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Stratigraphy and Palaeogeography of Miocene Deposits from the Marginal Area of Žumberak Mt. and the Samoborsko Gorje Mts. (Northwestern Croatia)

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Abstract

Miocene sediments rimming the Palaeozoic–Mesozoic–Palaeogene rocks, form Žumberak Mt. and the Samoborsko Gorje Mts. Spatial analysis of the setting and development of the surface Miocene stratigraphy, at the marginal areas of the Žumberak and Samoborsko Gorje Mts., allows four palaeogeographic areas to be distinguished: Žumberak, Plešivica–Sveta Jana, Samobor–Sveta Nedelja and Grdanjci. In the Miocene deposits (totaling 350 m), within the area of Žumberak, coarse-grained clastics from deltaic deposits of Pannonian age prevail. Here only, 50 m of sediments of Pliocene–Pleistocene age overlie the Miocene deposits whereas Mesozoic carbonates represent the basement. The Plešivica–Sveta Jana area is characterized by a 600 m sequence of Miocene deposits, mainly overlying Triassic dolomites, where finely-grained layers of marls and silts prevail. In this area, Miocene successions from the Badenian to the Pontian are characterized by a continuity of sedimentation with an inherited depositional environment. In the area of Samobor–Sveta Nedelja, the basement is diverse: Triassic dolomites, volcanogenic–sedimentary complex of Cretaceous age and a clastic–carbonate complex of Palaeogene age. The Miocene succession shows a regressive trend from the Badenian to the Pontian and the total thickness is estimated at 400 m. The area of Grdanjci differs considerably from the other Miocene palaeorelief. An approximately 50 m-thick series of coarse-grained clastics with coal is distinguished, of unclear stratigraphic age (Ottnangian?). Miocene sediments of the Grdanjci area are represented by both a transgressive type of conglomerates and shallow water limestones of Badenian age, with a total thickness of about 100 m.

The development of the Miocene stratigraphy of the Žumberak and Samoborsko Gorje Mts. is generally correlative with that in the other parts of the Pannonian area, though it does exhibit local variations. Comparison of the Miocene palaeorelief of Žumberak Mt. with the Samoborsko Gorje Mts., together with neighbouring areas, enabled wider correlation with other parts of northern Croatia, and the more distant Western and Central Paratethys.

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1. INTRODUCTION

Investigated area is located approximately 10–50 km SW of Zagreb, comprising the Miocene surface terrains of the southeastern slopes of Žumberak Mt. and the northeastern slopes of the Samoborsko Gorje Mts. (Figs. 1 and 2). These terrains are the main objects of interest, covering about 150 km^2, starting from Ozalj, Krašić and St. Jana in the south, along the southeastern slopes of Plešivica Mt., across to Svetonedeljski Breg, and the region surrounding Samobor (Figs. 1 and 2).

For comparison with neighbouring areas, the closest Miocene deposits of the Draganići structure and the southwestern part of Medvednica Mt. were used, along with those in the Karlovac–2 deep exploratory well (Figs. 1, 2 and 5).

From a palaeogeographic point of view, the study area belongs to the marginal area of the southwestern part of the Pannonian Basin (and the south-western part of Central Paratethys – Fig. 1). This position conditioned the specific evolution of the depositional area during the Miocene. Miocene sediments are most commonly in tectonic contact with Mesozoic carbonates while less often with Palaeogene rocks which constitute a major part of the core of Žumberak Mt. and the Samoborsko Gorje Mts. (ŠIKIĆ & BASCH, 1975; ŠIKIĆ et al., 1978). Towards the northeast, this area borders the Sava depression (Figs. 1 and 2). There are different types of relationships between the Miocene basins of the Žumberak Mt. and Samoborsko Gorje Mts. with other sedimentation areas, such as the Karlovac depression, western part of the Sava depression, and the basins of Hrvatsko Zagorje. During the Miocene, along the marginal faults (of NW–SE strike) and some younger transverse strike-slip faults (of NW–SE strike) "positive and negative structures" were formed that led to the observed lateral and vertical distribution of the depositional environments (ŠIKIĆ & BASCH, 1975). Synsedimentary tectonic movements conditioned the migration of depositional environments and facies, which is most pronounced in the frequent lateral and vertical changes of Miocene clastic and carbonate series (similar to concept of MAGYAR et al., 1999; Figs. 4 and 5).

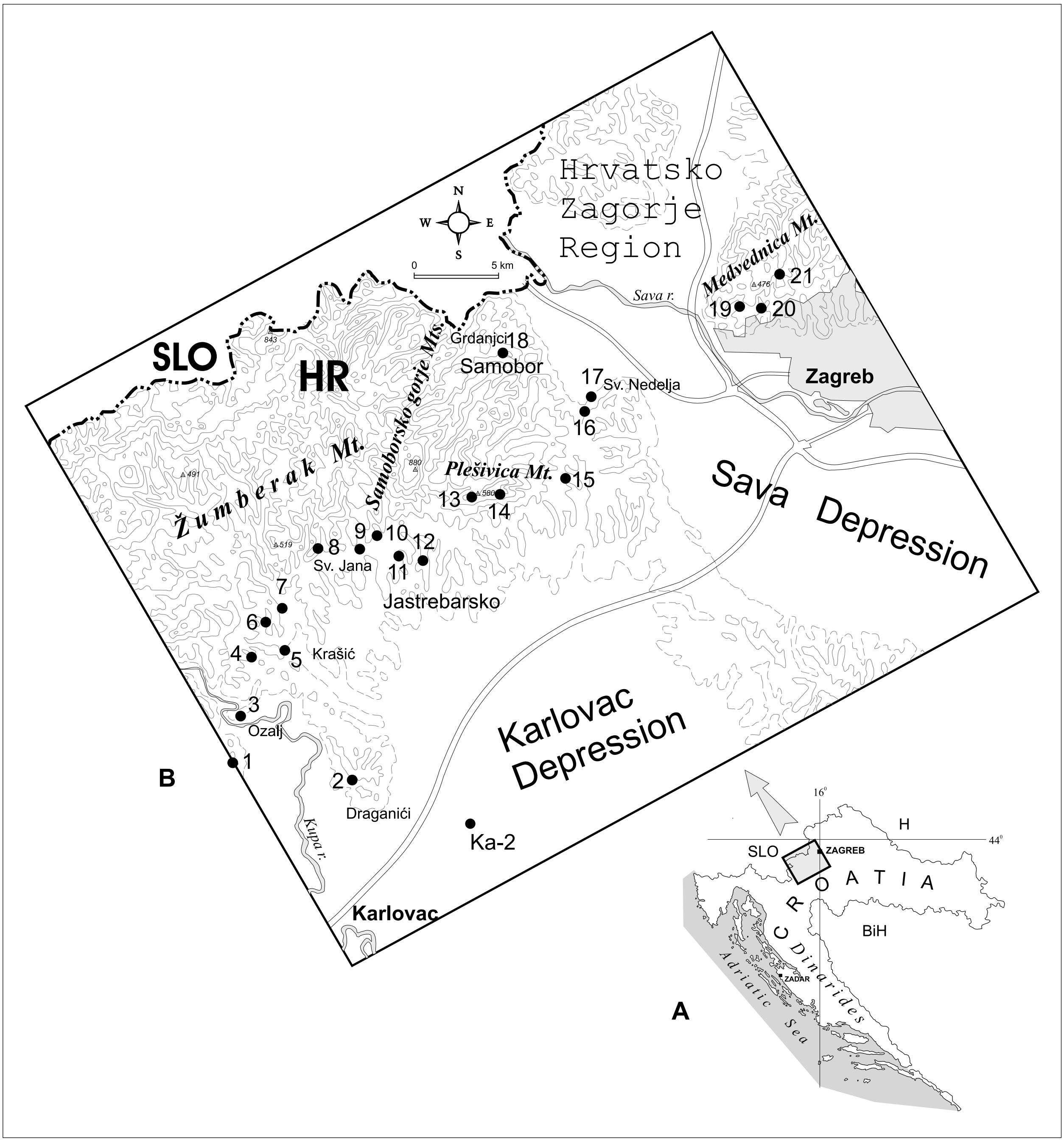

Fig. 1 Location map: A) Position of the study area within Croatia; B) Study area with main geological columns: 1 – Slapno; 2 – Draganići (= Draganići structure); 3 – Ozalj; 4 – Krnežići; 5 – Krašić; 6 – Hrženik; 7 – Kučeri; 8 – Dol (= Žumberak); 9 – Toplica–2; 10 – Toplica–1; 11 – Miladini; 12 – Malunje; 13 – Jurjevčani–2; 14 – Jurjevčani–1; 15 – Podgrađe Podokićko; 16 – Kladje–1; 17 – Kladje–2–3; 18 – Vrhovčak (= Samoborsko Gorje Mt.); 19 – Podsusedsko Dolje; 20 – Kostanjek; 21 – Bizek (= SW part of Medvednica Mt.); Ka–2 – Karlovac–2 well (= Karlovac depression).

The main method used in exploration was reconstruction of the Miocene palaeogeography using palaeontological and petrographic analyses of the sedimentary successions, and geological mapping of the area.

