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The Jurassic ophiolitic mélange in the NE Dinarides: Dating, internal structure and geotectonic implications

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Key words: Ophiolitic mélange, accretionary wedge, Jurassic, biostratigraphy, palynology, geotectonics, Dinarides

ABSTRACT

A chaotic complex (Repno Complex) exposed in the Inner Dinarides, NW Croatia, consists of a mixture of magmatic and sedimentary rocks in a dark shaly matrix. It exhibits the typical features of ophiolitic mélanges originating from subduction and accretionary processes. An Early Jurassic to Bajocian age of the fine-grained terrigenous sediments, now composing the shale matrix, is documented by palynomorph assemblages. Continental source areas with "eastern" affinities are envisaged for the shale matrix. The included bodies, millimetric to kilometric in size, consist of sandstones, cherts, red shales, pyroclastics, basalts, gabbro and ultramafics. The shale matrix shows a characteristic scaly cleavage. The preservation of the various inclusions depends on their rheological behaviour during accretion/subduction processes. The most mobile components were the fine-grained terrigenous sediments now represented by the shaly matrix. Subduction processes and formation of the mélange developed between the Middle Jurassic and the Hauterivian. The relevant ocean segment was presumably closed before the Barremian. It is suggested that the Meliata, Repno and Central Dinaric oceanic domains were parts of the single ocean belt neighbouring the Adria.

ZUSAMMENFASSUNG

Der in den Inneren Dinariden (NW-Kroatien) anstehende mesozoische Gesteinskomplex besteht aus einem chaotischen Gemisch magmatischer und sedimentärer Gesteine, die in einer dunklen tonigen Matrix eingeschlossen sind. Dieser Komplex zeigt die typischen Eigenschaften einer ophiolitischen Mélange, deren Genese mit Subduktions- und Akkretionsprozessen erklärt werden kann. Mit Palynomorphen lässt sich das Alter der tonigen Matrix zwischen dem Frühen und Mittleren Jura (Lias-Bajocian) einstufen. Für die Tonmatrix wird ein kontinentaler Ursprung «östlicher» Affinität angenommen. Die eingeschlossenen Komponenten variieren in ihrer Grösse vom mm- bis zum km-Bereich und umfassen Sandsteine, Cherts, rote Tonschiefer, Pyroklastika, Basalte, Gabbros und ultramafische Gesteine. Die tonige Matrix zeichnet sich durch eine schuppige Schieferung aus. Die Erhaltung der einzelnen Komponenten ist abhängig von ihrem rheologischen Verhalten während der Subduktions- und Akkretionsprozesse. Die mobilsten Komponenten waren die terrigenen, feinkörnigen Sedimente, die heute die tonige Matrix bilden. Die Subduktionsprozesse und die Bildung der Mélange fällt in die Zeit zwischen dem Mittleren Jura und dem Hauterivian. Das betreffende ozeanische Segment schloss sich wahrscheinlich vor dem Barremian. Wir nehmen an, dass die ozeanischen Domänen des Meliata, Repno (NW-Kroatien) und der zentralen Dinariden Teile eines einzigen Ozeans in der Nachbarschaft der Adria darstellen.

1. Introduction

The areas comprising ophiolitic mélanges *sensu* Gansser (1974) are characterised by a complex evolution and structure, due to a combination of various depositional, magmatic, tectonic and metamorphic processes related to plate tectonic evolution. Among important aspects of ophiolitic mélanges, insights into the mélange structure, as well as the dating of its components are crucial for understanding its origin and the behaviour of the crustal units involved. The present work deals with the internal structure and dating of a Mesozoic ophiolitic mélange exposed in the NW part of the Inner Dinarides, which is located in the SW part of the Pannonian Basin, between the Sava and Drava rivers (Figs. 1 and 2).

The geotectonic setting and kinematic evolution of the area presently buried below or bordering the Pannonian Basin is a matter of debate, and various interpretations have been envisaged. This is due to the incompletely elucidated paleostructural reconstruction of small continental fragments and intervening oceanic branches in this part of the western Tethyan belt

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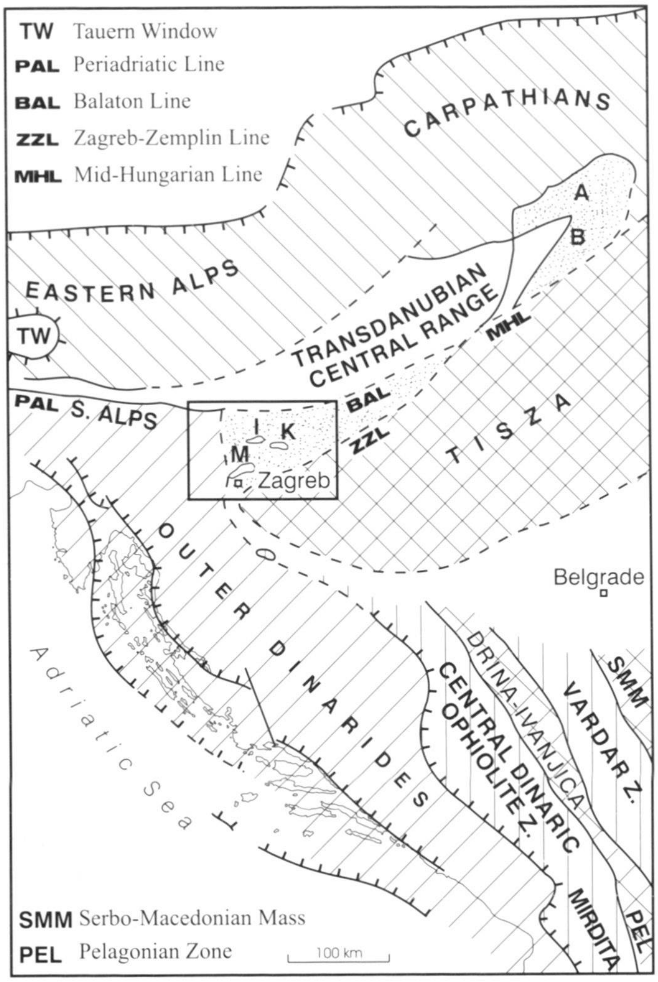

Fig. 1. Tectonic situation of the study area. Dotted areas: Complex intermediate zones located between Tisza and Alpine units. Apart from Central Dinaric Ophiolite, Mirdita and Vardar zones, ophiolite-bearing units occur in Mt. Medvednica (M), Mt. Ivanščica (I), Mt. Kalnik (K), Bükk Mts. (B) and Aggtelek-Rudabánya Mts. (A), compiled from different sources, mainly Haas et al. (2000), Haas & Kovács (2001) and Aubouin et al. (1970). White area south of Tisza contains granites, metamorphics, a variety of sedimentary units, ophiolites in its eastern part, and a widespread Tertiary sedimentary cover. It probably consists of several tectonic units and was designated as possible continuation of the Vardar Zone by Haas & Kovács (2001). Framed area is shown in Fig. 2.

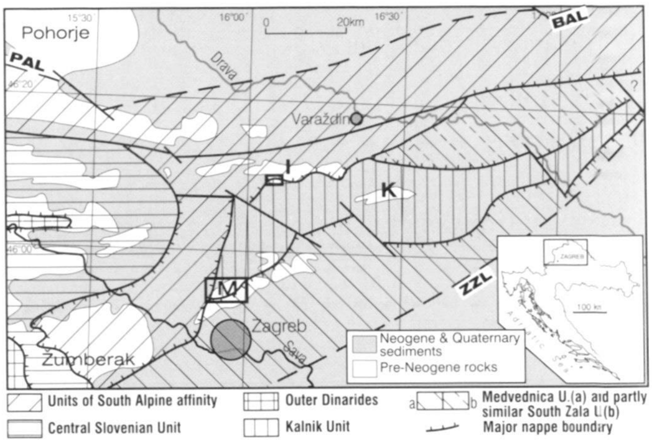

Fig. 2. Tectonic units located between Periadriatic-Balaton (PAL-BAL) and Zagreb-Zemplin (ZZL) lines, after Haas et al. (2000). Medvednica, South Zala and Kalnik units have been considered to show Dinaric affinities. M: Mt. Medvednica, I: Mt. Ivanščica, K: Mt. Kalnik. Note the extensive Neogene-Quaternary cover of SW Pannonian Basin. Boxes in M and I: Figs. 3 and 4. Insert: location of the area on map of Croatia. See text for details.

