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Tertiary Subsurface Facies, Source Rocks and Hydrocarbon Reservoirs in the SW Part of the Pannonian Basin (Northern Croatia and South-Western Hungary)

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Abstract

The Neogene sedimentary successions of the Drava, Sava and Slavonija–Srijem depressions in the SW part of the Pannonian Basin System are built up of three 2nd order megacycles separated by four major erosional unconformities. The first megacycle contains terrestrial to marine syn-rift and early post-rift sediments of Early to Mid-Miocene age. The second is built up of Late Miocene Lake Pannon deposits, while the third contains those sediments which were deposited in the remnants of Lake Pannon and in the subsequent fluvial systems, in areas of continuous subsidence associated with basin inversion from the Pliocene onwards. Most of the petroleum source rocks and reservoir rocks are of Miocene age and were formed during the first and second depositional megacycle. Conditions for the accumulation and preservation of large quantities of marine and terrigenous organic matter were most favourable during the Badenian, Sarmatian and Early Pannonian, in deep basin settings, partly associated with rifting. The generation of hydrocarbons was promoted by relatively high geothermal gradients during the initial and subsequent thermal subsidence. Various sedimentary environments produced deposits with good reservoir characteristics: e.g. fault-related talus breccia (mainly Lower Miocene), reefs (mainly Badenian), coastal, shallow marine (Karpatian, Badenian) and deltaic (Pannonian–Pontian) sand bodies or turbiditic sand lobes (mainly Pannonian). The hydrocarbon (HC) migration paths were often provided by the major unconformities bounding the three megacycles, as well as by faults, particularly around the basement highs.

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1. INTRODUCTION

Hydrocarbon exploration resulted in an enormous amount of data about the structure, sedimentary fill and evolution of the Pannonian Basin (HORVÁTH & ROYDEN, 1981; ROYDEN & HORVÁTH, 1988; BÉRCZI et al., 1988; SZENTGYÖRGYI & JUHÁSZ, 1988; JUHÁSZ, 1991, 1994; HORVÁTH & TARI, 1999; PRELOGOVIĆ et al., 1998; LUČIĆ et al., 2001; VELIĆ et al., 2002). Some of the most important results from the Croatian part of the study area regretfully remained unpublished (ŠIMON, 1980); they have been used here together with other data from the archives of INA, Zagreb (Croatian national oil company).

Above the historically complex basement the structure of the study area is complicated (CSONTOS et al., 1992; CSONTOS 1995; CSONTOS & NAGYMAROSY, 1998): elongated basement highs and narrow depressions developed during Mid-Miocene rifting (HORVÁTH & ROYDEN, 1981; HORVÁTH, 1993), refigured by several phases of basin inversion prior to, during and after the subsequent thermal subsidence (HORVÁTH, 1995; HORVÁTH & CLOETINGH, 1996; PRELOGOVIĆ et al., 1998; TARI & PAMIĆ, 1998; HORVÁTH & TARI, 1999; FODOR et al., 1999; PAVELIĆ, 2001; TOMLJENOVIĆ & CSONTOS, 2001; CSONTOS et al., 2002). A Neogene sedimentary succession up to 5–7 km in thickness was accumulated in these depressions which are separated by uplifted and partially eroded units. The aforementioned depressions (sub basins) – the most northern Mura, the western and the eastern part of the Drava, the Sava and the Slavonija–Srijem depressions (Fig. 1), are hosts of important source rocks and petroleum reservoir rocks. Some of the basement highs are exposed as Palaeozoic–Mesozoic Mountains (e.g. Mecsek, Villány, Papuk, Psunj, etc.), others are still covered by about a 1–2 km thick pile of Neogene sediments.

Conditions for the accumulation and preservation of large quantities of marine and terrigeneous organic matter were most favourable during the Badenian, Sarmatian and Early Pannonian in deep basin settings (HORVÁTH et al., 1988; DANK, 1988; ALAJBEG et al., 1990; BARIĆ et al., 1989, 1992; HERNITZ et al., 1995a, b). The generation of hydrocarbons was