There are relatively few papers published regarding the Miocene deposits of the Žumberak and Samoborsko Gorje Mts. GORJANOVIĆ-KRAMBERGER (1894) first detailed the entire geology of the Miocene. ŠUKLJE (1929) investigated the “Mediterranean deposits” in more detail (the term is from GORJANOVIĆ-KRAMBERGER, 1894), describing the rich community of molluscs from Zaprešić Brijeg in the Samoborsko Gorje Mts. PAVLOVSKY (1957, 1960) determined new elements of the molluscan fauna from the same locality, comparing these deposits with “Grund’s layers” of Tortonian (Badennian) age in the Vienna Basin. BAJRAKTAREVIĆ (1978), determined the Late Tortonian (Late Badenian) age of sediments from Zaprešić Brijeg locality on the basis of the foraminiferal community. After years of exploration, including part of the

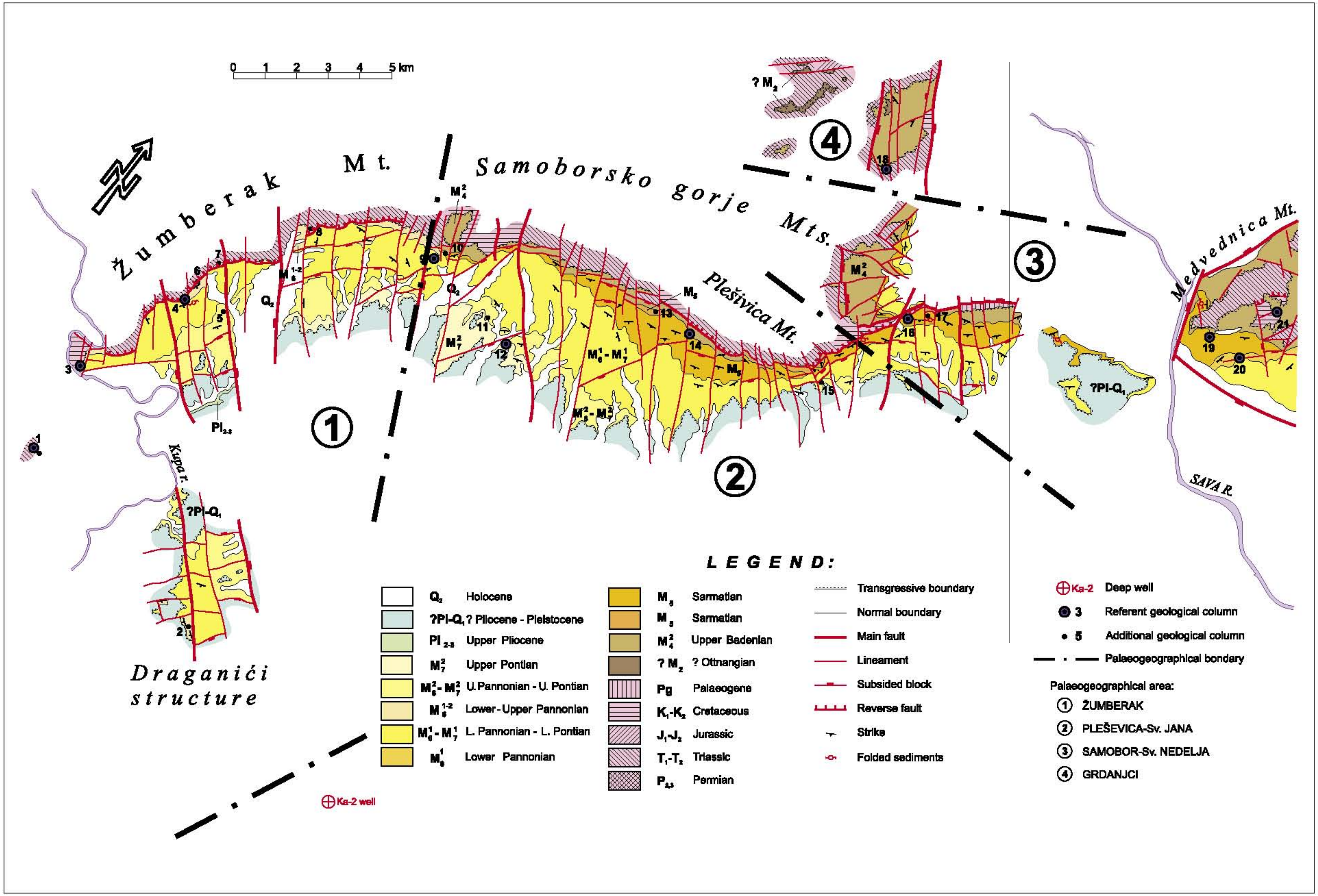

Fig. 2 Geological map of Miocene deposits of Žumberak Mt., the Samoborska gora Mts. and the SW part of Medvednica Mt. (modified according to ŠIKIĆ et. al., 1979; BASCH, 1995; VRSALJKO, 2003).

area of Žumberak Mt. and the Samoborsko Gorje Mts., ŠIKIĆ et al. (1978, 1979), published a general geological map, giving an overview of events from the Palaeozoic to the Quaternary. BAJRAKTAREVIĆ (1980) investigated the micropalaeontology of the Samoborsko Gorje Mts., and documented the existence of Badenian sediments at more localities. VELIĆ (1983) provided a new contribution to the Neotectonic relationships and development of this area during the Miocene, based on geological, geophysical and geomorphological investigations of the western part of the Sava depression. PIKIJA et al. (1984) explored the Miocene deposits of Jurjevčani (southeast slopes of the Plešivica Mt.; Fig. 2) in detail, together with examining the hydrocarbon potential of the wider area of Žumberak Mt., providing detailed lithological and stratigraphic descriptions of Miocene outcrops. PIKIJA et al. (1989) investigated "biolithitic and adjacent carbonate facies of the Sarmatian" of the Ozalj–Krašić area. TOMLJENOVIĆ & CSONTOS (2001) investigated Neogene–Quaternary structures of the Žumberak Mt. slopes and the Karlovac Basin itself, on the basis of geophysical and other data, whereas TOMLJENOVIĆ (2002) gave a detailed outlook on the geodynamic development of smaller individual Neogene basins in the region of the Medvednica and Samoborsko Gorje Mts. VRSALJKO (2003) within the frame of the project "Geological Map of the Republic of Croatia, 1:50,000" studied the Miocene sedimentary rocks in detail, and on the basis of a rich molluscan community from Žumberak Mt. and the Samoborsko Gorje Mts., suggested the zonal distribution of Miocene sediments.

2. RESULTS

2.1. Stratigraphy of Žumberak Mt. and the Samoborsko gorje Mts.

A number of localities with numerous outcrops were taken into consideration and geological columns were made from the south towards the north: Draganići, Slapno, Ozalj, Krnežići, Krašić, Hrženik, Kučeri, Dol, Toplica, Miladini, Malunje, Jurjevčani, Podgrađe Podokićko, Kladje and Vrhovčak (Fig. 2). The petrographic and palaeontological composition of sediments has also been analyzed. The spatial distribution of individual Miocene units, together with their relationship to basal and overlying strata is presented on a geological map (Fig. 2). Four Miocene palaeogeographic areas are singled out (Fig. 4): (1) Žumberak, (2) Plešivica–Sveta Jana, (3) Samobor–Sveta Nedelja, and (4) Grdanjci.

2.1.1. Žumberak

2.1.1.1. The Miocene basement

The Miocene basement consists of Triassic dolomites and Cretaceous limestones and clastics (Fig. 2). Dolomites are strongly tectonized as shown in the abandoned Slapno quarry. In the Ozalj area (Fig. 2) the basement is composed of Cretaceous–Palaeogene carbonates and flysch deposits (ŠIKIĆ et al., 1978, 1979; HERAK, 1986).

2.1.1.2. Sarmatian

Oldest Miocene horizons transgressively overlie the carbonate–flysch Cretaceous basement and are of Sarmatian age (Figs. 2, 4 and 8). Between the basement and overlying Pannonian clastics, 1–5 m thick clinoform bodies of matrix-supported breccia–conglomerates are found, with recurrent blocks of limestones up to 1 m thick. Coarse-grained clastics were most probably deposited from gravity flows on the very steep slope (VRSALJKO, 2003; VRSALJKO et al., 2003). Near the Krašić locality, biolithitic rocks of Sarmatian age were found, lying directly on pre-Miocene basement which consists of Triassic dolomites (PIKIJA et al., 1989). The Sarmatian age is proven by molluscs (*Pirenella picta* and *Modiolus incrassatus*) which occur among the bioclastic grains and within the sandy matrix of deposits originating in marine environment of reduced salinity (VRSALJKO, 2003; VRSALJKO et al., 2003).

2.1.1.3. Pannonian

Pannonian sediments transgressively overlie the Sarmatian deposits (Figs. 2, 4, 9 and 10). At Slapno, these are represented by silts and silty marls with coal-rich clastics, whereas by Ozalj these are calcarenites (Figs. 2, 4 and 9). Rare ostracods (*Hungarocypris auriculata, Hemicytheria reticulate* and others), determined from this level, indicate an Early Pannonian age (VRSALJKO et al., 2003). Conglomerates of proximal deltaic environments, and/or sandy–silty marls of a lacustrine sublittoral, i.e. of prodeltaic environment (Ozalj/Slapno; Figs. 2, 4 and 10), follow in the succession. The molluscan community found in marls (*Congeria partschi, C. zsygmundi, C. pancici* and *Lymnocardium* sp.) indicates a Late Pannonian age (VRSALJKO, 2003; VRSALJKO et al., 2003). The conglomerates are succeeded by calcarenites with a mixed fluvio–lacustrine community of molluscs (assemblage: *Theodoxus–Congeria–Melanopsidae–Lymnocardiidae*; VRSALJKO, 2003; locality Krnežići, Figs. 2 and 4). Similar deposits with an analogous community of molluscs were described from the Vienna Basin by PAPP (1953). In the sandstones an *in situ* mollusc community, indicates the youngest Late Pannonian level.

2.1.1.4. Pontian

Lower Pontian sediments were determined in the vicinity of Krašić (Figs. 2 and 11) based on *Paradacna abichi* found in silty marls (VRSALJKO, 2003).

Late Pontian communities of molluscs in which congerias and limnocardiidae dominate (*Congeria rhomboidea, C. croatica, Lymnocardium mayeri* and others) were recently discovered by investigations in the vicinity of Petrovina (southeast from Krašić; Figs. 2 and 11) where sediments are predominantly sands and silts (VRSALJKO, 2003).