(e.g., Abbate et al. 1986; Ziegler 1988; Kozur 1991; Robertson et al. 1991; Stampfli et al. 1991; Dercourt et al. 1993; Vörös 1993; Dal Piaz et al. 1995; Channell & Kozur 1997; Wortmann et al. 2001). The Mesozoic ophiolitic mélange in the SW part of the Pannonian Basin is exposed in the area of Mt. Medvednica, Mt. Ivanščica and Mt. Kalnik (Figs. 1 and 2), and has been named the Repno Complex (Babić & Zupanič 1978). A small area also occurs SW of Zagreb. The Repno Complex is located between the ophiolites and mélanges in the Bosnian and Serbian Inner Dinarides and related zones in Albania, Macedonia and Greece on one side, and similar formations in NE Hungary and the Inner Western Carpathians, and may represent a link between these two realms (Zupanič et al. 1981). However, the connections and correlations between these zones are not clearly understood. This is partly due to the isolated occurrences of strongly deformed pre-Neogene rocks, including the Mesozoic ophiolitic mélange. They are surrounded and partly covered by the Neogene and Quaternary deposits of the Pannonian Basin (Fig. 2). Tertiary tectonic processes greatly modified previous structures and patterns of crustal blocks, thus making interpretation of the already complex nature and evolution of ophiolite-bearing zones even more difficult.

Towards the SE, in Bosnia and Serbia, there are two relatively well-known ophiolite-bearing zones: the Central Dinaric Ophiolite Zone (CDOZ) and the Vardar Zone (VZ). They are separated by the Golija Zone (Aubouin et al. 1970), i.e., the Drina-Ivanjica Element (Dimitrijević & Dimitrijević 1973, 1976), a continuation of the Pelagonian Zone in Macedonia and Greece (Fig. 1), representing a continental slice (Robertson & Karamata 1994, with references).

In the CDOZ, envisaged to correspond to an ocean branch, ocean spreading presumably began in the interval between the Middle Triassic and Early Jurassic, the ophiolitic mélange originated in the Late Jurassic, and suturing occurred in the Tithonian (Robertson & Karamata 1994, with references). The probable continuation of the CDOZ in Albania and Greece is represented by the Mirdita and Pindos ophiolites. The Mirdita oceanic area is considered having developed in the Jurassic, the ophiolitic mélange in the Middle-Late Jurassic, and continental collision may be pre-Barremian in age (Bortolotti et al. 1996). The tectonic evolution of the Pindos oceanic domain includes the Late Triassic onset of ocean spreading, convergence initiating during the Mid-Jurassic, with a remnant ocean basin existing between the Late Jurassic and the Early Tertiary, and final suturing in the Tertiary (Jones & Robertson 1991; Robertson et al. 1991, with references). According to another model, the Pindos ophiolites are allochtonous and rooted in the Vardar ocean (Bernoulli & Laubscher 1972).

The evolution of the VZ encompasses Late Triassic rifting, with the onset of the spreading in the Early Jurassic. Subduction did not begin until the end of Jurassic time and continued until the Late Cretaceous (Channell & Kozur 1997, with references).

Ideas on the prolongation of the CDOZ into NW Croatia (Kišpatić 1918; Aubouin et al. 1970; Zupanič et al. 1981; Pamić 1997) contrast with views on the connection and common evolution of the VZ and Repno domains (Halamić & Goričan 1995; Haas et al. 2000).

Instead, the Repno Complex may be correlated with similar units in the NE, exposed in the Bükk Mts., NE Hungary (Haas & Kovács 2001, with references). Dextral movements along the Mid-Hungarian and Balaton lines (Fig. 1) have been considered responsible for the disconnection of the NE Hungarian segment from the Repno segment and the more southerly VZ portion of the formerly single ophiolite-bearing zone, and its displacement towards the NE. Hence, the evolution of the oceanic area recorded by the NE Hungarian ophiolite-bearing complexes would be similar to that of the VZ. The Mid-Hungarian Line represents a large-scale transpressional zone along which the Tisza microplate and the Transdanubian Central Range rotated in opposite directions, and finally came into juxtaposition during the Late Oligocene-Early Miocene (Csontos & Nagymarosy 1998). While the Tisza microplate was detached from Europe by the end of the Middle Jurassic (Vörös 1993), the Transdanubian Central Range, showing NW-verging nappe structures similar to those of the Upper Austroalpine (Szafian et al. 1999), was displaced from its previous western position N of the Southern Alps in the Tertiary (Kázmér & Kovács 1985; Schmidt et al. 1991).

The ophiolite complex of the Bükk Mts., together with the ophiolites located further to the N, in the Inner Western Carpathians, have been ascribed to the "Meliata" domain. The main rifting in the Meliata began in the Middle Triassic (Pelsonian), sea-floor spreading ended in the middle Carnian, subduction began in the latest Triassic, and final closure occurred in the Oxfordian (Kozur 1991). A connection between the Meliata and Vardar oceanic domains has been suggested in several reconstructions (e.g., Dercourt et al. 1993; Dal Piaz et al. 1995; Gawlick et al. 1999), and contradicted in others (e.g., Kozur 1991). A connection between the Repno and Meliata domains has also been proposed (Zupanič et al. 1981; Halamić & Goričan 1995; Halamić et al. 1999). However, a connection between the Inner Western Carpathian part of the Meliata domain and the Vardar domain is considered unlikely because of differences in their evolution and structural setting (Haas & Kovács 2001).

The isolated location of the Repno mélange, the fragmentary knowledge of its geological evolution and the surrounding areas, as well as the current hypotheses, inferences and correlations with other ophiolite-bearing zones show the need for new studies and reconsideration of existing data. In the present work, we describe the structure of the ophiolitic mélange in NW Croatia and present the first paleontological dating of the matrix of this rock complex. The palynological dating provides age constraints relevant to the origin of this mélange, as well as to the tectonic evolution of the area. The history of the Repno Complex, as presented here, may contribute to the knowledge of the evolution of this part of western Tethys.

2. The ophiolitic mélange

2.1. Geological outline

The Mesozoic ophiolitic mélange (= Repno Complex) occurs in the area consisting of displaced, sheared and strongly deformed tectonic units, largely buried below the Neogene-Quaternary deposits of the Pannonian Basin (Fig. 2). The structural position of the Repno Complex is poorly understood. In a tentative reconstruction by Haas et al. (2000) the Repno Complex is included in the "Kalnik Unit", which is dominated by ophiolitic mélange and envisaged to be overthrust by the units of South Alpine affinities from the NW, and those of Dinaric affinities from the SE (Fig. 2). Instead, the results of geological mapping suggest a general N to NW vergence of compressional structures for the same area. These results show that the Repno unit may be overthrust over the Cretaceous-Paleocene and Lower Miocene sediments at Mt. Medvednica and Mt. Kalnik, respectively, and overthrust itself by Paleozoic and Triassic sediments, Lower Cretaceous metamorphics, Senonian sediments in the central part of Mt. Medvednica, and Triassic carbonates at Mt. Ivanščica (Šimunić et al. 1981; Šikić 1995; see also Figs. 3 and 4).