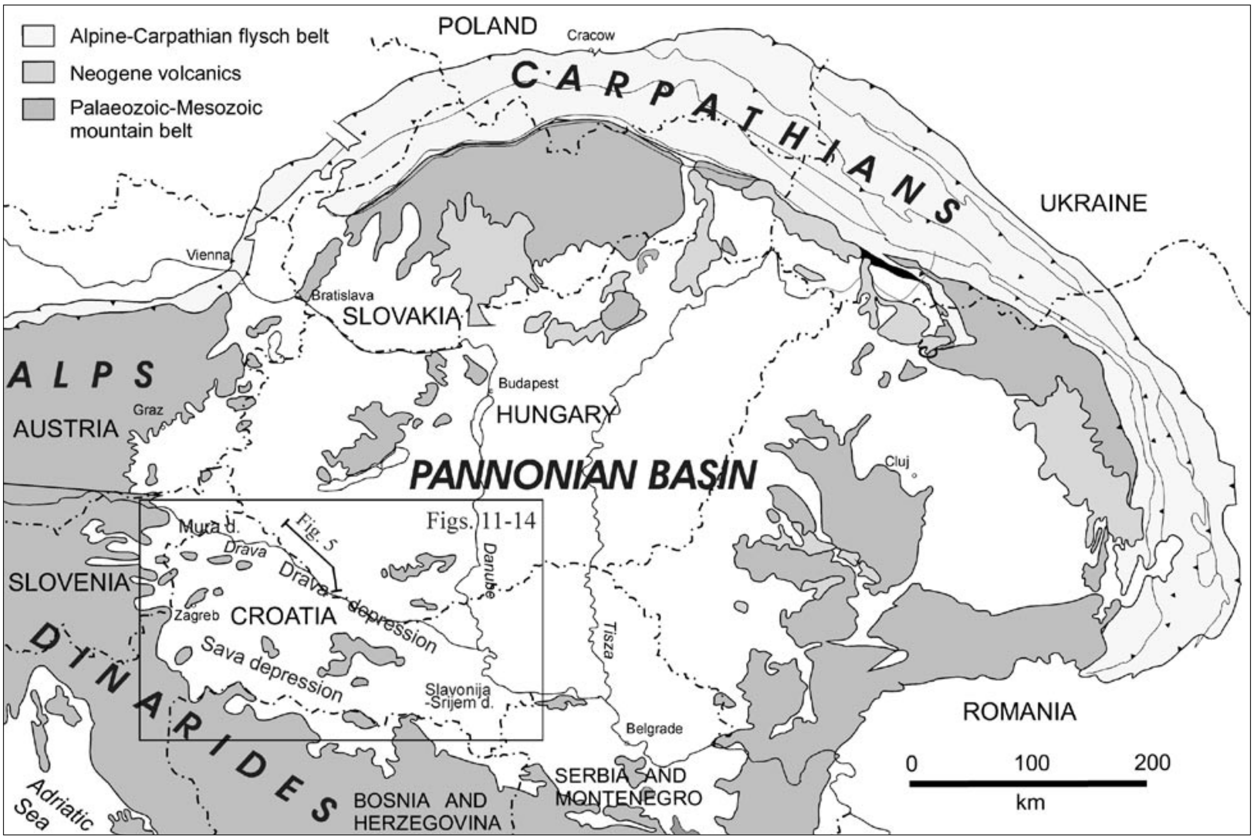

Fig. 1 Location map.

promoted by relatively high geothermal gradients (between 3–4 and 7ºC/100 m – HORVÁTH et al., 1988) during the subsequent thermal subsidence. Various sedimentary environments produced deposits with good reservoir characteristics (Fig. 2), e.g. fault-related talus breccia (mainly Lower Miocene), reefs (mainly Badenian), coastal, shallow and open marine (Karpatian, Badenian, Sarmatian) and deltaic (Pannonian–Pontian) sand bodies or turbiditic sand lobes (mainly Pannonian). These are only the most frequent occurrences; almost all of the mentioned environments existed contemporaneously. The HC migration paths were often provided by the major unconformities as well as by faults, particularly around the basement highs. The late stage inversion of the basin promoted accumulation of the hydrocarbons in areas of active uplift (HORVÁTH, 1995).

The aim of this paper is to review the sedimentary facies and depositional environments with special regard to the potential source and reservoir rocks in the SE part of the Pannonian Basin.

2. GEOLOGICAL SETTING

The studied sediments from SW Hungary and N Croatia were deposited in the Pannonian Basin, the largest intramontaine basin of Central Paratethys (Fig. 1). The Pannonian Basin is a historically complex basin developed parallel with the Alpine–Carpathian orogen. Its northern part, the Alcapa unit, escaped from the Alpine zone and was juxtaposed to the southern Tisza unit along the Mid-Hungarian Line during the Late Eocene–Early Miocene (CSONTOS & NAGYMAROSY, 1998, and references therein). Thereafter the Neogene Pannonian Basin proper, opened as a back arc basin in which extension was manifested through a set of low angle normal (TARI et al., 1999) and strike-slip faults. Extension was coeval with the compression within the Carpathian thrust belt (HORVÁTH & ROYDEN, 1981).

Paratethys was an enclosed sea existing from Oligocene to Middle Miocene times consisting of a chain of basins of various tectonic origin (BÁLDI, 1980). These basins were covered most of the time by the same mass of water, sharing a similar aquatic biota, communicating between the Mediterranean and the Indopacific realm. When Paratethys became separated from other seas in the beginning of the Late Miocene, the Lake Pannon individualized with decreasing salinity (cf. MAGYAR & GEARY, 1999; MÜLLER et al., 1999). As both Paratethys and Lake Pannon were characterized by an increasing rate of endemism, a local chronostratigraphic scheme was developed as used in Figs. 2–4 (for detailed discussion the reader is referred to VASS et al., 1987; RÖGL & DAXNER-HÖCK, 1996; VASS, 1999; MAGYAR et al., 1999a, b).

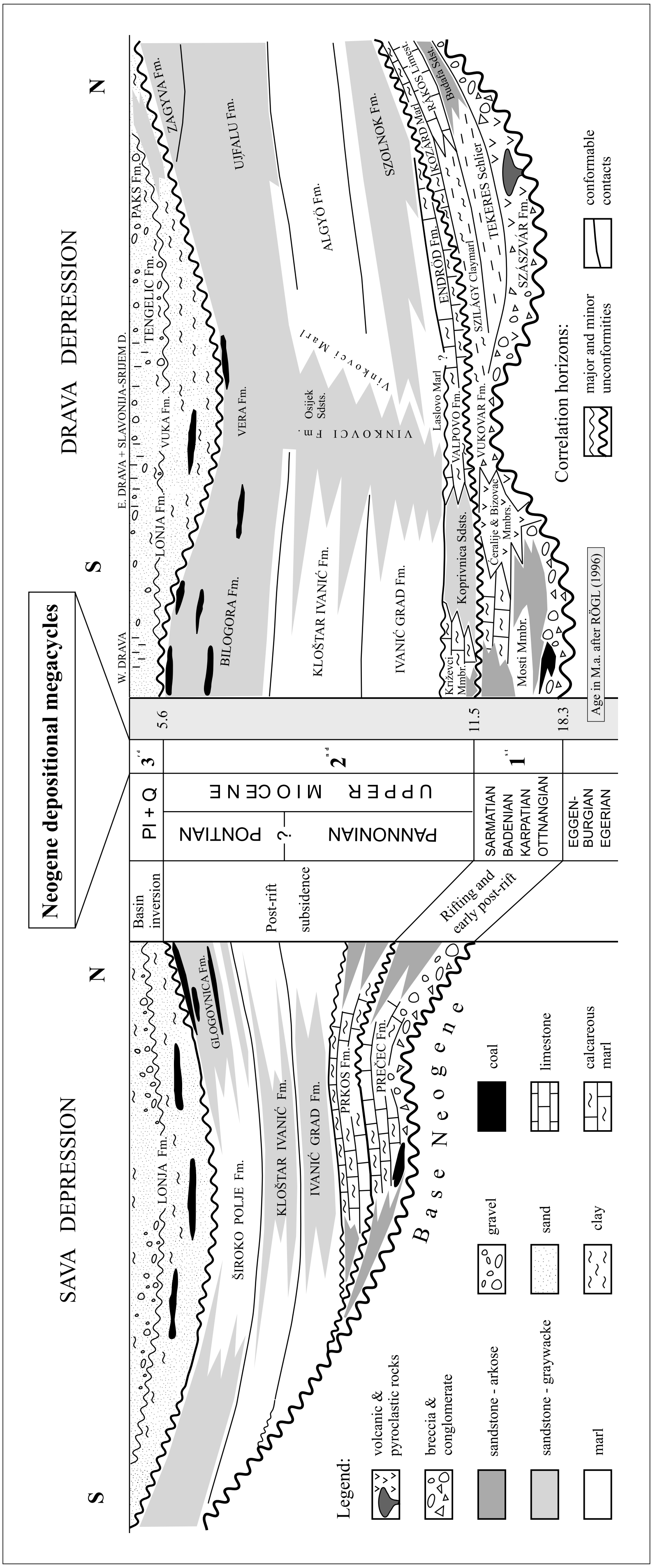

Fig. 2 Schematic section – lithostratigraphic units and the three Neogene depositional megacycles.