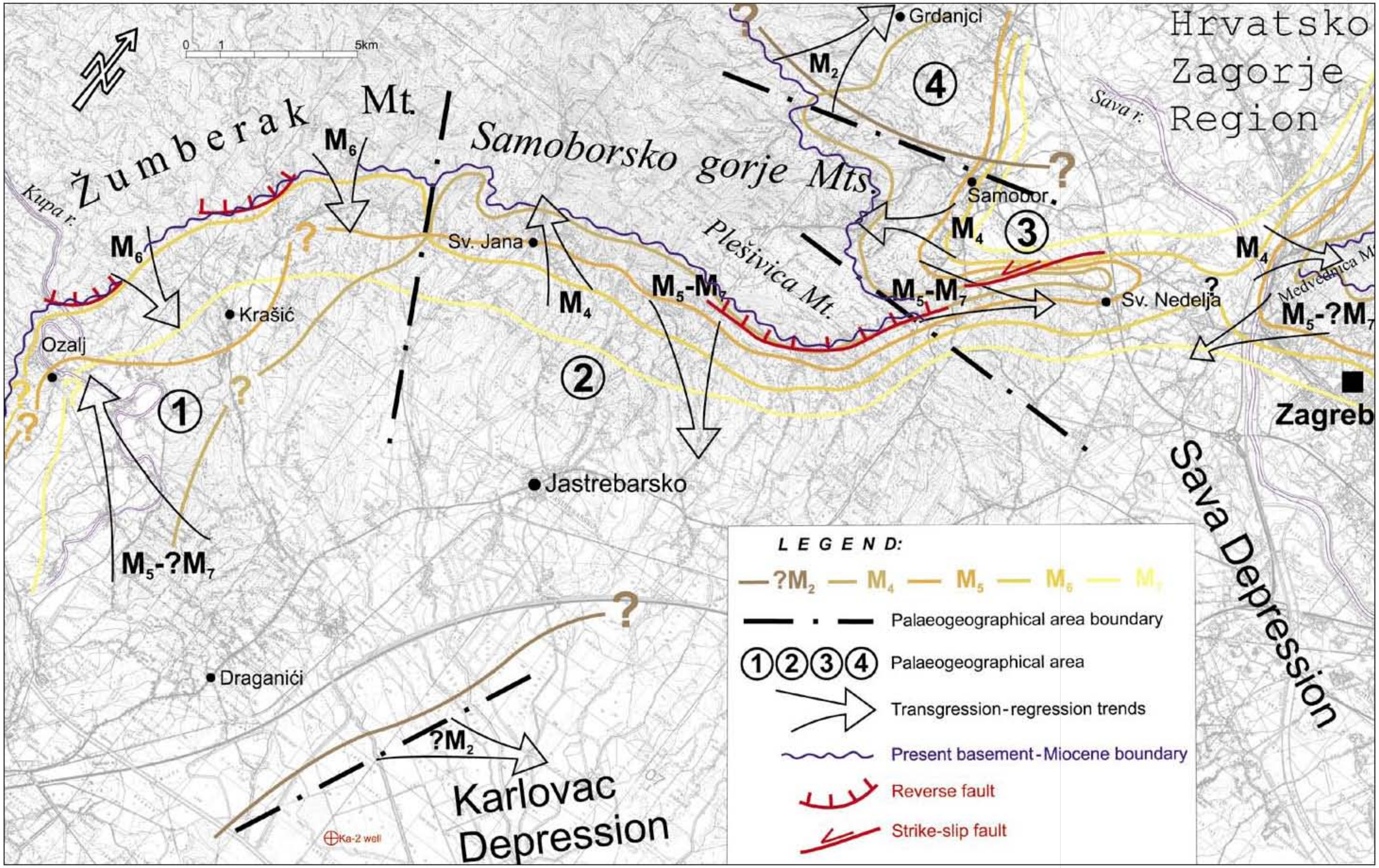

Fig. 3 Palaeogeographic map of Žumberak Mt. and the SW part of Medvednica Mt. (from VRSALJKO, 2003).

2.1.1.5. Pliocene and Pleistocene

The sediments of Pontian age are most often overlain by Pliocene–Pleistocene deposits, clays and gravels with coal intercalations. In the vicinity of Brezarić (south of Krašić; Figs. 2 and 4), coal layers were discovered containing a community of freshwater gastropods (*Melanopsidae*) determining the Pliocene age (VRSALJKO, 2003).

2.1.2. Plešivica–Sveta Jana

2.1.2.1. The Miocene basement

The basement deposits are mainly represented by Triassic dolomites, whereas in the area of Toplice, the pre-Miocene rocks are Cretaceous limestones (Fig. 2). At Plešivica Mt., the current structural setting of the Triassic complex indicates that it is partly reversely uplifted onto Miocene deposits (Badenian and Sarmatian; see Figs. 2 and 3).

2.1.2.2. Upper Badenian

Badenian sediments are most clearly observed in the wider area of Jurjevčani (southeastern slopes of Plešivica Mt.; Figs. 2 and 7). The lowest parts of the Badenian are represented by marine shallow water conglomerates and algal limestones on which the deep-water marls were deposited. A Badenian age is proven by the abundant macrofauna (*Corbula*, *Nucula*, *Pecten*, etc.) The uppermost part of the Badenian deposits is characterized by horizontal lamination in marls and clays with lesser proportions of biogenic components (Fig. 4).

2.1.2.3. Sarmatian

Sarmatian layers are conformable on the Badenian with no visible traces of any lithological discontinuity. Foraminifera, ostracod and mollusc (*Ervilia, Musculus, Modiolus, Cardidae* and others) communities define the Badenian–Sarmatian biostratigraphic boundary, and the transition from an open marine environment towards a basin with reduced salinity (VRSALJKO, 2003).

The Lower Sarmatian is mainly composed of marls and clays, with sporadic, cm-thick intercalations of calcarenites and conglomeratic sandstones. The middle parts of the Sarmatian are characterized by the presence of varve-like laminated marls and clays, with scarce intercalations of sandstones which could have been deposited from turbidity currents (Fig. 4). Rhytmites composed of laminites, limestones and sandstones comprise the upper parts of the Sarmatian, while in the uppermost ten metres layers of marls and clays dominate, varying in thickness from millimetres to centimetres.

2.1.2.4. Pannonian

The Lower Pannonian layers, known as the "Croatica limestones" are not developed in this area, possibly because the depositional environment was deeper at that time (Figs. 2 and 9). Rare forms of brackish ostracods are the only basis for suggesting an Early Pannonian age. These occur in the approximately 20 m thick lacustrine marl facies from deeper (sublittoral) waters. The boundary with the underlying Sarmatian layers is conformable with the inherited depositional environments (Figs. 4 and 8).

Upper Pannonian layers are most often developed in the marls, silts and sands facies, which is dominated by massive marls. The marls are poorly fossiliferous and well bioturbated. In the middle and upper part of the Upper Pannonian sequence (approximately 200 m total thickness, Fig. 4) conglomerates of lens-like geometry occur within the marls (region of Toplice and Sveta Jana; Figs. 2 and 10). These are probably a consequence of a fluvial influx of terrestrial material from the immediate hinterland into the deeper lacustrine environment.

2.1.2.5. Pontian

Pontian deposits are approximately 130 m thick (Fig. 4). Lower Pontian sediments are represented by massive marls and occasionally silts, as an extension of the Pannonian sedimentation cycle. The age is inferred from a scarce brackish community of ostracods (VRSALJKO, 2003). The significant occurrence of sands and silts indicates that the Late Pontian was characterized by variable depositional environments from a lacustrine basin into a deltaic environments (Figs. 4 and 11). In the uppermost parts of the Pontian sands a recognizable community of molluscs prevail (coarse *Congeria* and Lymnocardiidae – VRSALJKO, 2003).

2.1.2.6. Pliocene and Pleistocene

The Pontian and frequently the Pannonian layers are covered by mostly gravels and clays, which are of uncertain stratigraphic position, and could be of Pliocene and/or Pleistocene age (Figs. 2 and 4). The upper boundary between the Miocene layers and their overlying strata is unconformable, i.e. erosional.

2.1.3. Samobor–Sveta Nedelja

2.1.3.1. The Miocene basement

Miocene basement rock types are very variable in Samobor–Sveta Nedelja area. Triassic dolomites are the most common, but there are localities where the basement is composed of volcanogenic–sedimentary complexes of Cretaceous age, or Palaeogene limestones and clastics (Kladje and Svetonedeljski Breg localities; Fig. 2). The Cretaceous and Palaeogene basement is uplifted along the "Zagreb–Balaton" fault, which explains how these rocks most probably came to the surface forming land areas during Miocene times (ŠIKIĆ & BASCH, 1975; TOMLJENOVIĆ & CSONTOS, 2001). *Lithophaga* sp. in basement rocks provides evidence for the existence of the Badenian coastline (e.g. Svetonedeljski Breg locality; Figs. 2 and 7).

2.1.3.2. Upper Badenian

The oldest Miocene sediments in this area are of Badenian age (Fig. 2). Algal limestones were most com-

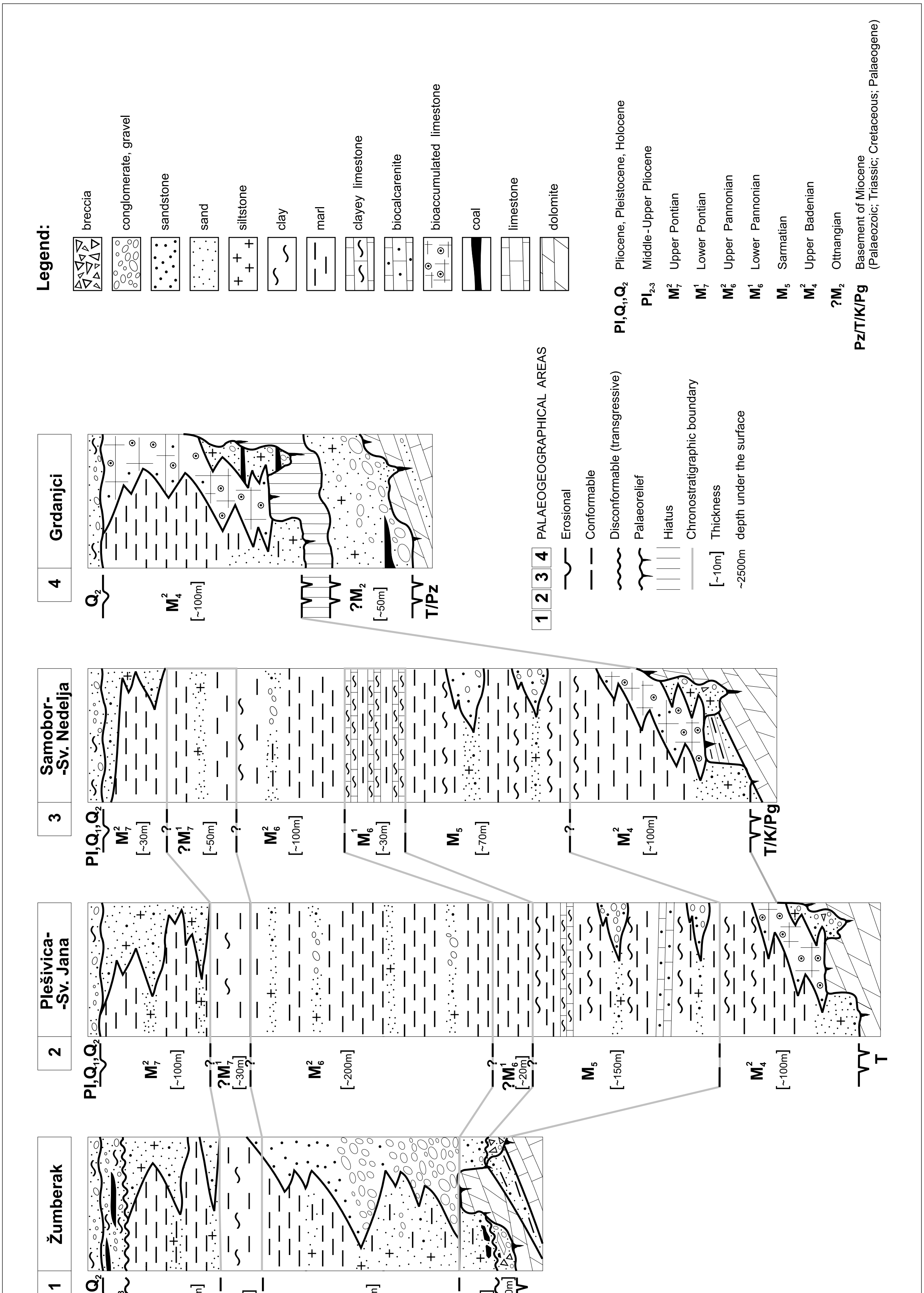

Fig. 4 Lithostratigraphic columns of palaeogeographic areas of Žumberak Mt. and the Samoborsko Gorje Mts.: (1) Žumberak; (2) Plešivica–Sveta Jana; (3) Samobor–Sveta Nedelja; (4) Grdanjci.

