafics were intruded as solid bodies (Fig. 2). It was further discovered that larger ultramafic masses were thrust onto the surrounding sedimentary rocks of the Diabas-Hornstein Formation, and that associated gabbro and diabase bodies are also in tectonic contact with the surrounding sediments.

5) It was noticed that amphibolites, in some places with eclogites, occur along the marginal parts of ultramafic massifs with common interlayering. This represented evidence for KIŠPATIĆ's (1897) idea on the mutual close genetic relationship between the ultramafic rocks and amphibolites.

6) It was also quite obvious that the interlayering of basalts with shales and graywackes of the Diabas-Hornstein Formation occurred at many outcrops.

Some of these new data were successfully published even in foreign journals, and represented the basis for the search for new solutions and more adequate interpretations amplify. On the basis of new structural and petrological data correlated with new geophysical prospecting data from recent oceans, it was concluded, 5-6 years before new ideas on plate tectonics appeared, that the Dinaridic ultramafic bodies intruded as solid bodies (protrusions), and that they originated at deep parts of the lithosphere, i.e., the upper mantle (PAMIĆ, 1964; TRUBELJA & PAMIĆ, 1965).

In this transitional period, new data obtained in the early elaboration of the Basic Geological Map of the Bosnian part of the Ophiolite zone, clearly showed that the geosyncline concept was unable to explain the complex problem of ophiolite generation. Ophiolite researchers of the northwestern Dinarides did not have such problems at that time because they only began about 10 years later with the mapping of their ophiolite terrenes.

2.4. PLATE TECTONIC PERIOD

ISACKS et al. (1968) published their geophysical pioneer paper on plate tectonics which was soon followed by many geological publications (e.g. DEWEY

& BIRD, 1970, and others). It seems that no single geological problem experienced such revolutionary changes in interpretation as did that of the orogenic ophiolites. In a few years several crucial papers (COLEMAN, 1971, 1977; DEWEY, 1976; MOORES & JACKSON, 1974 and others) essentially changed our conceptions of ophiolites.

The new ideas were accepted very quickly and after a few years the term "Diabas-Hornstein Formation" had been forgotten. As sometimes happens in such decisive situations, it appeared a dangerous exaggeration with "new" ideas. In fact, in these first years, tendency was expressed that the complex problem of the Dinaridic ophiolites would be covered by the term "mélange".

Working on the Californian ophiolites, HSUE (1968) recovered GREENLY's (1919) idea on the "Ankara mélange" in Turkey in order to emphasize the chaotic features of the ophiolite complexes. This mélange idea was very quickly accepted for the Dinaridic ophiolites. According to this, the Dinaridic ophiolitic complex as a whole was interpreted as a huge mélange, i.e., the chaotic formation which originated at first by an olistostrome mechanism with subsequent processes of recycling, i.e., tectonics (DIMITRIJEVIĆ & DIMITRIJEVIĆ, 1973). Based on these ideas, all ophiolitic rocks including large ultramafic massifs with surfaces of 500-1000 km^2 were considered to represent olistoliths included in the mélange.

3. DISCUSSION

The advent of plate tectonic theory generated a host of new ideas with the potential to significantly alter the basic approach to ophiolitic investigation. However, by not entirely rejecting ideas concerning the chaotic features of ophiolites these terrenes have been continuously mapped, new data systematically collected and considered and interpreted according to new geodynamic ideas, i.e., plate tectonics. Numerous papers have been published on ophiolites from different parts of the Dinaride Ophiolite zone (BABIĆ et al., 1979; BELAK et al., 1995; LANPHERE et al., 1975; LUGOVIĆ et al., 1991; MAJER, 1978, 1993; MAJER et al., 1979; PAMIĆ, 1982, 1993; HERAK, 1991, 1995; ŠIKIĆ et al., 1979; ŠIMUNIĆ & ŠIMUNIĆ, 1979; ŠIMUNIĆ et al., 1981; ŠPARICA, 1981; ŠPARICA et al., 1979; ŠUŠNJAR & GRIMANI, 1986; TRUBELJA et al., 1995; ZUPANIČ et al., 1981 and others) from which the following conclusions may be drawn:

1) Ophiolitic rocks are spatially and genetically related to two different formations which originated in two different environments.

a) The Radiolarite Formation in which radiolarite predominates over shale, micrite and synsedimentary basalt. This formation originated in the pelagic parts of the Dinaridic Tethys from the Late Triassic to the Early Cretaceous.

b) The shale-graywacke formation, also with synsedimentary basalts, which covers most of the Dinaride Ophiolite zone. Normal profiles with "bed to bed" alternating shale, graywacke and basalt are only preserved in some areas. Lithologically homogeneous terrenes composed only of graywacke, or shale, or basalt alone are rare. No characteristic fossils to date have been found in the graywacke and shale, but based on uncharacteristic microfossils found in rare interstratified micrites, a Jurassic age can be suggested. Early palaeofloristic data suggest an Early Cretaceous age for the sedimentary parts of the graywackes.