In the Pannonian Basin, Early Miocene subsidence and sedimentation began as a result of the first syn-rift extensional tectonic phase (HORVÁTH & ROYDEN, 1981; TARI, 1994; TARI & PAMIĆ, 1998; LUČIĆ et al., 2001; PAVELIĆ, 2001). This extension was also synchronous with the major extension of two microcontinents: Alcapa and Tisza. Subsidence from the end of the Karpatian corresponds to the eastward motion and possible rotation of the Tisza unit under a transtensive stress field (CSONTOS et al., 1992, 2002; CSONTOS, 1995). In SW Hungary in the vicinity of the Mecsek Mts. the presence of syn-sedimentary half grabens of Karpatian–Badenian age was proved by several studies (POGÁCSÁS, 1984; BERGERAT & CSONTOS, 1988; TARI, 1992; BENKOVICS, 1997; CSONTOS & NAGYMAROSY, 1998; FODOR et al., 1999). Following a short terrestrial period, marine deposition occurred in these depressions connected by the huge water mass of Paratethys. The sea-floor had significant relief: in small, but deep depressions the palaeo-water depth often exceeded 500 m (BÁLDI et al., 2002); these depressions were surrounded by shallow submarine platforms and an archipelago (HÁMOR, 2001). Generally in this time period, bathymetric changes were controlled principally by movements of the basin floor. The first compressional event indicates the end of rifting at about the Late Badenian (cf. POGÁCSÁS, 1984; TARI, 1994), followed by only moderate rates of subsidence. The subsequent palaeobathymetric changes, still within the Badenian, were mainly controlled by global sea level variations (BÁLDI et al., 2002).

The first early post-rift event of basin inversion took place during the Sarmatian (HORVÁTH & TARI, 1999) resulting in a widespread pre-Pannonian unconformity. Afterwards quiet and relatively slow thermal subsidence occurred (HORVÁTH & ROYDEN, 1981), coupled with uplift and erosion of the surrounding Alpine–Carpathian–Dinaric mountain belt. This supplied huge amounts of sediment via large fluvial to deltaic systems into Lake Pannon (BÉRCZI et al., 1988; SZENTGYÖRGYI & JUHÁSZ, 1988; JUHÁSZ, 1991, 1994), resulting in the accumulation of post-rift sedimentary successions several thousand metres thick. This unit was subdivided into several 3rd order depositional sequences (POGÁCSÁS et al, 1988; UJSZÁSZI & VAKARCS, 1993; VAKARCS et al., 1994; VAKARCS, 1997; TÓTH-MAKK, 2003), which seemingly are in phase with global sea level changes. Others argue for simple climatic correlation (SACCHI et al., 1999), while a tectonically controlled stratigraphic subdivision is suggested by HORVÁTH & TARI (1999). Because the facies boundaries within the lacustrine succession are time-transgressive (POGÁCSÁS et al., 1988, 1993), a combination of litho-, bio-, magneto- and (seismo-) sequence stratigraphy is used to establish reliable correlation between sub basins. Bypassing of the delta front through the northern part of the study area (southern Transdanubia) is estimated to have occurred between 9–7 Ma (Late Pannonian – UJSZÁSZI & VAKARCS, 1993; VAKARCS et al., 1994; VAKARCS, 1997; SACCHI et al., 1999), whereas it happened in Croatia during the Pontian (7–5 Ma).

The third phase of basin evolution is represented by repeated compressional events in relation to basin inversion from the Pliocene onwards (HORVÁTH, 1995; CSONTOS et al., 2002). All of the compressional events resulted in the reactivation of former faults mainly as reverse types, and gentle folding of the overlying strata (see Fig. 5 and Figs. 6–9). Between the areas of active uplift, subsidence continued mainly in the deepest depressions resulting in the formation of an occasionally thick Pliocene–Quaternary succession (HORVÁTH & CLOETINGH, 1996; PRELOGOVIĆ et al., 1998; HORVÁTH & TARI, 1999; LUČIĆ et al., 2001; VELIĆ et al., 2002).

3. SEDIMENTARY FACIES AND ENVIRONMENTS

An overview of the major lithostratigraphic units in the study area, their composition and contacts is given in Fig. 2, with more details and description of depositional characteristics in Figs. 3 and 4. The Neogene to Quaternary basin fill in Croatia starts with Egerian–Eggenburgian sediments documented in the Mura depression, in the Hrvatsko zagorje region and in the nearby westernmost part of the Drava depression. This was referred to as the “Western marginal part of the Pannonian basin” (LUČIĆ et al., 2001) interpreted to be the place of formation of the first depocentres, concurrent with the initial tectonic transport in the formation of the Pannonian Basin System. In the basal sections coarse clastics, sandstones and clays with coal were observed, deposited in paralic environments. The marine tuffaceous sandstones (“Macelj sandstones”) are interpreted to be of Eggenburgian age (LUČIĆ et al., 2001). These sediments were not drawn in Figs. 2–4 because they belong to the end of the Palaeogene basin cycle and not to the rifting of PBS. Anyway, they are present only in the NW corner of the study area and we wanted to emphasize the most important similarities between the Hungarian and Croatian stratigraphic data. The most important of these is that the overlying Ottnangian sediments are found in a much wider area – in all of the structural depressions in the southern part of the Pannonian basin (Figs. 3 and 4). They are usually coarse-grained clastics deposited in river-to-lake environments. Lacustrine sedimentation was influenced with pyroclastics. Lakes prevailed in the upper part of these successions but they still probably remained isolated until the main marine transgression occurred in Karpatian times. Based on the data from outcrops (e.g. between Mt. Psunj and Mt. Papuk after PAVELIĆ et al., 1998) the Ottnangian lake was gradually transformed into a marine environment during the Karpatian. Karpatian marine sediments – composed of sandy and clayey marl with tuff intercalations – were found in the Hrvatsko zagorje region