monly the first deposits on the older palaeorelief, followed both laterally and vertically by silty marls (Fig. 7). The limestones contain numerous organisms (including algae, bryozoa, molluscs, and foraminifera) which define the shallow marine environment. Marls contain an abundant mollusc community (including *Pecten*, *Nucula*, *Macoma*, *Tellina* etc.), which characterize the deep-water sediments (VRSALJKO, 2003). The uppermost part is represented by laminated marls with cm-thick laminae and a sparse fossil community. Considerable deepening of the area during the Badenian probably led to deposition of a thicker sequence of marls (Fig. 4).

2.1.3.3. Sarmatian

Sedimentation continued conformably on Badenian deposits in reduced salinity environments (PIKIJA et al., 1984). The boundary between the two stages can only be defined biostratigraphically, on the basis of foraminifera and molluscs (VRSALJKO, 2003). In the area of Svetonedeljski Breg, well developed Sarmatian sediments can be found, dominated by distinctly laminated marls. Occasionally, especially in the lower part of the Sarmatian deposits, metre-thick sand beds occur which are probably deposited from gravity flows (Figs. 4 and 8). Sandstones consist of biogenic detritus, mainly redeposited from Badenian rocks. The total thickness of Sarmatian deposits is approximately 70 m.

2.1.3.4. Pannonian

In the Samobor–Sveta Nedelja area, Lower and Upper Pannonian layers can be distinguished (Fig. 4). Lower Pannonian deposits are approximately 30 m thick, and are represented by clayey limestones and marls where hard limestones, with a poor shallow-lacustrine community of molluscs dominate (radices, planorbises, valvatae and limnocardii). Limestones, known as “Croatica beds” (JENKO, 1944), continually and conformably overlie Sarmatian marls and are to be found northwest of Svetonedeljski Breg (around Rakovica, south of Samobor; Figs. 2 and 9).

The Late Pannonian sub-stage is represented by ~100 m of sediments where massive marls dominate (Figs. 4 and 10). Occasionally, intercalations of decimetre-size gravel occur. A community of tiny brackish molluscs from a deeper lacustrine environment is defined in the marls (congeriae and limnocardii; similar to MÜLLER et al., 1999). The boundary between Lower and Upper Pannonian deposits is marked by a gradual transition from limestone to calcite-rich marl with a considerably different fossil content (Fig. 4).

2.1.3.5. Pontian

Scarce outcrops of Pontian age only occur in the surroundings of Rakovica and Molvice (south of Samobor; Figs. 2 and 11), and their estimated thickness is ~80 m. The Lower Pontian rocks are mainly massive, bioturbated silty marls with tiny molluscs (limnocardii and congeriae), while sands and silts, together with a community of thick-shelled molluscs (congeriae), conformably follow, indicating a Late Pontian age (Fig. 4).

2.1.3.6. Pliocene and Pleistocene

Miocene deposits are mainly covered with younger sediments, possibly of Pliocene–Pleistocene age (Figs. 2 and 4). The uppermost ones consist of gravels, clays, and reddish silts which are probably the sediments of fluvial and lacustrine environments.

2.1.4. Grdanjci

2.1.4.1. The Miocene basement

The Miocene basement deposits of Grdanjci (west of Samobor; Figs. 2 and 6) consist of rocks previously dated as Palaeozoic, while ŠIKIĆ et al. (1978, 1979) determined them as being of Mesozoic age (mostly Triassic). The specific feature of this area is the lack of Sarmatian, Pannonian and Pontian sediments (Figs. 2 and 4).

2.1.4.2. Ottnangian?

The oldest Miocene deposits unconformably overlie the basement (ŠIKIĆ et al., 1978, 1979). By stratigraphic correlation with very similar deposits (gravels, sands, silts and coal) occurring in North Croatia, they are defined as fresh-water “Helvetic”, meaning they could belong to the Ottnangian. The assumed thickness of these sediments is about 50 m.

2.1.4.3. Upper Badenian

The contact of the Badenian with older clastic sediments (?Ottnangian) has not been observed. Gravels, silts, and coal intercalations comprise the lower parts (ŠIKIĆ et al., 1979). This package of deposits probably represents the products of terrestrial deposition immediately before the Late Badenian transgression (Figs. 4 and 7). They are overlain by silts and sands rich in malacofauna, defining them as “Tortonian” (ŠUKLJE, 1929; PAVLOVSKY, 1957, 1960; BAJRAKTAREVIĆ, 1978), i.e. of Badenian age. Due to a lack of better outcrops this opinion cannot be proven, i.e. deposits cannot be biostratigraphically investigated in detail. Biogenic limestones from shallow marine environments are the most widespread sediments in the upper parts. These are most clearly visible in the region of Otruševac (southwest of Samobor; Figs. 2 and 7). Predominance of biogenic limestones in the uppermost parts of the column suggest gradual formation of shallows by the end of the Badenian. Badenian sediments are approximately 100 m thick.

2.1.4.4. Holocene

Gravels and clays, are most probably Holocene sediments overlying Miocene deposits, primarily those of Badenian age (Figs. 2 and 4). Sediments of Sarmatian, Pannonian and/or Pontian have not been determined on the surface in the Grdanjci area.

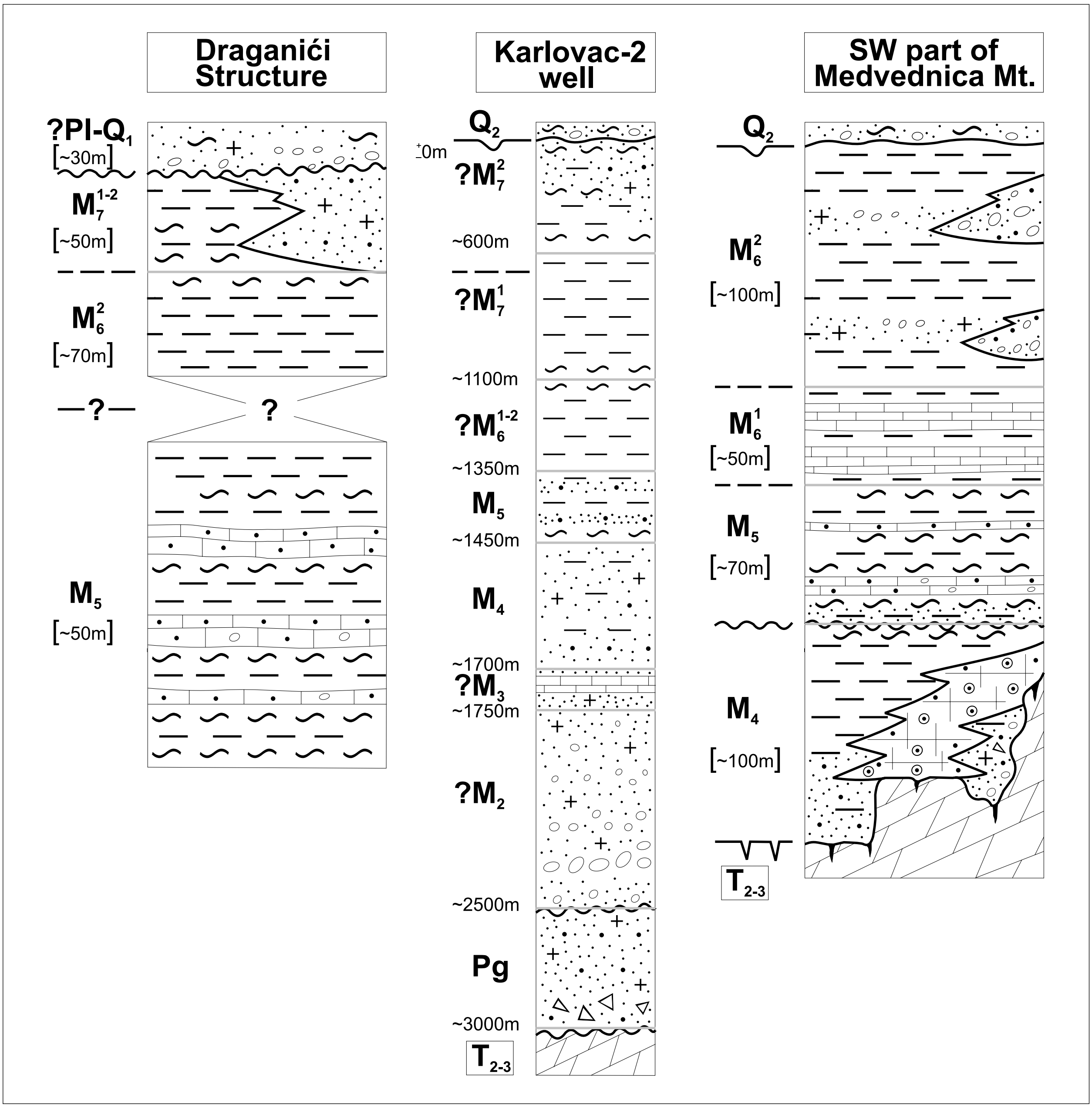

Fig. 5 Lithostratigraphic columns showing Miocene deposits from neighbouring areas – Karlovac–2 well and SW part of Medvednica Mt. For legend see Fig. 4.