The kinematic history of the area and derivation of the smaller tectonic units mentioned above (Fig. 2) are poorly known. They are located in the vicinity of larger crustal units of the Tisza, Transdanubian Central Range, Southern Alps and Outer Dinarides (Fig. 1). The motions of these units, particularly the clockwise rotation of the Tisza (Csontos & Nagymarosy 1998), were responsible for the clock-wise rotation of Paleogene structures in this area and their present-day NW-directed vergence (Tomljenović, oral comm. 2001). Instead, the Outer Dinarides rotated counter-clockwise, assuming their present-day NW-SE trend and SW-directed vergence of tectonic structures (Csontos & Nagymarosy 1998). Miocene tectonism also modified previous structures and produced both extensional and compressional structures, mostly directed NW-SE and N-S (Šimunić et al. 1981; Šikić 1995; Tomljenović & Csontos 2001).

Except for the unconformably overlying Neogene and Quaternary sediments, the exposed contacts of the ophiolitic mélange with neighbouring units are mostly tectonic. At Mt. Medvednica, the mélange may be unconformably overlain by shallow-water Lower Cretaceous and Senonian sediments, al-

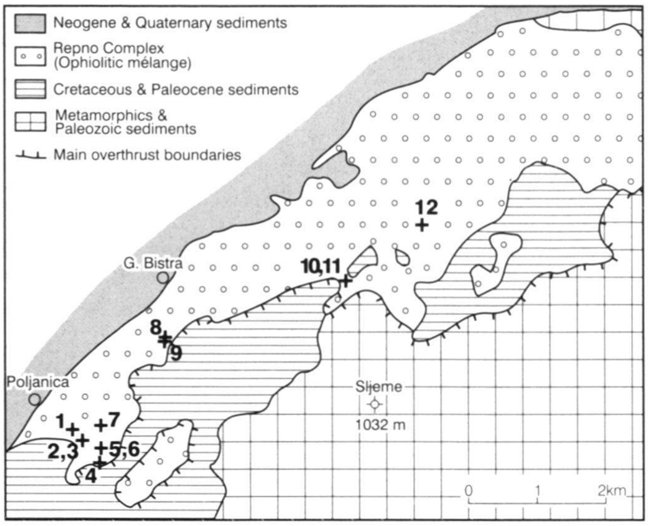

Fig. 3. Repno Complex (ophiolitic mélange) and surrounding units in central Mt. Medvednica. 1 - 12: Location of samples with palynomorphs. Simplified geology based on Šikić (1995), Crnjaković (1987, 1989), Halamić (1998) and unpublished data. In contrast to Tomljenović (1995) and Pamić (1997), Cretaceous and Paleocene deposits on NW Medvednica slopes are not included into the Repno Complex.

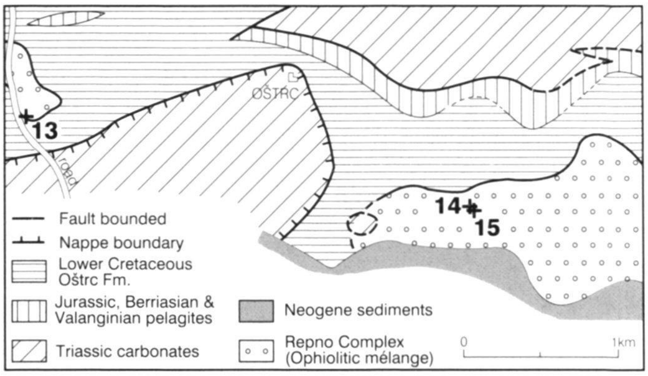

Fig. 4. Repno Complex (ophiolitic mélange) and surrounding units in SW Mt. Ivanščica (after Zupanič et al., 1981, and unpublished data). 13 - 15: Location of samples with palynomorphs.

though there is no direct evidence. The disconformable relationship with the Senonian sediments envisaged by Halamić (1998: Fig. 62) in central Mt. Medvednica is here regarded as a tectonic surface.

The Repno Complex has been described as a chaotic assemblage of shales, sandstones, cherts, pillow lavas, and minor gabbro and ultramafics, and interpreted as part of a Mesozoic subduction-related accretionary wedge, generated by piling up of deep-sea sediments, slices of oceanic crust and lithospheric mantle, as well as a few blocks of carbonate rocks (Babić & Zupanič 1978; Babić et al. 1979, 1992; Šimunić & Šimunić 1979; Crnjaković 1987; Tomljenović 1995). Details of the internal structure of this unit are given below.

The Triassic onset of ocean spreading in the Repno ocean segment is based on the direct depositional contact of the Upper Triassic radiolarian chert overlying pillow lava of MORB affinities (Halamić & Goričan 1995). The closure of the basin is indicated by the Hauterivian-Barremian supply of ophiolite detritus into the turbiditic Oštrc basin, located on a continental block and in front of a nappe or overthrust consisting essentially of ophiolites (Zupanič et al. 1981). Another continental unit was probably located on the rear of this nappe. This pattern has been interpreted as an example of continent-continent collision. Another view suggests continuation of subduction and formation of mélange, until final ocean closure in the Eocene. This view is based on the assumption that the Tithonian-Valanginian, Cretaceous and Paleocene sediments are included in the mélange (Tomljenović 1995; Pamić 1997).

Halamić and co-workers (Halamić & Goričan 1995; Halamić 1998; Halamić et al. 1998, 1999) proposed a differentiation of the Repno Complex into several stratigraphic units. In their view, it consists of the following units:

(1) Middle-Upper Triassic Kestenik Unit, comprising radiolarian-dated cherts, basaltic lavas and minor shales; (2) Markovčak Unit, consisting of diabases, gabbros and peridotites, and the Podbreg Unit, consisting of tuffs, both assumed to be Jurassic in age; (3) Kraljev Vrh Unit, of presumed Middle Jurassic age, consisting of basalts and basic tuffs with intercalated debris-flow conglomerates, dominated by sandstone clasts; (4) Latest Bajocian to Early Callovian Poljanica Unit, comprising radiolarian-dated cherts, debris-flow conglomerates dominated by sandstone clasts, and pillow lavas of MORB affinities; (5) The youngest Markov Travnik Unit of presumed Late Jurassic age, disconformably overlying other units and also including debris-flow conglomerates and minor tuffs.

We propose below the chaotic origin of the Repno Complex, in contrast with the "stratigraphic" interpretation of Halamić and coworkers. Our sampling strategy for palynologic dating aimed at representative distribution over the different areas of the Repno Complex, and also the representation of all four shale-bearing units of Halamić and co-workers (Halamić & Goričan 1995; Halamić 1998; Halamić et al. 1998, 1999) (see sample distribution in Figs. 3 and 4, and Appendix).

2.2. Internal structure

Most of the outcrops in Mt. Medvednica, Mt. Ivanščica and Mt. Kalnik consist of shale matrix and inclusions of various rock types, showing a very wide size range. In the following description, the terms "matrix" and "inclusions" are understood as purely descriptive terms.

Matrix

The shale matrix is dark grey to black, locally reddish, mostly siliceous, partly sandy, and free of carbonate. In most cases, the matrix is pervasively sheared (Figs. 5-8), and displays scaly

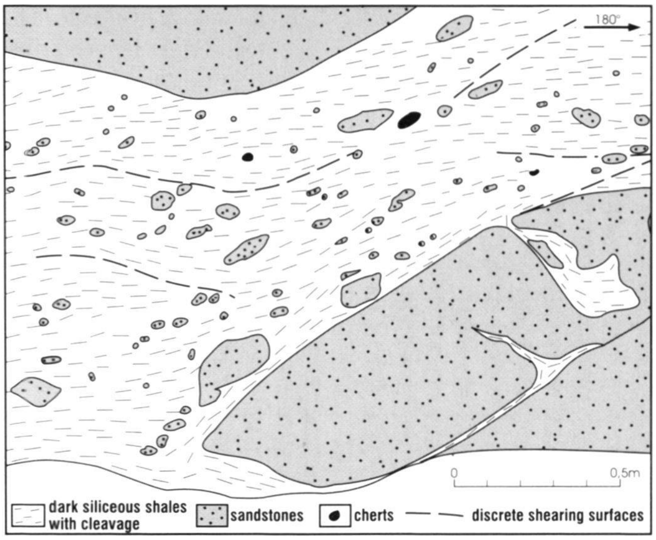

Fig. 5. Sketch of the relationship between shales and inclusions (mostly sandstones) typical for Repno Complex. Note differences in packing, orientation of foliation in shales and large shale embayments inside sandstones. This outcrop, described by Crnjaković (1987), is located 100 m south of sampling sites 10 – 11 on Mt. Medvednica (Fig. 3). Geographic co-ordinates: x = 5086150, and y = 5573300.