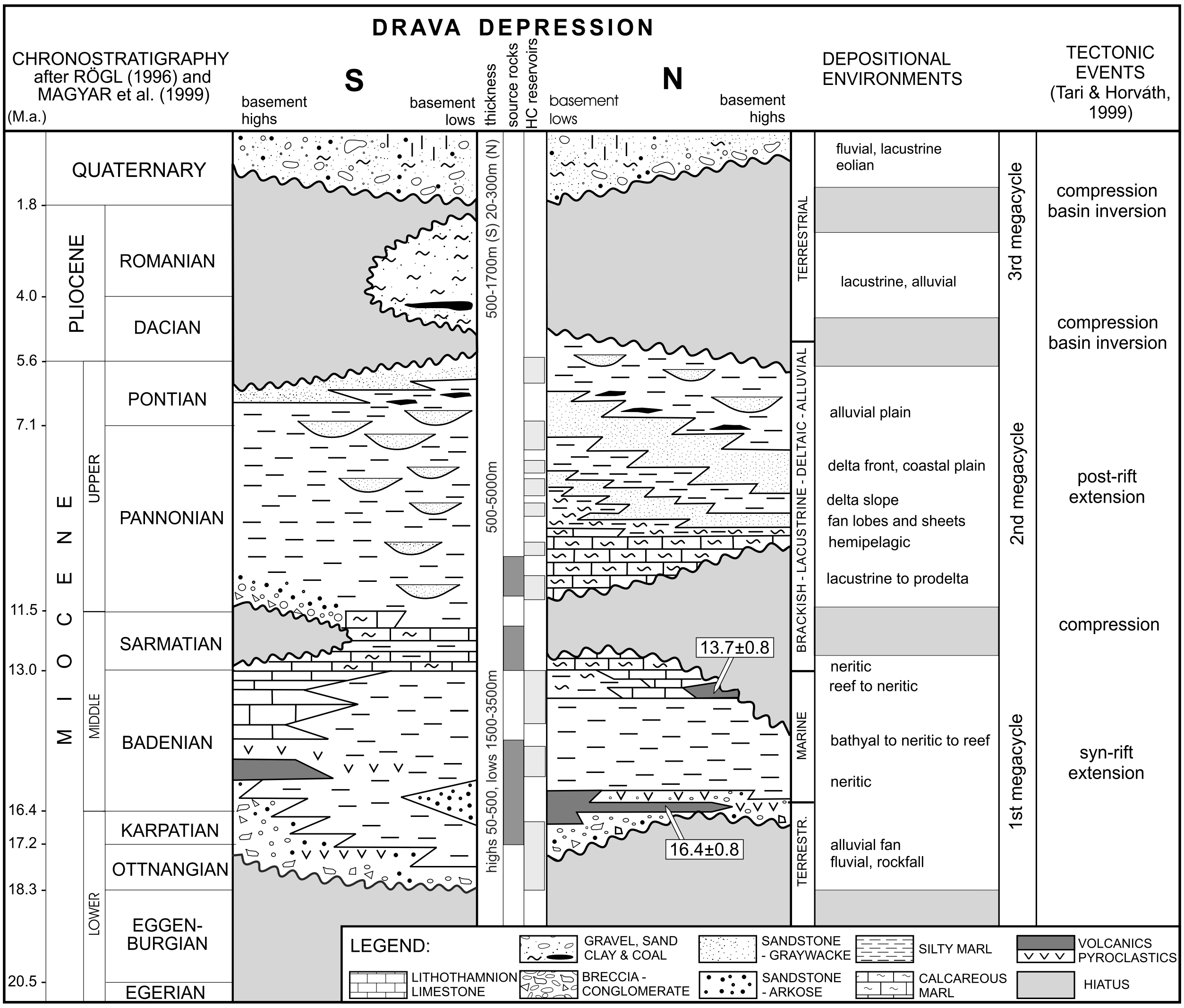

Fig. 3 Stratigraphic column of the Drava depression.

and in the central and eastern part of the Drava depression (both in wells and at outcrops – PAVELIĆ, 2001). Karpatian marine sedimentation was also documented in the NW marginal part of the Sava depression, on the margins of Mt. Psunj and also in the Požega valley.

The first Neogene sediments overlying the Palaeozoic–Mesozoic basement in SW Hungary (in the Mecsek Mts. and the surrounding basins both to north, west and south) are Ottnangian to Karpatian terrestrial deposits – conglomerates, sandstones, siltstones, even coal-bearing clay – of large alluvial fans and lakes (Fig. 3). These are interfingered with the "Lower" Rhyolite Tuff which largely contributed to the infilling of the continental basin (HÁMOR, 1970; TARI, 1992). Thick intercalations of Dacite Tuffs (15.3–17.4 Ma – ÁRVASÓS & MÁTHÉ, 1992) mark the Karpatian/Badenian boundary. The thickest epiclastic–volcanoclastic successions can reach 500–1500 m.

The Early Badenian sea-level rise covered the Karpatian deposits in Croatia. A pronounced facies differentiation is recorded by interfingering of calcarenitic biogenic sandstones, turbidites with blue-grey and brownish marls and platy marls (LUČIĆ et al., 2001). In the Mura and Drava depressions occasionally very thick sequences of lava and pyroclastics of andesitic to basaltic composition were documented, sometimes in two intervals (Fig. 3). In SW Hungary, the fish-scale bearing lacustrine clayey marl and the *Congeria*-bearing sands represent the transition from Karpatian brackish water to Badenian fully marine conditions. These are overlain by coarse clastics (sands, sandstones, and conglomerates) that were deposited from foreshore to nearshore areas (the Budafa Formation and the overlying "regressive complex") and by dark grey, sandy siltstones and marls (Tekeres Schlier) rich in foraminifera, which formed in an open marine environment (Fig. 2). The thickness of the schlier rarely exceeds 200–400 m, the coeval nearshore clastics may reach 600–700 m (HÁMOR, 2001). The Tekeres Schlier was generally believed to be deposited in a rather shallow environment, referred to mostly as being upper neritic or sublittoral (HÁMOR, 1970, 2001; SZENTGYÖRGYI & JUHÁSZ, 1988). Recent quantitative palaeoecological analysis of foraminifera, however, proved that it was