However, the shale-graywacke formation is mainly chaotic and represented by mélange. The graywackes are included in a shaley-silty matrix in the form of flow-ball and slumps as well as larger or smaller fragments of indegenous basalts. These are associated with tectonically embedded erratic blocks of limestones, which originated in different environments from the Middle Triassic to the Tithonian-Valanginian. However, the most common and characteristic are tectonically included fragments of ophiolites - diabase, gabbro and serpentized peridotite, the size of which ranges from a few millimetres-centimetres to huge bodies reaching decakilometre in diametre. Consequently, in their complete development, the Dinaridic ophiolites are spatially associated with the shale-graywacke formation.

The opinion prevails that the shale-graywacke formation of the Alpine-Himalaya belt originated along the active Tethyan margin. For the Dinarides there are insufficient analytical data on the sedimentological features of the formation (TIŠLJAR, 1973; BABIĆ et al., 1979). When subduction processes began at the end of the Late Jurassic and the beginning of the Early Cretaceous, rocks of the Mesozoic oceanic crust were emplaced in the shale-graywacke formation. The emplacement (obduction) was accompanied by dismembering of the obducting oceanic crust and subsequent southwestward thrusting.

2) Due to this emplacement and the chaotic character of the shale-graywacke formation, rocks of the oceanic crust, i.e., the ophiolites, are preserved as tectonic fragments regardless of size. The field relationships and geophysical prospecting data suggest that the largest ultramafic massifs, a few hundred kilometres in the surface area, represent sheets, up to 2000 m thick, which were thrust onto the shale-graywacke formation and the mélange, respectively (Fig. 2). Isotope crystallization ages measured from ultramafics, amphibolites and gabbro-diabases range between 189 and 136 Ma which correspond to the Lias to Neocomian periods. These data, together with the aformentioned stratigraphic data indicate that the Dinaridic oceanic crust was generated during the Jurassic and lower parts of the Cretaceous. Such a conclusion fits with the global interpretation of the Alpine-Himalayan belt.

3) The Dinaridic ophiolites are in many areas unconformably overlain by conglomerate, breccia and lithic sandstone in which ophiolites and genetically related sedimentary rocks are redeposited. Laterally, this formation is in some places interlayered with reef limestones of Tithonian-Valanginian age, but in some other places the overstepping sequences are Late Jurassic to Late Cretaceous in age.

4) The Dinaridic ophiolites are overlain by allochthonous Triassic formations of the typical Alpine development, only locally with Lias limestone, and Palaeozoic semimetamorphic formations, i.e. the Pannonian Nappe (MILADINOVIĆ, 1974) or the Palaeozoic-Triassic Nappe (PAMIĆ & JURKOVIĆ, 1996). Stacking of the allochthonous masses was accompanied in some areas by greenschist facies metamorphism which took plase 125-115 Ma ago (BELAK et al., 1995). Emplacement of these nappes was probably related to the final phases of Late Jurassic/Early Cretaceous obduction processes. This conclusion is supported by the fact that the Palaeozoic-Triassic nappes are unconformably overlain by Lower Cretaceous clastic rocks including ophiolites and genetically related sediments.

5) The Dinaride Ophiolite Zone is bounded in the southwest by Mesozoic clastic and carbonate sedimentary rocks of the passive continental margin of the Dinaridic Tethys - "flysh bosniaque" of the French geologists (AUBOUIN et al., 1970). These formations are Jurassic and Cretaceous in age and thus penecontemporaneous with the generation of the Dinaridic oceanic crust.

6) The Dinaride Ophiolite Zone as a whole is overlain northward by formations of the Late Cretaceous-Palaeogene flysch which are partly preserved in the Prosara, Motajica and Majevica Mts. of the northernmost Dinarides (the Vardar Zone *sensu lato*). The Late Cretaceous-Palaeogene flysch, which is synsedimentarily interlayered with upper mantle basalts and continental crust rhyolites, is in some places underlain by strongly tectonized ophiolite mélange indicating that the evolution of ophiolites also continued through the Late Cretaceous.

In the northern part, rocks of the Late Cretaceous-Palaeogene flysch were affected by Alpine regional metamorphism related to the main Alpine deformational event (the Pyrennean phase). The metamorphism was accompanied by synkinematic granite plutonism whose Sr-isochron age is 48 Ma. All these crystalline rocks originated along the active continental margin of the Dinaridic Tethys represented by a magmatic arc and trench, i.e., the subduction zone (PAMIĆ, 1993).

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