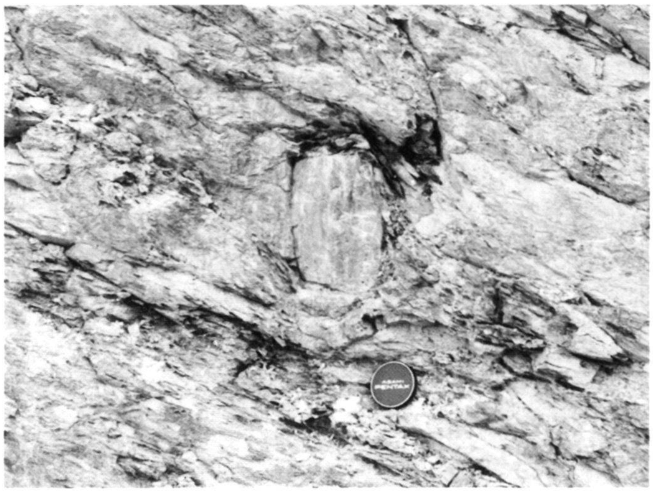

Fig. 7. Rotated sandstone inclusion within sheared dark shales. Sampling site 13, Mt. Ivanščica. (Lens cap for scale: 5.7 cm in diameter).

Fig. 8. Pervasively sheared dark shale and lenticular inclusions of cherts and sandstones (both as prominent light rocks, 8 to 22 cm long). Sampling site 4, Mt. Medvednica. Bar = 10 cm.

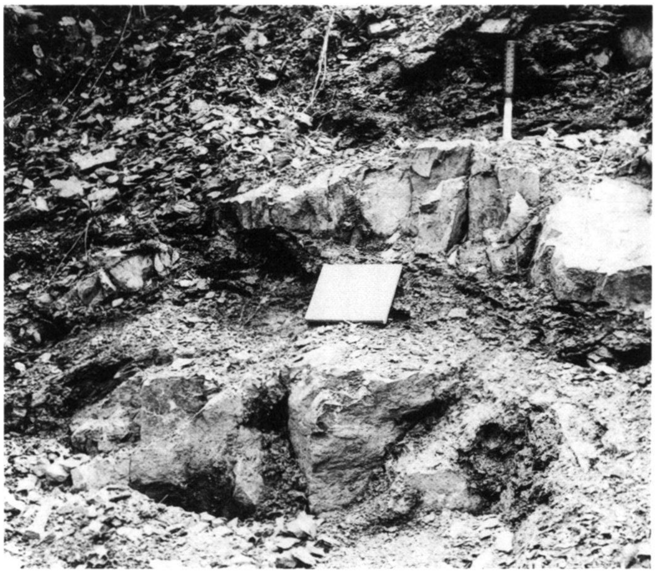

Fig. 6. Two lenticular sandstone inclusions embodied within sheared dark shales, below and above notebook (notebook for scale: 30 x 22 cm). Two decimetric sandstone lenses are on the left of notebook and in dark hollow to the right of hammer. Sampling site 19, Mt. Kalnik.

cleavage bounding lenticular shale chips with polished surfaces and striations. At the inclusion contact, the foliation either follows the inclusion shape or is discordant. Fractures, faults and folds of the shale foliation may also be observed.

Inclusions

Most of the **microscopic to decametric inclusions** embodied in the shale matrix are represented by sandstones. Less common are cherts, siltstones and shales. Recrystallised, silicified limestones, spilites, tuffs and serpentinites are rare. Blocks of diabase and gabbro have also been reported (Crnjaković 1987; Pamić 1997; Halamić 1998). A few blocks of Triassic limestone have been considered as embedded in the mélange (Šimunić & Šimunić 1979), although some Triassic blocks were probably brought into contact with the mélange by Quaternary landslides. Clasts as young as Tithonian-Valanginian, Late Jurassic and Early Cretaceous in age, reported earlier from the mélange in Mt. Kalnik (Šimunić & Šimunić 1979) are in fact not incorporated into it (Šimunić et al. 1981). They are probably derived from the overlying Miocene conglomerates and gravels, which contain this type of clasts.

The microscopic to decametric inclusions are usually dispersed in the shaly matrix, with centimetric to metric spacing

(Figs. 5-8), and are packed in a few cases. The shape of the inclusions varies from rounded to angular; many are lensoid. Their elongation mostly parallels the matrix foliation, although examples of oblique and perpendicular orientations do occur (Figs. 5-8). In rare cases, the sandstone inclusions represent fragments of folds. The sandstone/shale contacts are usually smooth and may show slickensides, striations, irregular protrusions, embayments and shale flames (Fig. 5). On polished surfaces and in thin sections, the sandstones may show either homogeneous fabric or laminations and shears marked by films of sandy shale. Some are marginally disintegrated to a mixture of sand and shale. Smaller inclusions of other lithologies are mostly lensoid in shape, and oriented parallel to the foliation of the matrix. The shale inclusions comprise greenish-grey, black and red varieties.

Numerous large, **decametric to kilometric rock bodies** may also be observed. Where visible, their contacts with the shale matrix are sheared. Many of the large bodies not showing direct contacts with the shale matrix are surrounded by shales containing the small-scale inclusions described above. The cleavage in these shales follows the orientation of large bodies. The large bodies may consist of pillowed and massive basalts, cherts, red shales, and more rarely of diabases, tuffs, sandstones, gabbro and peridotites. The entire lithologic spectrum of these larger bodies is exposed on Mt. Medvednica and Mt. Kalnik, whereas only volcanic masses are known from Mt. Ivanščica. Chert bodies show either well-preserved bedding or intense internal shearing features, folding, and local brecciation. Red shales are characterised by pronounced internal shearing. Field observations on the large bodies, together with the presence of small-scale inclusions of the same lithologies, suggest that these rock masses are also embedded within the shale matrix. In our view, this is also applicable to both the Middle to Late Triassic and latest Bajocian to Early Callovian cherts, dated by radiolarians (Halamić & Goričan 1995; Halamić et al. 1999). Thus, the sections described by Halamić at al. (1999) as interbedded Middle Jurassic cherts with matrix-supported conglomerates (i.e. shales containing small-scale sandstone and the chert inclusions described above), show intense shearing, both within and between cherts and shales (Fig. 3: sites 2, 3, 5 and 6; Appendix). These features contradict the interpretation of normal stratigraphic successions. Our palynological data indicate a Toarcian age for the shale which, according to Halamić et al. (1999), is presumed to be intercalated in the radiolarian-dated latest Bajocian-Early Callovian cherts (site 6 in Figs. 3 and 10; Appendix). This evidence reflects the isolated nature of chert bodies included in the mélange. Similarly, the contact interpreted by the above authors as a disconformity between their Poljanica and Markov Travnik units shows strong shearing between the cherts and overlying shales enclosing sandstone and chert inclusions, which in our view advocates against a normal stratigraphic relationship (site 4, Fig. 3; Appendix). Therefore, field observations do not support the stratigraphic subdivision of the Repno Complex proposed by Halamić (1998) and Halamić et al. (1999). In the same way, there is no evidence for "bed-by-bed" interlayering of basalt lavas, shales, mudstones, cherts and limestones, hence for the normal stratigraphic succession from the Middle-Upper Triassic up to the Lower Cretaceous, which was reported as common by Pamić (1997) in the Mt. Kalnik area. Neither can we confirm the existence of "commonly preserved" interlayered basalts, shales and greywackes also reported from Mt. Kalnik by the same author. A large body of pillow basalt, dated as Middle Triassic on the basis of conodonts in enclosed limestones (Mt. Medvednica, Halamić et al. 1998) is also regarded here as a large inclusion in the mélange. Two blocks of diabase and gabbro from Mt. Kalnik, which yielded radiometric ages of 190 and 185 Ma, respectively (K-Ar, whole rock) are also enclosed in the mélange (Pamić 1997).