2.2. Stratigraphy of neighbouring area

The Miocene deposits of Žumberak Mt. and the Samoborsko Gorje Mts. have been compared to the Draganići structure (~10 km north of Karlovac), the south-western part of Medvednica Mt. (surrounding Podsused), and the Karlovac–2 well (approximately 10 km NE of Karlovac) (Figs. 1 and 2). The terrains and objects mentioned are those closest to the study area; however, each represents a unique individual geological unit (Figs. 1–3 and 5).

2.2.1. The Draganići structure

North-west of Draganići a gently uplifted structure has been observed (Fig. 1). The core consists of Miocene strata and is rimmed with Pliocene–Pleistocene sediments (Fig. 2). Towards the southeast, the Karlovac depression is located with exposed marshland to lacustrine Pleistocene–Holocene sediments.

The oldest Miocene sediments are of Sarmatian age, and are about 50 m thick. Laminated marls and silts dominate, whereas in the lower parts metre-thick intercalations of sandstones occur (Figs. 5 and 8). A sparse community of foraminifera is observed in the marls, but there are no macrofaunal remains (VRSALJKO, 2003). Some beds are heavily disturbed by synsedimentary sliding.

In fault-contact with the Sarmatian deposits, the Pannonian marls have an assumed thickness of ~70 m (Fig. 2). Their age is determined as Late Pannonian, based on

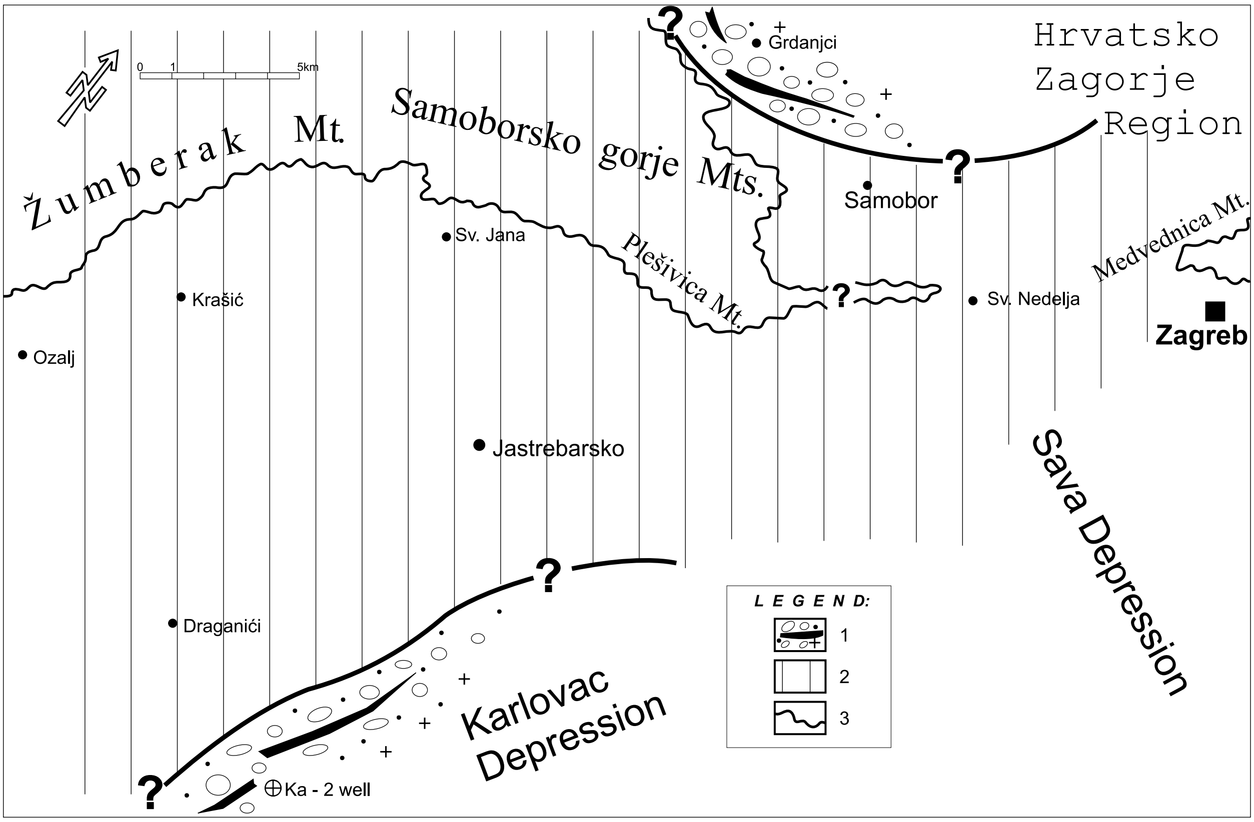

Fig. 6 Palaeogeography during the Early Miocene (?Ottnangian) in the wider area of Žumberak Mt. and the Samoborsko Gorje Mts. Legend: 1 – fresh-water clastics (? fluvial); 2 – pre-Miocene basement; 3 – SW boundary of Miocene outcrops.

a poor ostracod community and rare tiny limnocardids (VRSALJKO, 2003).

The uppermost part of the Miocene sediments consists of silts and sands ~50 m thick (Fig. 5). Coarse congeria shells determine a Pontian age (VRSALJKO, 2003). The transition from Pannonian marls to Pontian silts is most probably gradual (Figs. 10 and 11). Miocene sediments are covered by gravels, sands and clays, probably of Pliocene–Pleistocene age (Figs. 2 and 5).

2.2.2. The Karlovac–2 well

This well is 4145 m deep (Fig. 5) and comparison of the cores with the existing sedimentary column allows some reinterpretation of the stratigraphic sequence. The boundary between Mesozoic carbonates and clastics of Palaeogene in the pre-Miocene basement, and Miocene rocks can be located at approximately 2500 m depth (Fig. 5).

The oldest Miocene sediments are represented by an ~800 m thick series (from about 1750 to 2500 m), represented by the intercalation of conglomerates, siltstones, shales and sandstones (Fig. 5). These sediments when correlated with surface rocks could belong to the fresh-water Ottnangian and not to the "Oligo–Miocene–Egerian" series as previously thought (TOMLJENOVIĆ & CSONTOS, 2001).

Foraminifera determined from limestones at 1734–1738.7 m depth, indicate a Karpatian to Early Badenian age (M. MIKNIĆ, pers. comm. 2005). It is very probable that a common sedimentary basin in the Karlovac depression had already been formed at this time, and the first Miocene, i.e. Karpatian transgression occurred (Figs. 6 and 7).

The core from the upper interval (1641–1645 m) is a silty marl with foraminifera, spiculae and mollusc shells (pectinacea), most likely of Badenian age (VRSALJKO, 2003). Cores from two intervals (1392–1394 m and 1462–1467 m) comprise laminated marls with fish remains which were determined as a feature of surficial Sarmatian sediments at outcrop.

From 1340–1343 m the core is represented by hard marls with ostracods and relics of terrigenous macroflora, and is most probably of Pontian age.

2.2.3. The South-Western part of Medvednica Mt.

The Miocene of the SW part of Medvednica Mt. is largely different from its other parts. According to previously published papers, Neogene development is known as the "Doljanski Miocene", being different from the "Čučerjenski" and "Zelinski" types (KOCHANSKY-DEVIDE, 1944; ŠIKIĆ, 1967, 1968; KRANJEC et al., 1973; KOCHANSKY-DEVIDE & BAJRAKTAREVIĆ, 1981; BASCH, 1983a; VRSALJKO, 1997, 1999).

On the SW part of the Medvednica Mt., the base of Miocene sediments mainly consists of Triassic dolomite with a clearly visible palaeorelief (Figs. 2 and 5).

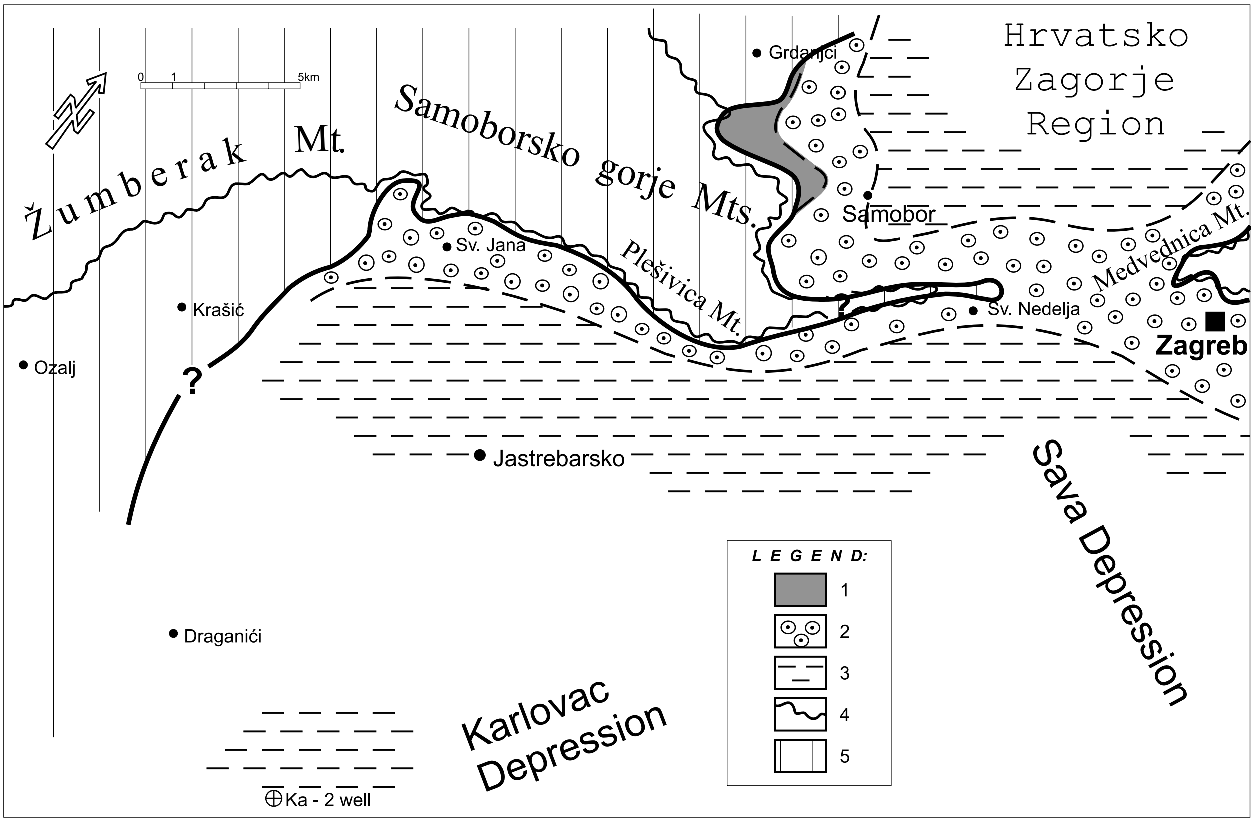

Fig. 7 The palaeogeographic situation during the early Middle Miocene (Badenian) in the wider area of Žumberak Mt. and the Samoborsko Gorje Mts. Legend: 1) "coaly series"; 2) shallow water carbonates; 3) slope to basin deposits; 4) SW boundary of Miocene outcrops; 5) Pre-miocene basement.