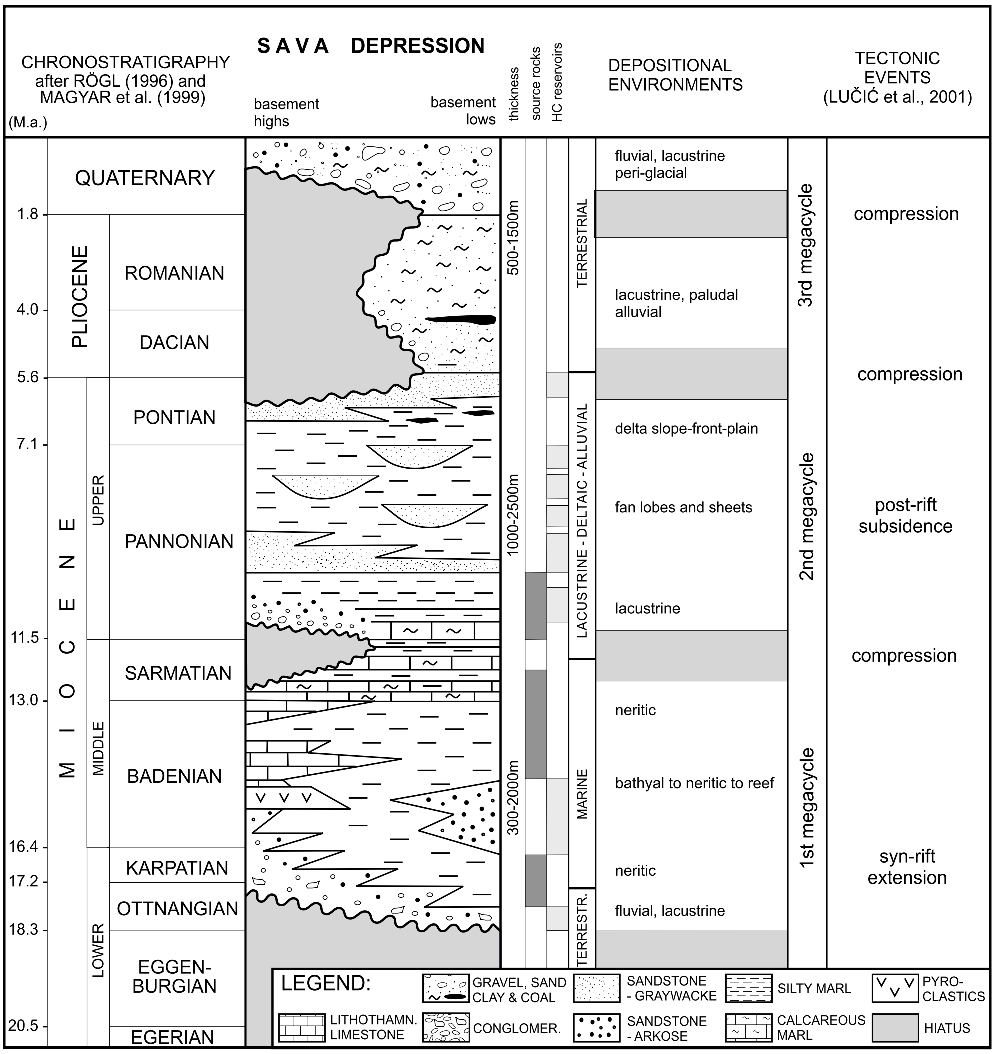

Fig. 4 Stratigraphic column of the Sava depression.

deposited in bathyal depths (BÁLDI et al., 2002). The Late Badenian is represented by *Turritella–Corbula* bearing clay-marls (Szilágy Fm.) – up to 100 m in thickness – indicating a shallow open marine realm. The clay–marl interfingers with the *Lithothamnion*-bearing lower and upper Leitha Limestones which were formed in the nearshore to littoral zone. Both limestones are made up of carbonate cemented conglomerates, mollusc-bearing to oolitic calcarenites and reefs up to about 50 m thick. The Badenian was the last fully marine period in the life of Paratethys. The Late Badenian sea-level rise, as a consequence of re-opening of the Indo-pacific seaway (RÖGL, 1996), caused flooding of uplifted blocks on many places in northern Croatia. The boundary in the base of Upper Badenian deposits may be compared with the acknowledged Middle Badenian unconformity, and is considered as a syn-rift/post-rift boundary (HORVÁTH, 1995; PAVELIĆ, 2001). In northern Croatia, thin Sarmatian deposits are found in conformable successions. The thin-bedded calcareous marls (occasionally with some sandstones) contain a characteristic small-sized brackish faunal assemblage. In addition, varve-like laminites (LUČIĆ et al., 2001; PAVELIĆ, 2001) are also known. Volcanic activity dramatically decreased and is reflected in the local deposition of pyroclastics (Fig. 3).

Following the Sarmatian, the contemporaneous structural changes in the surrounding Alpine–Carpathian mountain belt led to the final isolation of the sea and formation of Lake Pannon (for the best recent summaries see MAGYAR & GEARY, 1999; MAGYAR et al., 1999a, b; MÜLLER et al., 1999).

Depending on the palaeogeographic position, namely the tectonically determined coeval relief of the basin floor, Lake Pannon sediments either conformably overlie Sarmatian layers (Figs. 3 and 4), or they unconformably cover older sediments, or occasionally even the crystalline basement on uplifted blocks. Lake Pannon deposits are described from north to south because this approximates the general direction of sediment transport and the progradation of the facies belts. The southernmost depressions (Sava and partly the Slavonija–Srijem) were partly separated by inselbergs situated perpendicular to the main sediment transport direction (PAVELIĆ, 2001), thus the palaeogeographic situation (in sense of the basin fill directions) becomes more complex to the south.