The example of basalt normally overlain by radiolarian-dated Late Triassic cherts (Halamić & Goričan 1995), as well as rare examples of the close association of red shales and lavas (Halamić 1998) may be interpreted as locally preserved segments of primary, normal successions, which now represent separate bodies included in the mélange.

3. Palynology

23 samples of dark shales have been studied for palynology. They represent the matrix of chaotically arranged inclusions of different types and sizes (e.g., Figs. 5-8). The most important elements of the palynomorph assemblages of 19 productive samples are listed in Fig. 9. As mentioned above, the sampling sites cover the entire area and include all four shale-bearing units of Halamić & Goričan (1995), Halamić (1998) and Halamić et al. (1999). For other details and location see Appendix and Figs. 3, 4 and 10.

3.1. Palynofacies

The palynofacies of the studied samples is quite homogeneous. The organic residues are strongly dominated by woody and coaly debris. Palynomorphs of terrestrial origin are common in most samples. Dominant forms are long-ranging bisaccate pollen and smooth trilete spores. In most productive samples, a marine environment is documented by the presence of relatively rare dinoflagellate cysts. In a few cases, these forms are relatively frequent (Fig. 9). Triassic sporomorphs occurring in the two samples of Early Jurassic age (sites 1 and 7) are the only evidence for reworking. Pollen and dinoflagellate cysts exhibit a brown to dark brown colour, indicating a thermal alteration index (T.A.I.) between 5 and 6. This range corresponds to vitrinite reflection values of 1.3 - 2%. Thus, the maturity of the organic matter reflects a temperature range between 120° and 170° (Batten 1996).

3.2. Dating

Most of the ages are based on concurrent ranges of dinoflagellate cysts and a few groups of gymnosperm pollen (Figs. 9 and 10). Considering their mediocre to very poor preservation, the

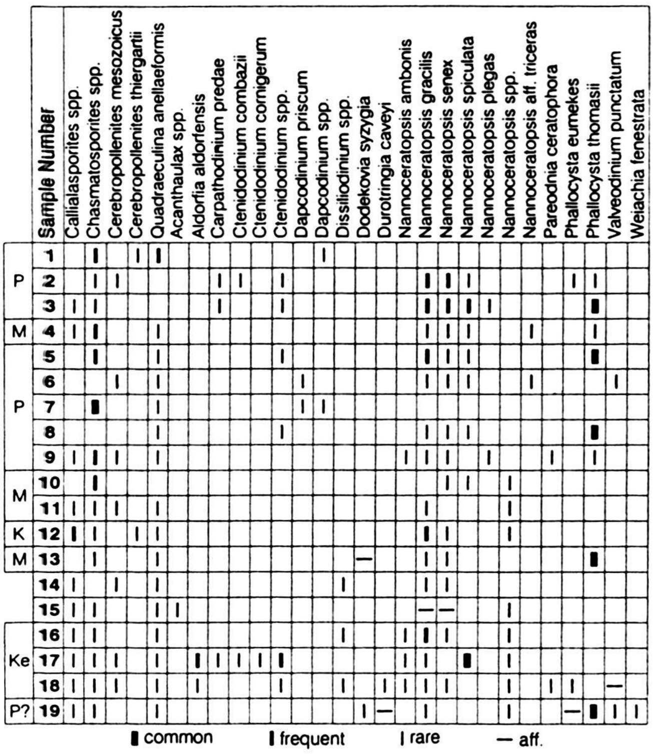

Fig. 9. Distribution of selected palynomorphs from samples 1 to 19. The corresponding outcrops belong to the following units proposed by Halamić (1998), Halamić & Goričan (1995) and Halamić et al. (1999): P: Poljanica, M: Markov Travnik, K: Kraljev Vrh, Ke: Kestenik. For sampling locations, see Figs. 3 and 4, and Appendix. For taxonomic references, see Williams et al. (1998) and Schulz (1967).

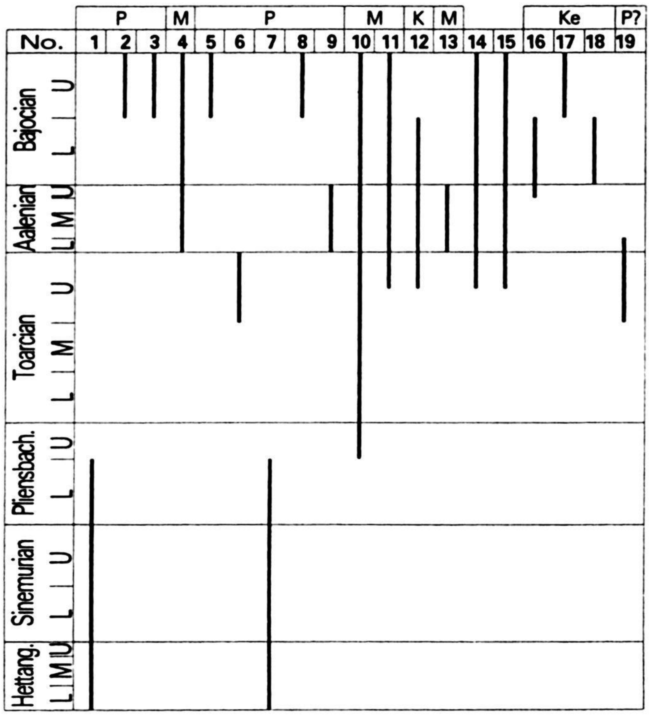

Fig. 10. Vertical ranges of palynomorph associations identified in samples 1–19. Units P, M, K, Ke as in Fig. 9. Sample location in Figs. 3 and 4, and Appendix.

regular record of marker species is regarded as indication of originally common occurrences. The stratigraphic ranges of dinoflagellate cysts are well-known from the Boreal realm of NW Europe, whereas those from the Tethyan realm are based on relatively few studies (Feist-Burkhardt 1992; Feist-Burkhardt & Wille 1992; Partington et al. 1993; Ioannides & Riding 1998). Thus, the age interpretations of our assemblages are essentially based on the NW European evidence. Similarly, the ranges of marker pollen are also essentially based on central European records (Schulz 1967; Partington et al. 1993). Since only a few data are available from the Tethyan realm, minor differences in the ranges of palynomorphs may exist compared to the distribution schemes of northern areas.

All palynomorph assemblages fall within a stratigraphic range from Hettangian to Bajocian. Based on the palynological datings, two groups of samples can be discriminated: the first one includes the lower part of the Early Jurassic (Hettangian-Early Pliensbachian). These relatively poor assemblages contain common pollen grains including *Chamatosporites* spp. and *Quadraeculina anellaefomis,* and rare dinoflagellates belonging to the *Dapcodinium* group. The second group of samples covers the interval between the Late Pliensbachian and the Bajocian (Fig. 10). The corresponding assemblages are characterised by the regular occurrence of dinoflagellates, mainly of the *Nannoceratopsis* group. Typical for some samples is the common occurrence of *Phallocysta thomasii.* Most samples of the latter group fall within an interval between the Aalenian and the Late Bajocian.