Upper Badenian breccias and conglomerates transgressively overlie the basement. The Triassic dolomites are overlain by shallow marine algal limestones (PIKIJA et al., 1995), with lateral and superimposed deposition of shelf and/or lagoonal marls. The uppermost 10 m of the Badenian is characterized by weakly fossiliferous, laminated marls and clays (Fig. 5). The total thickness of the Badenian sediments is about 100 m.

Sarmatian sediments mainly conformably overlie Badenian deposits with no recognized lithological difference. The biostratigraphical boundary can only be defined on the basis of changes in the micro- and macrofaunal communities between the two stages. The transgressive characteristics of the Sarmatian sediments in certain areas are to be expected, e.g. near Podsusedsko Dolje, where the angular unconformity occurs between the Badenian and Sarmatian deposits (Figs. 2 and 5).

Most commonly, shallow water Badenian limestones underlie the Sarmatian clastics, whereas the deepwater marine marls lie beneath the laminated Sarmatian marls, which were deposited in a lower-salinity environment (VRSALJKO, 1999). In the lower and middle parts of the Sarmatian, metre-thick intercalations of coarse-grained clastics are present, whereas in the uppermost parts remarkably well laminated marls dominate (Fig. 5). The thickness of the Sarmatian sediments is approximately 70 m. Lower Pannonian deposits (the "Croatica beds" – JENKO, 1944) are fully developed and are dominated by clayey limestones and marls. The limestones contain numerous ostracods and molluscs suggesting brackish, shallow-lacustrine environments (KRANJEC et al., 1973; VRSALJKO, 1997, 1999). These sediments conformably overlie the Sarmatian marls and clays and are about 50 m thick. The Upper Pannonian "Banatica beds" continuously overlie the Lower Pannonian, with a gradual decrease of carbonate content towards the younger deposits (Fig. 5). Deposits of the Upper Pannonian consist mainly of massive, bioturbated marls with deep-water molluscs and ostracods (VRSALJKO, 1997, 1999). In the central part gravels and sands commonly occur, as reflections of strong floods on the land (Figs. 5 and 10). The uppermost Pannonian sediments are represented by massive marls, which are mainly covered by Pliocene–Pleistocene gravels and clays. The thickness of the Upper Pannonian beds is estimated at approximately 100 m.

2.3. Comparison of the Miocene stratigraphy of Žumberak Mt. and the Samoborsko Gorje Mts.

Even though the Miocene stratigraphy of Žumberak Mt. and the Samoborsko Gorje Mts. occupies a relatively small area, characterized by expected similarities in development, there are also some differences. These mainly relate to the thicknesses of the Miocene deposits; not only to the total thickness, but also the thickness

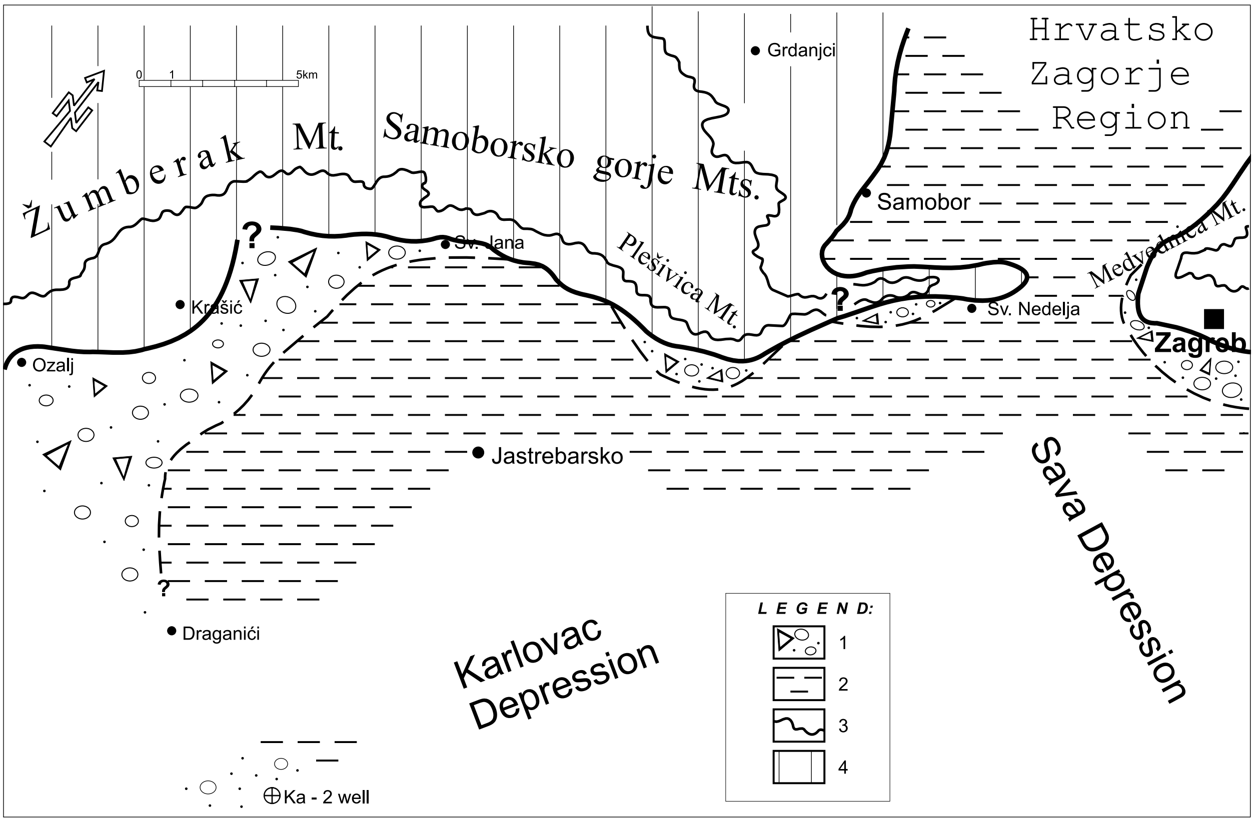

Fig. 8 Palaeogeography during the late Middle Miocene (Sarmatian) in the wider area of Žumberak Mt. and the Samoborsko Gorje Mts. Legend: 1) littoral clastic rocks; 2) basin deposits; 3) SW boundary of Miocene outcrops; 4) Pre-Miocene basement.

of individual stages of sedimentation. For example, the maximum thickness of Miocene deposits is found at Plešivica–Sv. Jana (>600 m; Fig. 4), whereas the minimum occurs at Grdanjci (~150 m; Fig. 4).

In the Grdanjci unit, clastic sediments have been found which could belong to the Ottnangian, as well as coaly silts and biogenic limestones of most probably Late Badenian age (near Otruševec – BAJRAKTAREVIĆ, 1978, 1980; VRSALJKO, 2003; Figs. 2 and 7). These are special features of this unit as such sediments are not present in other units of Žumberak Mt. and the Samoborsko Gorje Mts. In the palaeogeographic area of Grdanjci, Sarmatian and Upper Miocene sediments are not developed (Fig. 2).

Additionally, the transition from the Sarmatian towards the Pannonian is marked by the development of different environments across the wider areas of Žumberak Mt. and the Samoborsko Gorje Mts. (Figs. 2, 8 and 9). While the palaeogeographical area of Plešivica–Sv. Jana remained within a relatively deeper (sublittoral) environment during the Early Pannonian, shallow-water (littoral) environments formed within the area of Samobor–Sv. Nedelja (Figs. 9 and 10). At the same time, in the area of Žumberak land existed, which afterward served as the source of clastic material which was deposited in a lacustrine delta (VRSALJKO, 2003; VRSALJKO et al., 2003; Figs. 9 and 10).

During the Late Pannonian in the palaeographic area of Žumberak, mainly sublittoral clastics, and to some extent, deep-water marls were deposited, while the areas of Plešivica–Sv. Jana and Samobor–Sv. Nedelja were characterized primarily by deposition of marls of a deeper brackish lacustrine basin with the occasional influx of clastic material (Figs. 2 and 10).

The Early Pontian is marked at all three palaeogeographic areas with very similar types of sedimentation. Marls prevail with rare occurrences of siltstones (Fig. 11), and these are characterized by a scarce macro-faunistic and ostracod community (VRSALJKO, 2003).

In the Late Pontian, the basin was infilled, mainly with sandy material, and this is a characteristic of all three areas. Sedimentary and petrographic analyses of Pontian sediments show the gradual domination of regional influences on sediment source (?Alpine), over the local influences (?Dinarides), towards the end of Miocene (Marijan KOVAČIĆ, pers. comm., 2005).

Pliocene, Pleistocene and Holocene compressional tectonics significantly influenced the creation of spatially reduced fresh-water environments in which the material, primarily from local sources, was deposited (HORVATH, 1995; TOMLJENOVIĆ, 2002).