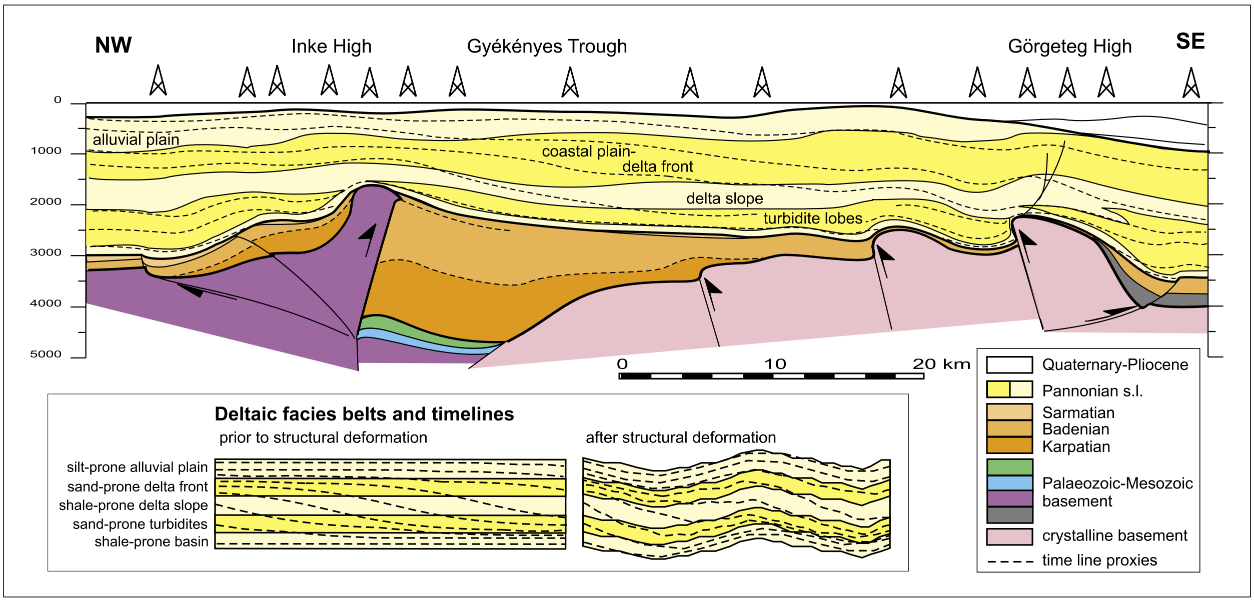

Fig. 5 Geological cross-section based on correlation of well-log data (location in Fig. 1).

In the northern part of the Drava depression, the transgressive deposits usually begin with conglomerates of destructive coasts, fining up into nearshore sandstones, mainly above the pre-Neogene basement highs (BÉRCZI et al., 1988; SZENTGYÖRGYI & JUHÁSZ, 1988). Above this thin coarse-grained veneer, dark grey calcareous marls that gradually turn into clayey marls (Endrőd Fm. – Fig. 2) of hemipelagic origin are found basin-wide, indicating a longer period of basin starvation. The clayey marl is already an indicator of the slowly approaching siliciclastic input. The colour of the marls varies from black to brown indicating an alternation of anoxic to dysoxic bottom conditions. It was found that the colour lightens towards the basement highs (SZENTGYÖRGYI & JUHÁSZ, 1988). It is difficult if not impossible to estimate water depth by palaeoecological tools because a completely endemic mollusc and ostracod fauna developed in Lake Pannon (JUHÁSZ & MAGYAR, 1992; MÜLLER et al., 1999). Despite these difficulties, the depositional environment is thought to be generally deep during this period, particularly because several series of fine-grained sandstones of turbiditic origin can be found in the immediate overlying sequence (Szolnok Fm.). These are supposed to be formed mainly on turbidite fan lobes and sheets (BÉRCZI et al., 1988; POGÁCSÁS et al., 1988; SZENTGYÖRGYI & JUHÁSZ, 1988; JUHÁSZ, 1994). The thickness of individual sandstone bodies usually varies in the range of 3–10 m, and they are separated by 2–20 m thick intercalations of marls. The thickness of the whole turbiditic succession, however, shows great variation depending on the topography of the basin floor: it pinches out towards the basin margins and is significantly thinner above basement highs, while it can reach 1500 m in the deepest parts of the depressions (Fig. 5).

Silty clayey marls and siltstones are widespread all over the basin above the turbiditic succession, in connection with the approaching delta slope (Algyő Fm. – Fig. 2). In the Drava depression deltaic progradation occurred from the N–NW. Fine grained slope sediments contain up to 2–40 m thick lentoid sandy intercalations of different mass flow origin. The thickness of the strongly progradational delta slope reflects palaeowater depth (POGÁCSÁS, 1984) and varies from 50 m to several hundred metres. According to reflection seismic sections the slope angle also changed from rather gentle and ramp-like, to steep in the deepest depressions (UJSZÁSZI & VAKARCS, 1993).

The overlying well-developed, thick sandstones were accumulated mostly on the delta front and delta plain as distributary mouth bar, channel fill or wave-reworked shore-face deposits. Due to the high rate of subsidence a very thick (700–1000 m) aggradational unit (Újfalu Fm.) was formed reflecting several episodes of minor relative lake-level oscillations. The flooded delta plain gradually gave way to an alluvial plain, on which thin-bedded, often variegated silty clays, occasionally lignites alternate with sand beds a few metres thick (Zagyva Fm.). The fine grained deposits are of floodplain, wet plain and shallow lacustrine (pond) origin, while sands mainly represent fluvial channel fills. The thickness of this unit is about 300–400 m in the Drava depression, but elsewhere it was considerably eroded during the Pliocene (Fig. 2).

As illustrated in Fig. 4, Late Miocene sediments in the southern part of the study area are generally the same as in the north, but with local differences. A pronounced unconformity was identified at the base of the Pannonian sediments, as described from exposures in the region between Mt. Moslavačka gora and Mt. Psunj (BLAŠKOVIĆ, 1982; BLAŠKOVIĆ et al., 1984).