4. Discussion

4.1. Depositional environment and source area for shales and sandstones

Since all the palynologically dated dark shales fall in the age bracket between the Early Jurassic and the Bajocian, we suspect that most or possibly all dark shales have similar ages. Common features of all the studied shales include the absence of Ca-carbonate and composition of the particulate organic matter, suggesting very similar depositional settings. The abundance of coaly and woody debris associated with relatively common terrestrial palynomorphs and rare dinoflagellate cysts of marine origin indicates a marine environment with strong terrestrial influx. The same conclusion is valid for the palynologically barren samples, as they are also rich in coaly debris. The absence of palynomorphs is interpreted to be due to strong oxic degradation. The absence of Ca-carbonate may be related to deposition below carbonate compensation depth. Hence, the dark shales originated from dominant terrigenous, siliciclastic muds, presumably deposited in a deep marine environment.

According to the cumulative range of dated samples (Fig. 10), these conditions prevailed from the Early Jurassic to the Bajocian. Gradual transitions between the shale matrix and sandstone inclusions, as well as the dark sandy shale laminae in some sandstone inclusions, suggest a mutual depositional setting for the shale and sandstone protoliths, i.e. former muds and sands. The chemical composition of some shale samples points to acid to neutral magmatic rocks and clastic sediments as sources (Halamić 1998), whereas the particle types and heavy mineral associations characterising the sandstones reveal derivation from low-grade metamorphic, plutonic and volcanic rocks and clastic sediments (Babić & Zupanič 1978; Babić et al. 1979; Crnjaković 1987). Hence, the same continental origin may be inferred for both the dark shales and the sandstones.

4.2. The origin of the structure of the Repno Complex

The rounded forms of sandstone inclusions, gentle protrusions, embayments and flames suggest early ductile flow and strata disruption. These features were caused first by gravitational compaction and migration of pore fluids from mud to sandy layers, and then by increased pore pressure in sands due to accretion and tectonic load (Lash 1985). Consequently, the formerly interlayered cohesive mud became a strong sediment and failed brittlely, with development of scaly cleavage, otherwise typical for mélanges (e.g., Raymond 1984; Cowan 1985). The diffuse boundaries between sandstone inclusions and shale probably developed prior to dewatering. The brittle disruption of sandstone beds may have occurred in partly consolidated sediments. The different orientation of some elongated inclusions with respect to matrix foliation indicates that some rotation occurred after disruption of the primary bedded and laminated fabric. Although sliding and sediment flows may have been important during the evolution of the Repno mélange, early tectonic shearing is clearly deduced from the features and processes described above. Very rare examples of less sheared shales containing dispersed small inclusions may represent relics of mudflow deposits.

The peculiar association of radiolarian cherts and terrigenous clastics in the chaotic structure may reflect the process by which oceanic rocks were provided to the accumulation areas of continental-derived clastics and incorporated together into an accretionary wedge. This is consistent with the presence of slices of oceanic crust and lithospheric mantle, which were also included in the wedge during this process. The dark shales - the most mobile component - were remoulded and became the matrix of the stiffer rock components.

As mentioned above, large bodies embedded in a dark shale matrix also include radiolarian cherts of latest Bajocian-Early Callovian age. These cherts are at least partly younger than the Early Jurassic to Bajocian fine-grained sediments, now representing the shale matrix. This relationship may be explained by the different rheological behaviour of the materials involved, and by a variety of processes which may operate in accretionary wedges. These include gravitational mass movements, tectonic shearing, dewatering and diapirism (Gansser 1974; Raymond 1984; Cowan 1985), which may be repeated and/or alternate. In addition, individual parts of the wedge may have moved and been deformed repeatedly and in different ways. The final result is a mixture of different types of sediments and ophiolites of different ages. While the fine-grained sediments (Early Jurassic - Bajocian), now representing the shale matrix of the Repno Complex, deformed easily, the Triassic and Jurassic cherts behaved as relatively stiff components and underwent folding, internal shearing, disruption into isolated blocks and smaller lensoid fragments, and brecciation. The red shales disintegrated into small chips or larger, internally deformed blocks. Magmatic rocks were fragmented into inclusions of various scales.

Occasionally observed discrete fracturing, faulting and folding of the Repno shale foliation, must represent young, probably Tertiary features. The reverse faults and overthrusts locally observed within the Repno Complex may be coeval with similar structures involving Lower Cretaceous, Upper Cretaceous and Paleocene sediments.

4.3. The role and place of the Repno Complex in geological evolution

The earliest evolutionary stage recorded in the Repno Complex relates to the pillow lava of MORB affinity depositionally overlain by Triassic ribbon cherts, interpreted as evidence for the Triassic onset of ocean spreading (Halamić & Goričan, 1995; Halamić 1998; Halamić et al. 1998, 1999), and here considered to belong to an isolated body enclosed in the mélange. The inferred age is similar to that interpreted for the Meliata Ocean (Channell & Kozur 1997), the CDOZ (Robertson & Karamata 1994) and the Pindos domain (Jones & Robertson 1991), however, it differs from the Jurassic age inferred for the Mirdita domain (Bortolotti et al. 1996), usually regarded to have occupied an intermediate position between the CDOZ and Pindos. Thus, the Repno ocean segment may represent a link connecting Meliata and CDOZ. Concerning the VZ, a Triassic versus Jurassic onset of Vardar ocean spreading is still debated (e.g., Channell & Kozur 1997).

After the palynological dating presented in this study, deposition of muds and sands, now represented by dark shale matrix and sandstone inclusions, occurred between the Early Jurassic and the Bajocian. As indicated by heavy mineral associations, the particle composition of sandstones, and the chemical composition of dark shales, deposition must have taken place between a continental crustal block and a distal, dominantly pelagic realm. Considering the identity of this continental block, the Adria plate may be excluded, owing to its carbonate cover, so that a location on the other, "eastern" side of the Repno oceanic domain is to be envisaged (Fig. 11-A). Following various reconstructions (e.g., Abbate et al. 1986; Kozur 1991; Robertson et al. 1991; Dercourt et al. 1993; Vörös 1993;

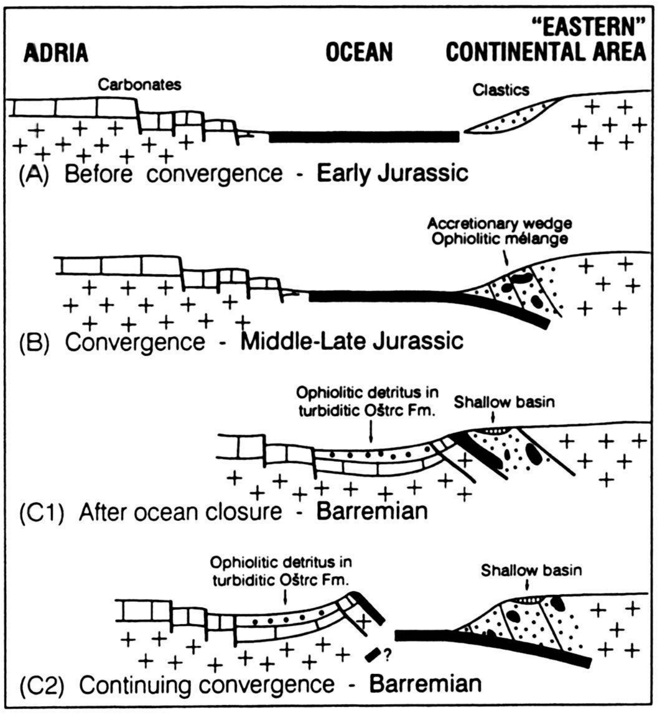

Fig. 11. Scheme of Early Jurassic to Early Cretaceous tectonic evolution of Repno oceanic domain and its suroundings. (C1) and (C2) represent two possible scenarios. C1, adapted from Zupanič et al. (1981), depicts more probable scenario. "Shallow basin": Lower Cretaceous shallow-marine deposits exposed on northern slopes of central Mt. Medvednica (Crnjaković 1987, 1989). See text for details.