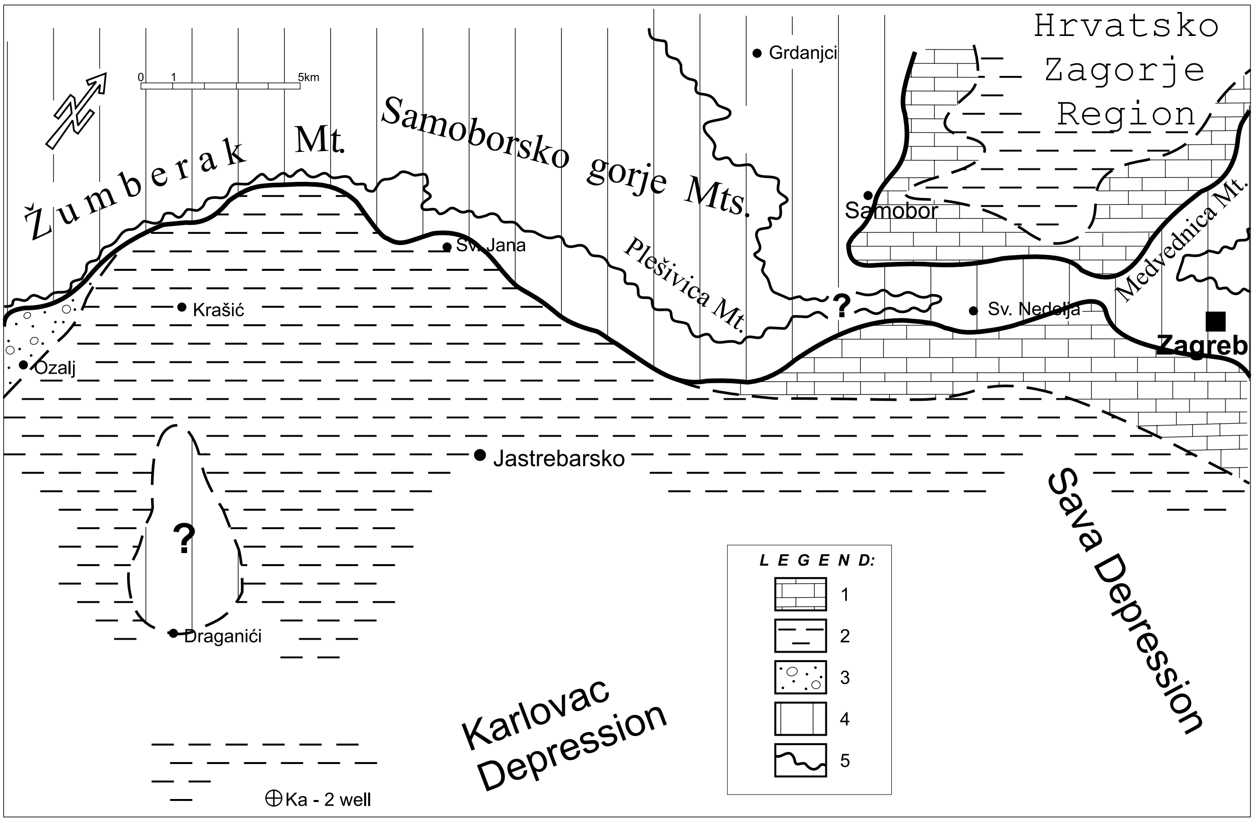

Fig. 9 The palaeogeographic situation during the Late Miocene (Early Panonian) in the wider area of Žumberak Mt. and the Samoborsko Gorje Mts. Legend: 1) fluvial deposits; 2) deposits of proximal parts of the delta fan; 3) prodeltaic deposits; 4) lacustrine basin; 5) Pre-Miocene basement; 6) SW boundary of Miocene outcrops.

2.4. Comparison of the Miocene stratigraphy of Žumberak Mt. and the Samoborsko Gorje Mts. with neighbouring areas

2.4.1. The Miocene basement

The Miocene basement varies a lot over the relatively small area explored, which is a consequence of the Mesozoic–Palaeogene depositional evolution. At Žumberak, the basement is composed of Mesozoic carbonates (most often Triassic dolomites), while at the Samoborsko Gorje Mts. it consists of Palaeozoic–Mesozoic–Palaeogene carbonates and clastic rocks (Fig. 2).

In the Karlovac–2 well the basement of the Miocene rocks consists of Palaeogene clastics (Fig. 5). In contrast, in the SW part of Medvednica Mt. the basement is mainly represented by Triassic dolomites (see Figs. 2 and 5).

2.4.2. Ottnangian (?)

These sediments, being determined by stratigraphic correlation as Ottnangian, are exposed in the Samoborsko Gorje Mts. area (Grdanjci Unit; Figs. 2 and 6), and also occur in the Karlovac–2 well. Correlation with the surrounding areas of Northern Croatia (i.e. central part of Medvednica Mt. – KOCHANSKY-DEVIDE & SLIŠKOVIĆ, 1978; PAVELIĆ et al., 1995) is problematic and questionable.

2.4.3. Karpatian (?)

In the Karlovac–2 well (1754–1759 m depth) the existence of Karpatian sediments is significant (Fig. 5), and can be correlated to some extent with similar, neighbouring terrains (i.e. central parts of Medvednica Mt. – ŠIKIĆ, 1968).

2.4.4. Upper Badenian

Upper Badenian deposits are often found both in the immediate and broader study, occurring as beds immediately overlying the older basement (Figs. 2, 4 and 5). Late Badenian sedimentation could be interpreted as a consequence of a short, but very intense marine transgression due to eustatic sea level rise with the opening of the connection of Central Paratethys with the Indo–Pacific ocean (RÖGL & STEININGER, 1984). The most representative exposed sediments are shallow water algal limestones. In some areas, such as the Karlovac depression, the first sediments are deep-water marine marls, possibly of Badenian age, which continuouslyoverlie Karpatian deposits (Figs. 5 and 7).

2.4.5. Sarmatian

Sarmatian layers are most often conformable on Badenian strata, but in the area of Žumberak Mt. they also occur as transgressive deposits overlying the Mesozoic basement (PIKIJA et al., 1984; VRSALJKO, 2003; VRSALJKO et al., 2003; Figs. 2, 4 and 8). The Sar-

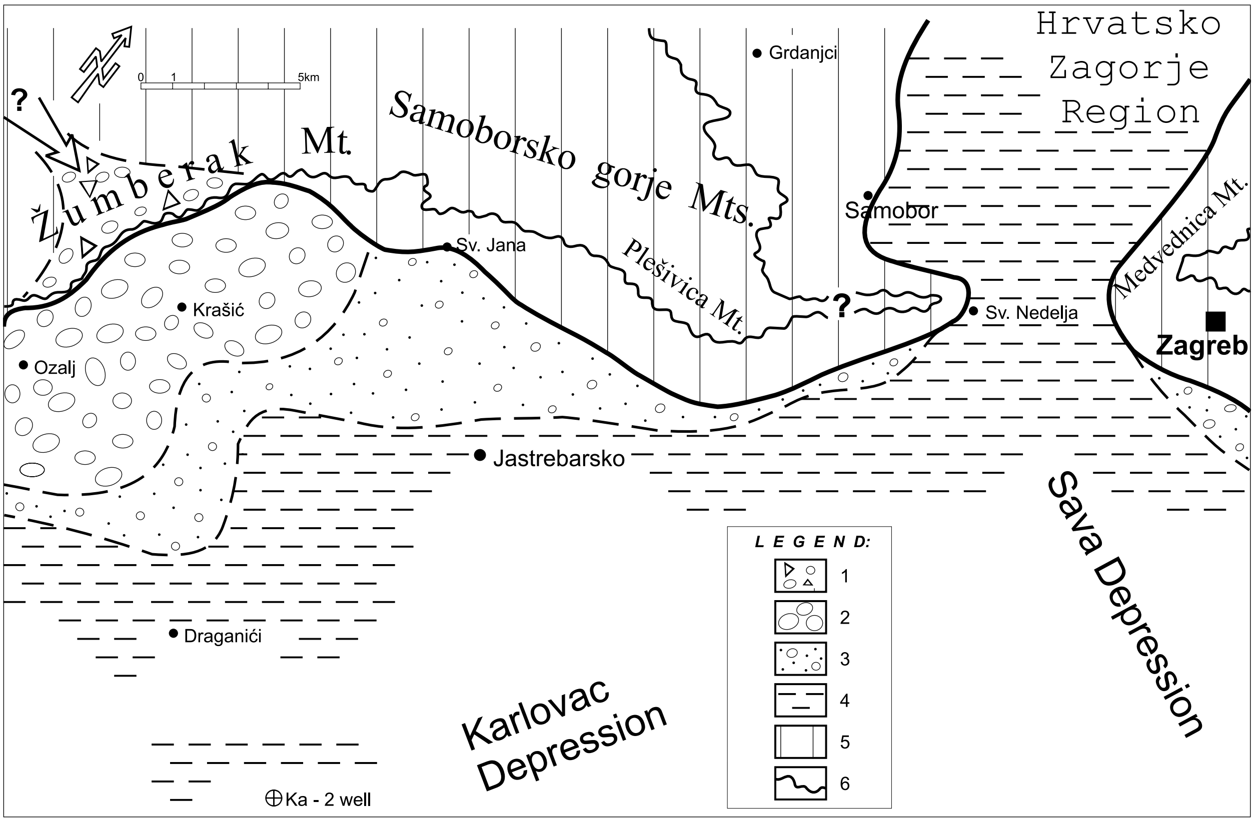

Fig. 10 Palaeogeography during the Late Miocene (Late Panonian) in the wider area of Žumberak Mt. and the Samoborsko Gorje Mts. Legend: 1) fluvial deposits; 2) deposits of the proximal parts of the delta fan; 3) prodeltaic deposits; 4) lacustrine basin; 5) Pre-Miocene basement; 6) SW boundary of Miocene outcrops.

matian sequence is characterized by the intercalation of marls and carbonate clastics deposited in a reduced-salinity environment. They are easy to correlate over the wider area of Northern Croatia because of their lithological characteristics (varve-like) and unique fauna (VRSALJKO, 1999, 2003). The end of the Sarmatian is characterized by shallowing and emergence, which could be a consequence of the restricted connection to the sea (RÖGL & STEININGER, 1984). The presence of land could be a consequence of tectonic movements caused by intraplate stress which overtook the whole Pannonian Basin at the end of the Sarmatian causing its inversion (HORVATH, 1995; TOMLJENOVIĆ & CSONTOS, 2001; PAVELIĆ et al., 2003).

2.4.6. Lower Pannonian

The Lower Pannonian deposits of shallow water lacustrine environments are to be found in the area of south-western Medvednica Mt. and Samobor–Sv. Nedelja area (Figs. 2 and 9). Elsewhere, they are developed in the deep-water marls facies where they could be biostratigraphically determined on the basis of rare occurrence of ostracods. At Žumberak, for the clastic development the uppermost part of the Late Pannonian has been presumed (see Slapno and Ozalj localities; Figs. 2, 9 and 10).

2.4.7. Upper Pannonian

The Upper Pannonian strata (so-called "Banatica Beds") are widespread, and represented by deep-water, lacustrine marls. However, at the south and central parts of Žumberak Mt. and Samoborsko Gorje Mts., sequences of coarse-grained clastics exist, reflecting occasional flooding of the land. At Žumberak, the prevailence of coarse-grained clastics, i.e. the accumulation of terrestrial material in river deltas is significant (Fig. 10). These coarse-grained clastics locally occur on Žumberak Mt. and Medvednica Mt., and indicate the formation of land, its strong erosion and accumulation of material in the lake (VRSALJKO, 1997, 1999, 2003; VRSALJKO et al., 2003).