Lower Pannonian sediments – mainly calcareous marls and limestones (Prkos or Valpovo Fm. – Fig. 2) – were deposited in a shallow lacustrine environment (Figs. 3 and 4), but there are also minor deltaic bodies along the faulted margins of depressions. The composition of these sandstones is closely associated with the underlying rocks so they are interpreted to be locally derived. In the western part of the Drava depression in Croatia (Fig. 3) this is already the time when the first turbidite sandstones were transported from the NW (Koprivnica Ssts. – Fig. 2), found to be lithologically identical with the overlying units. The following, mainly Upper Pannonian to Pontian sandstone–shale sequence (Ivanić Grad, Kloštar Ivanić and Široko Polje Formations in the Sava depression – see ŠIMON, 1973, 1980) was deposited in locally very deep troughs, especially in the western part of the Drava and Sava depressions. The troughs were largely isolated from the rest of the Pannonian basin by islands or by subaqueous basement highs. These sediments are of fairly uniform lithological composition: a sequence of sand/sandstone (subgreywacke and calcarenite–subgreywacke) bodies interlayered with silts and marls (Fig. 2). Sands and sandstones are grey-coloured, with a predominance of quartz grains, and some lithoclasts (usually limestone), platy minerals and feldspar grains. The mineralogical composition of the sandstones (subgreywackes) is almost the same and is interpreted as being a consequence of an external and distant sedimentary source (in contrast to the older Miocene sediments – ŠĆAVNIČAR, 1979). The morphology of these multiple sandstone bodies indicates a turbidite fan to delta system. Sedimentary transport from the N–NW resulted in progradation of firstly the turbidites and then the prodelta, delta slope to delta front clastics, with the aerial distribution of lithofacies largely influenced by the elongated shape of the depositional basins. A depositional model was constructed with the source of sediments in the Alps, and transport by turbidity currents (ŠIMON, 1980). In this process, coarser grains were deposited in the deepest parts of the depressions and fine-grained material at the basement highs. In the Upper Pannonian sediments of the western Sava depression this was later confirmed by the investigations of VRBANAC (2002a, b), substantiated by a large data set of core investigations. Analysing the aerial distribution of the Lower Pontian turbidites in the western part of the Sava depression SAFTIĆ (1998) confirmed that regionally recognisable E-log markers delimit numerous sandstone members as genetic units. The markedly uniform petrographic composition of both sandstones and marls, together with their sedimentological characteristics, are congruent with the external sedimentary source. More detailed dating of high-resolution units still remains a problem nevertheless, it appears that the deltaic environment was formed almost ubiquitously in the Late Pontian, except in the deepest parts of the Sava depression.

During the Pliocene and partly in the Pleistocene, there remained several deep or shallow lakes in the SW Pannonian basin where sedimentation continued in the same environments (Figs. 3 and 4). Infilling of the remnants of Lake Pannon occurred with a variety of coarse clastics mixed with clay, and lignite seams formed in delta plain marshes. These were followed by meandering river systems. As climatic change coupled with basin inversion and uplift of mountainous areas took place in the Quaternary (FRISCH et al., 1998), not only sandstones but also gravel beds appeared as channel fills. The oldest gravels in the Mura and Drava river valley are the Belvedere gravels (oldest Quaternary or Pliocene–Quaternary) while the Sava river brought mainly carbonate-clasts as sandy gravels only in the Holocene. During the Pleistocene glacial periods loess mainly accumulated in the area and there are also aeolian quartz sands deposited in the western part of the Drava depression. Lacustrine–marsh sediments are characteristic for the warmer periods – more detailed recent descriptions of these sediments can be found in the work of VELIĆ & SAFTIĆ (1991), VELIĆ & DURN (1993), VELIĆ et al. (1999) and BAČANI et al. (1999), where results of mainly hydrogeological explorations are used for stratigraphic interpretation.

4. NEOGENE SEDIMENTARY MEGACYCLES

The Neogene to Quaternary basin fill in the SW marginal parts of the Pannonian basin usually has an average thickness in the range of 500–1500 m, except in the central parts of depressions where much bigger values – around 4000 m in the Slavonija–Srijem depression, 5500 m in the Sava and Mura depressions, and close to 7000 m in the Drava depression are found (Fig. 10). This huge sedimentary pile can be subdivided into three main sequences.

The cyclic character of the Neogene sedimentary successions of the region was recognized long ago (FILJAK et al., 1969; HÁMOR, 1970) and the three units were later defined by ŠIMON (1980) as the "macro-rhythms of sedimentation". The comparable units were later named "megacycles" (VELIĆ et al., 2002), as their inferred time-span is of 6.8, 5.9 and 5.6 Ma respectively (measured on the geochronological scale of RÖGL, 1996; cf. Figs. 2, 3 and 4). Each of these megacycles encompasses rocks deposited during 2nd order transgressive–regressive cycles, influenced mainly by tectonics (VAIL et al., 1991).

The megacycles are separated by major unconformities, as follows:

– Base Neogene unconformity, which usually separates the historically complex basement from either the Early, Mid- or even Late Miocene sediments. On seismic sections it is an onlap surface (Figs. 6, 8 and 9); in outcrops or borehole successions it is usually covered by a transgressive lag of coarse clastics of various ages. This is usually regarded as the synrift unconformity (cf. HORVÁTH & TARI, 1999),

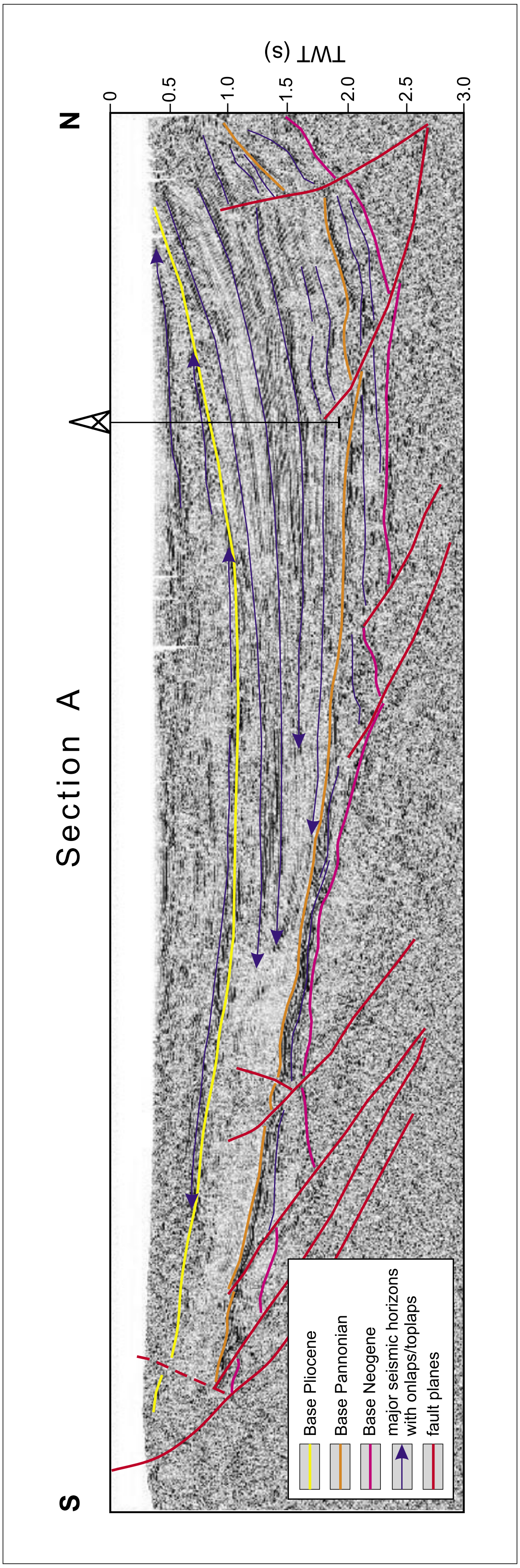

Fig. 6 Section A – western Sava depression (see location in Figs. 10–13).