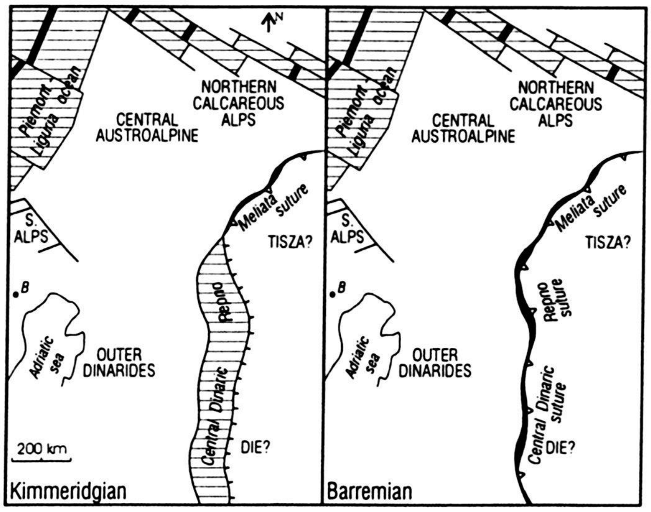

Fig. 12. Hypothetical reconstruction of the closure of the oceanic belt consisting of Meliata, Repno and Central Dinaric Ophiolite Zone segments after the closure of the Meliata sector (Kimmeridgian) and after the closure of the Repno and Central Dinaric sectors (Barremian). In both figures the pattern of Alpine units and Meliata suture corresponds to the time of the Jurassic-Cretaceous boundary and is adopted from Froitzheim et al. (1996, with references). N: present-day north for Europe. B: Bologna.

Dal Piaz et al. 1995; Channell & Kozur, 1997; Wortmann et al. 2001), microplates such as Tisza, Rhodope or the Pelagonian Massif may be envisaged as possible continental source areas.

Nevertheless, the Repno ocean domain included gabbros and diabases, now represented by islolated bodies in the mélange. Two of them have been radiometrically dated (K-Ar; whole-rock dating) as 190 and 185 Ma, respectively (Pamić 1997), and these data may indicate the existence of an oceanic crust already in the Early Liassic or possibly Middle Jurassic (Figs. 11-A and 11-B). The latest Bajocian-Early Callovian radiolarian cherts, also included in the mélange, appear to have been deposited within the same ocean domain (Fig. 11-B).

Based on the youngest dated rocks in the Repno Complex, i.e., the cherts of latest Bajocian-Early Callovian age, subduction/accretion processes were active after the Early Callovian (Fig. 11-B), but may have started earlier, possibly in the early Middle Jurassic. This is close to the subduction onset times interpreted for the CDOZ, Mirdita and Pindos domains (Robertson & Karamata 1994; Bortolotti et al. 1996; Jones & Robertson 1991), and later than the Norian subduction onset in the Meliata zone (Channell & Kozur, 1997). However, these differences may have occurred along a single mutual oceanic belt (Fig. 12).

Information on the subsequent evolution of the Repno domain comes from the Lower Cretaceous Oštrc Fm. outcropping at Mt. Ivanščica. The delivery of ophiolitic detritus into the Oštrc basin, which formed above a continental basement (Figs. 11-C and 13; Zupanič et al. 1981), is considered reflecting the presence of an ophiolite overthrust or nappe emplaced over the marginal portion of the Adria plate (Figs. 11-C and 12). Complementary information comes from the radiometric dating of low- and very low-grade metamorphism, yielding ages between 123 and 115 Ma and involving a variety of Silurian to Upper Triassic sediments and minor interlayered basalts at Mt. Medvednica (Fig. 13; Đurđanović 1973; Sremac & Mihajlović-Pavlović 1983; Belak et al. 1998; Belak et al. 1995). Metamorphism in this sedimentary-metamorphic complex have started prior to the origin of the micas measured by the radiometric method, probably in the Late Jurassic, or even earlier. So far, associated blueschists have not been dated. Their origin has been related to the same subduction zone (Belak et al. 1998) and their association with low- and very low-grade metamorphics is suggestive of their comparatively greater age (Middle or Late Jurassic). Thus, the origin of the Oštrc basin, subaerial exposure of the ophiolites and metamorphism were all related to the same tectonic processes.

The provenience of the tectonic unit consisting of the sedimentary-metamorphic complex of Mt. Medvednica mentioned above is not clear. Haas et al. (2000) suggested its Dinaric affinity. Instead, this terrane may represent a sheared fragment of Tisza, which was included in the Alpine structures, or a continuation of DIE, itself representing a continental fragment (Robertson & Karamata 1994, with references).

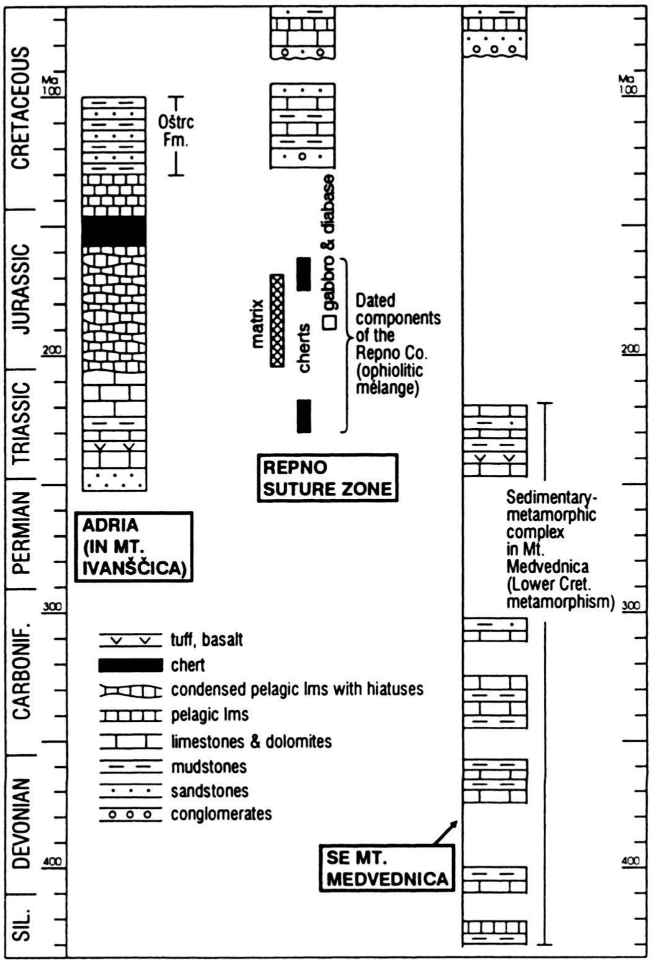

Fig. 13. Simplified chronostratigraphic logs representing three large-scale Mesozoic tectonic units. For Adria: based on sedimentary succession in the main part of Mt. Ivanščica (Triassic, after Šimunić et al. 1981; Jurassic and Lower Cretaceous, after Babić & Zupanič 1973, 1978; Babić 1974; Babić et al. 1979; Zupanič et al. 1981). Interpretation of Repno suture zone is based on Repno mélange of entire study area, as well as associated shallow-water Lower Cretaceous sediments on NW slopes of central Mt. Medvednica described by Crnjaković (1987, 1989). The right column is based on information from SE Mt. Medvednica (dated portions of sedimentary-metamorphic complex, after Đurđanović 1973 and Sremac & Mihajlović-Pavlović 1983; Belak et al. 1995). Note coeval Senonian successions in two columns, compiled from various sources. Tertiary not included. See text for details.