2.4.8. Lower Pontian

Lower Pontian deposits have only been determined with certainty in the area surrounding Krašić, which could indicate deep-water, lacustrine sedimentation (Figs. 2 and 11). At the same time, a similar sedimentation regime probably existed within the area of the Karlovac depression (surroundings of Karlovac–2 well; Figs. 5 and 11). Elsewhere in the study area, the Lower Pontian sediments are barely identifiable. Only marls and silty marls with very scarce and atypical fossils indicate the development of the Early Pontian, known as "Abichi beds".

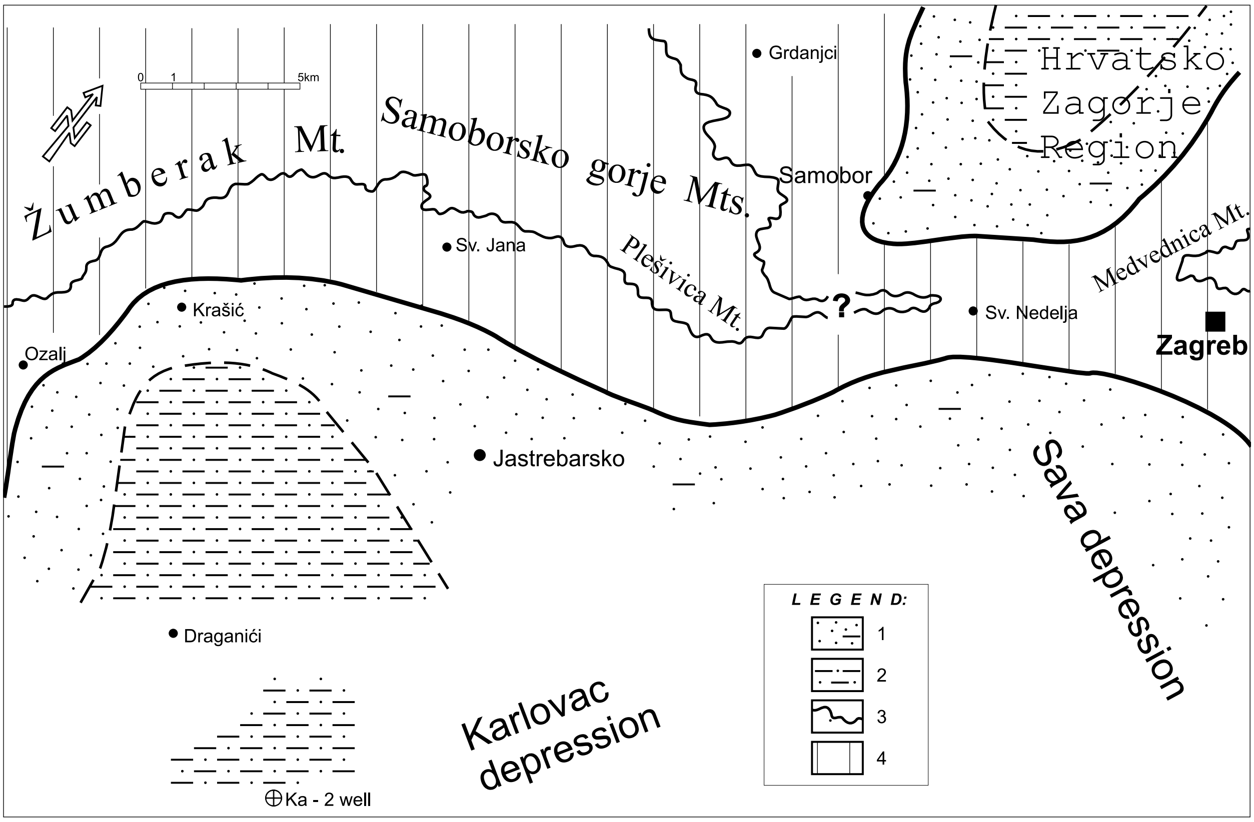

Fig. 11 The palaeogeographic situation during the Late Miocene (Pontian) in the wider area of Žumberak Mt. and the Samoborsko Gorje Mts. Legend: 1) deltaic deposits; 2) prodeltaic deposits – proximal to lacustrine basin; 3) SW boundary of Miocene outcrops; 4) Pre-Miocene basement.

2.4.9. Upper Pontian

Sediments of the Upper Pontian are distributed over a wide area of the southeast slopes of Žumberak Mt. and the Samoborsko Gorje Mts. (Figs. 2 and 11). At Grdanjci, and on the southwestern parts of Medvednica Mt., these sediments are either missing, due to their erosion during the Plio–Quaternary, or are covered by younger layers. They are represented by silts and sands with characteristic coarse-shelled molluscs defining the layers known as the “Rhomboidea beds”.

2.4.10. Pliocene

Stratigraphically determined Pliocene sediments are found only in the area surrounding Brezarić, not far from Krašić (Figs. 2–4; Žumberak area – VRSALJKO, 2003). They can be lithologically as well as stratigraphically correlated with freshwater “Paludina layers”, which are found near the surface just northeast of the Vukomeričke gorice structure (BASCH, 1983b).

2.4.11. Pleistocene and Holocene

These sediments consist mainly of gravels, clays and silts of unclear stratigraphic affiliation. This series most probably represents young, fluvial–swamp residues (ŠIKIĆ & BASCH, 1975; ŠIKIĆ et al., 1978, 1979). Due to the lack of fossils it is difficult to determine the age of these layers; however, according to superposition, they are classified as Pleistocene–Holocene.

3. CONCLUSIONS

Within Northern Croatian Miocene deposits the areas of Žumberak Mt. and the Samoborsko Gorje Mts. represent the mere southwestern rim of Central Paratethys and the Pannonian Basin. During the Miocene, these parts of the northern Croatian Neogene basin represent, to some extent, a specific area of sedimentation. Miocene sediments surround older rocks of Žumberak Mt. and the Samoborsko Gorje Mts., and are exposed at the surface at Ozalj, Krašić, Sveta Jana, Plešivica, Sveta Nedelja, Samobor and Grdanjci. They can also be observed at the nearby locations – the Draganići area, the southwestern part of Medvednica Mt. and in the subsurface in the Karlovac depression, allowing wider correlation of the deposits.

Spatial analysis of stratigraphic units from the geological map suggests that the terrains of Žumberak Mt. and the Samoborsko Gorje Mts. can be divided into four palaeogeographic areas. These exhibit common similarities as well as differences in some stratigraphic sections of the Miocene: the Žumberak Mt. (1), Plešivica–Sv. Jana (2), Samobor–Sv. Nedelja (3) and Grdanjci (4).

The oldest Miocene beds are of uncertain age as determined from Grdanjci area and at approximately 2500 m depth, from the Karlovac–2 well. Superposition of the rocks of the clastic complex with coal intercalations in the Grdanjci area is unclear, but signifies fresh-water Ottnangian deposits.

In the Karlovac–2 well, deposits of Karpatian age are identified which cannot be found elsewhere in the study area. Deposits of Late Badenian age are the most common, representing the base of the Miocene on most of the outcrops in the study area. They are mainly composed of algal shallow-water limestones and to a lesser extend marls of shelf and deep-water marine environments. The Žumberak palaeogeographical area shows a transgression commenced with Sarmatian beds, directly overlying the Mesozoic carbonates, which is not the case elsewhere in the study area.

The Lower Pannonian shallow-water carbonates, known as the "Croatica beds" are only to be found within the Samobor–Sv. Nedelja area, and could be correlated with similar deposits of the southwestern parts of Medvednica Mt. Elsewhere, these beds are missing, most likely due to significantly different conditions of sedimentation.

The Upper Pannonian beds, known as the "Banatica beds", are found in many places, while a strong terrestrial influence is observed towards the southwestern parts of Žumberak Mt. and the Samoborsko Gorje Mts. This is demonstrated by increased proportions of clastics, which are most often intercalated with deeper-water lacustrine marls. Scarce deeper water lacustrine molluscs and ostracods occur in the marls, which can be compared with typical Late Pannonian associations in other parts of Croatia. The Žumberak area is characterized by an increased proportion of coarse-grained clastics in the Pannonian.

The Pontian sediments are less well known since they are mostly overlain by younger deposits. Deltaic–lacustrine deposits occur repeatedly, and are classified with uncertainty as Upper Pontian, whereas Lower Pontian layers known as the "Abichi beds" are rarely determined (near Krašić).

The Miocene sediments are overlain by clastics (gravels, silts, coaly clays) conditionally determined as Pliocene, Pleistocene and Holocene. Only in the area south of Krašić (Žumberak area) Pliocene sediments could be unquestionably determined which may correlate with contemporaneous beds known as the "Paludina beds".

Vertical and lateral distribution of some Miocene units in the Žumberak Mt. and Samoborsko Gorje Mts. shows clear overprint of variable depositional conditions. Today, their relationship is largely masked by younger tectonic movements. Significant geological variability noticed in the study area enabled interpretation of the palaeogeographic evolution during the Miocene (Figs. 6–11).

Some attributes of all the Miocene terrains of the Žumberak Mt. and Samoborsko Gorje Mts. have to be emphasized as they differentiate this area from others in northern Croatia:

a) clastic, non-fossil beds from Grdanjci are questionably determined as fresh-water Ottnangian deposits;

b) the occurrence of a thick clastic succession (~800 m thick) in the Karlovac–2 well, directly overlying Palaeogene clastics, which is conditionally determined as being of Ottnangian age;

c) layers of Karpatian age were detected in the Karlovac–2 well;

d) coal bearing horizons of the area surrounding Samobor (Vrhovčak), determined with uncertainty as fresh water Badenian, directly underlie the Upper Badenian algal limestones;

e) the appearance of Sarmatian transgressive layers within the area of Žumberak Mt. (Slapno and Ozalj);

f) significant thicknesses (about 150 m) of Sarmatian beds on the southeastern flanks of Plešivica Mt.;

g) the appearance of a significant thickness (~150 m) of Pannonian coarse grained clastics within the area of Žumberak Mt. (Slapno and Ozalj);

h) the lack of "Croatica limestones" in most parts of the study area;

i) wide-spread cover of the Miocene layers of Žumberak Mt. and the Samoborsko Gorje Mts., particularly Pontian strata.

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