Two scenarios describing possible tectonic evolution and pattern are shown in Fig. 11. In the first (Fig. 11-C1; Zupanič et al. 1981), the ophiolites are a part of the former accretionary wedge, which was overthrust by a continental unit, possibly Tisza microplate. The presence of this continental unit is indicated by a small proportion of continent-derived detritus in the Oštrc sandstones. The overall pattern implies the final closure of the Repno ocean sector (Zupanič et al. 1981). The accretionary wedge, with a neighbouring part of the continental hinterland were transformed into propagating nappes, and the Oštrc basin represented a peripheral foreland basin located in front of the tectonic front. Lower Cretaceous shallow-water sediments located within the area of the Repno fields in central Mt. Medvednica may indicate the formation of a shallow basin carried piggy-back on top of the mélange nappe. The detrital constituents of this sedimentary unit indicate the exposure of ophiolitic, metamorphic, acid magmatic and sedimentary rocks (Crnjaković 1989), i.e., a derivation from both ophiolitic and continental overthrusts (Fig. 11-C1). Hence, the sedimentary evolution of both lower plate and former accretionary wedge was related to and controlled by the same tectonic processes. The Cenomanian-Turonian deformation indicated by unconformable Senonian successions above both the mélange rocks of the Repno suture zone and the sedimentary-metamorphic complex in Mt. Medvednica (Fig. 13) reflects the subsequent tectonic evolution of the nappes and formation of piggy-back basins above the nappes.

An alternative scenario includes thrusting of oceanic crustal material over the Adria plate margin, a still existing oceanic realm, and continuation of subduction/accretion processes on the "eastern" side of the ocean (Fig. 11-C2). In this scenario, the continental detritus in the Oštrc Fm. derived from an overthrust fragment of the lower plate, which otherwise provided detritus of the Jurassic pelagic limestones found in the Oštrc sediments, and was located in front of the ophiolite nappe (Zupanič et al. 1981). The Lower Cretaceous shallow-water sediments of central Mt. Medvednica (Crnjaković 1989) would reflect the formation of a shallow basin carried on top of the accretionary wedge (Fig. 11-C2). The Cenomanian-Turonian deformation indicated by unconformable Senonian successions above both the mélange rocks and the sedimentary-metamorphic complex in Mt. Medvednica (Fig. 13) may reflect the final closure of the Repno ocean domain during the Cenomanian-Turonian time, followed by formation of piggy-back basins above the nappes. Instead, an Eocene age for the latest accretionary processes and mélange formation, followed by the final ocean closure, have been proposed by Tomljenović (1995) and Pamić (1997), based on the Lower Cretaceous and Senonian-Palaeocene sediments locally found as fault-bounded units inside the area of the Repno Complex in Mt. Medvednica (Šikić 1995).

The first scenario is favoured here for the following reasons:

(a) Palynological data indicating Early Jurassic to Bajocian ages for the mélange matrix and the absence of any younger ages.
(b) The approximately coeval, Early Cretaceous formation of the turbiditic Oštrc basin located on the Adria plate, and the shallow-water basin located on the Repno Complex, both receiving ophiolitic and continental detritus (Fig. 11–C1).
(c) Cretaceous to Paleocene sediments inside the area of the Repno Complex in central Mt. Medvednica may represent relics of the sedimentary cover units post-dating suturing. So far, the structural relationship between the Repno Com-

plex and the Lower Cretaceous Oštrc Fm. in Mt. Ivanščica is not clear. However, it may have resulted from several Tertiary deformations of a Repno nappe over the sediments of the Adria domain.

The fundamental changes in the Repno oceanic domain, reflected in the formation of the Lower Cretaceous Oštrc basin and the ophiolite overthrust, are coeval with the plate tectonic reorganisation in the western Tethys between the end of the Jurassic and the Early Cretaceous (e.g. Dercourt et al. 1993). These changes included final closure of the Meliata ocean in the Oxfordian (Channell & Kozur 1997), final closure of the CDOZ sector in the latest Tithonian (Blanchet 1977; Robertson & Karamata 1994), possible pre-Barremian final closure of the Mirdita domain (Bortolotti et al. 1996), and partial closure of both, the Pindos domain (Jones & Robertson 1991) and the Vardar ocean (Channell & Kozur 1997). Although poorly understood, the structural position of the Repno Complex generally conforms with that of the CDOZ in their juxtaposition to the Adria plate. The evolution of these two areas seems to be related, and their former oceanic connection is probable. Figure 12 depicts the possible evolution that lead to the closure of this mutual oceanic belt, integrating the Meliata, Repno and CDOZ domains.

5. Conclusions

Our work confirms that the chaotic Repno Complex, outcropping in the Inner Dinarides of NW Croatia, is an ophiolitic mélange in the sense of Gansser (1974). It is comparable to chaotic units typical for convergent-plate margins characterised by the specific accumulation and shearing of different types of sedimentary and ophiolitic rocks.

Palynological data indicate that the fine-grained sediments now representing the dark shaly matrix of the ophiolitic mélange, were deposited during Early Jurassic to Bajocian times. These shales are uniform in their palynofacies and composition of palynomorph assemblages, which indicate marine conditions and strong terrigenous influence. Shales from widely dispersed sites represent the same depositional setting. A continental unit of "eastern" affinities is suggested as the source area for the dark shales and sandstones.

The preservation of various mélange components depends on their rheological behaviour during subduction-accretion. The fine-grained terrigenous sediments, now represented by the dark shaly matrix, were the soft, mobile components; other components, including Triassic and Jurassic bedded cherts, red shales and ophiolitic rocks, behaved as relatively stiff bodies.

The subduction processes and formation of the Repno Complex developed between the Middle Jurassic and the Hauterivian. The Repno ocean segment presumably closed before the Barremian.

We suggest that the Meliata, Repno and Central Dinaric oceanic domains are parts of a single ocean belt neighbouring the Adria's eastern margin.

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Appendix

Geographic co-ordinates of the studied samples from the Repno Complex. Essential information on these occurrences from Halamić 1998 (a); Halamić et al. 1999 (b); Babić & Zupanič 1978 (c); Babić et al. 1979 (d); Halamić & Goričan 1995 (e). cgls: conglomerates.

1) x=5083930, y=5569330 Poljanica Unit, "debris-flow cgls" (a,b).
2) x=5083820, y=5569445 Poljanica Unit, 1.7 m thick intercalation of "debris-flow cgls" in radiolarite succession, shown in log "Poljanica A" (a,b).
3) x=5083820, y=5569445 As for sample 2 (a,b).
4) x=5083520, y=5569790 Markov Travnik Unit, "debris-flow cgls", disconformably overlie radiolarites of Poljanica Unit, outcrop "PC50" (a,b), Fig. 61 (a).
5) x=5083710, y=5569750 Poljanica Unit, "debris-flow cgls" at the base of the succession shown in log "Poljanica C" (a,b).
6) x=5083710, y=5569750 Poljanica Unit, chert/shale alternation in the lower part of the succession shown in log "Poljanica C" (a,b).
7) x=5083960, y=5569780 Poljanica Unit, "debris-flow cgls" (a).
8) x=5085415, y=5570695 Poljanica Unit, "debris-flow cgls" (a,b).
9) x=5085395, y=5570705 Poljanica Unit, "debris-flow cgls" (a,b).
10) x=5086240, y=5573270 Markov Travnik Unit, "debris-flow cgls" (a).
11) x=5086240, y=5573270 Markov Travnik Unit, "debris-flow cgls" (a).
12) x=5087000, y=5574400 Kraljev Vrh Unit, "debris-flow cgls" intercalated in volcanic succession (a).
13) x=5113750, y=5582375 Repno Complex, ophiolitic mélange (c,d). Stop 3, Fig. 4 in (c). Markov Travnik Unit, "debris-flow cgls" (a).
14) x=5113385, y=5585035 Repno Complex, ophiolitic mélange (d).
15) x=5113375, y=5585050 Repno Complex, ophiolitic mélange (d).
16) x=5111745, y=5609275 Kestenik Unit, shale with sandy interlaminae (a,e).
17) x=5113055, y=5611370 Kestenik Unit, shale with sandy interlaminae (a,e). Middle part of the road on the eastern side of the Hruškovec quarry.
18) x=5112840, y=5611635 Kestenik Unit, shale with sandy interlaminae (a,e). Uppermost part of the road in the eastern side of Hruškovec quarry.
19) x=5111900, y=6384765 Poljanica Unit?, "debris-flow cgls" (a).