however, the onlapping younger deposits (e.g. Late Miocene) indicate that this surface is often a composite unconformity. The following Basal Late Badenian unconformity is usually considered to be the syn-rift/post-rift boundary (ROYDEN & HORVÁTH, 1988; TARI, 1994; HORVÁTH, 1995; VAKARCS, 1997; PAVELIĆ, 2001). It is not as straightforward to identify seismically as the younger one.

– The Base Pannonian is the next major unconformity. Lake Pannon deposits are onlapping either the basement (Figs. 5 and 9) or older Miocene deposits (Figs. 6–8) with a transgressive lag (POGÁCSÁS et al., 1988; SZENTGYÖRGYI & JUHÁSZ, 1988; HÁMOR, 2001). Seismic sections clearly reveal the erosional character of this surface, as it cuts the previously tilted Badenian–Sarmatian successions (Figs. 5 and 8). The Base Pannonian unconformity is a result of uplift and erosion caused by the first compressional (inversion) event, proved both by seismic and outcrop-scale structural data (TARI, 1994; HORVÁTH & TARI, 1999; CSONTOS et al., 2002).

– The Base Pliocene unconformity seems to be the result of another compressional event, generating both uplift of the pre-existing basement highs with the overlying Lake Pannon deposits, formation of new highs and subsidence between these areas. Thus sediments above this unconformity are onlapping in character (Figs. 5, 6, 8 and 9). In areas of continuous subsidence an uninterrupted Miocene–Pliocene sedimentation is recorded. Even a fifth, Quaternary unconformity exists, as the reflection of the youngest basin-wide and local Quaternary uplift/compressional event (DUNKL et al., 1994; TOMLJENOVIĆ & CSONTOS, 2001; CSONTOS et al., 2002). In some places it can be well observed on seismic sections (Fig. 6).

A description of the main characteristics of distribution/composition of rock units grouped in the three megacycles follows, illustrated by thickness maps (Figs. 10–13).

4.1. Terrestrial to marine deposits (Base Neogene – top Sarmatian)

The succession from the Base Neogene unconformity to the erosional top of the Sarmatian sediments is referred to as the 1st megacycle, which is the sedimentary response to syn-rift and early post-rift structural evolution of the Pannonian Basin. On the thickness map of this unit (Fig. 11) the darkest spots mark regions where all the underlying older formations are exposed. These range from the oldest, Palaeozoic crystalline rocks, through a variety of Mesozoic formations (mostly in the inselbergs) to the youngest pre-basinal unit – Cretaceous–Eocene flysch in the contact zone with the Inner Dinarides (W of Varaždin – “Vz” and SE of Karlovac – “Ka”). Areas where the thickness exceeds 1 km are loci of the main depocentres and are shaded by grades of light grey.

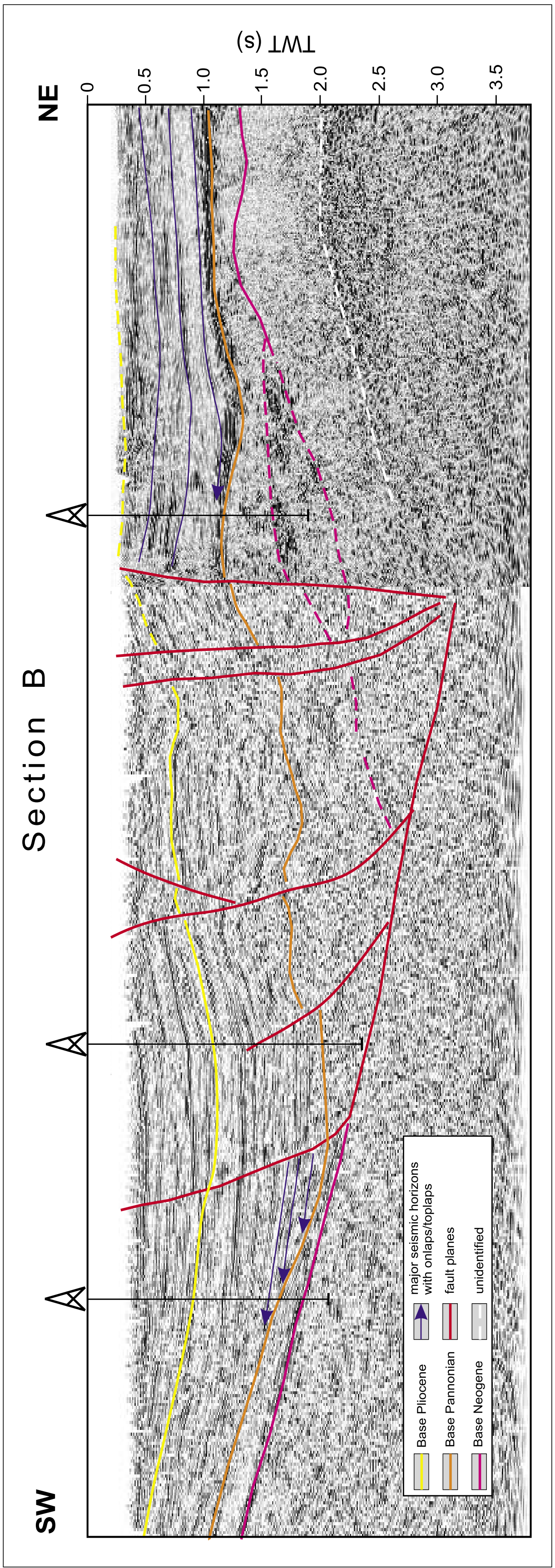

Fig. 7 Section B – central Sava depression (location in Figs. 10–13).

The deepest troughs, thus the thickest successions, are found in the northern part of the Drava depression (Fig. 11, also sections in Figs. 5 and 9). These half grabens are thought to be associated with stretching of large lithospheric units during eastward motion and rotation (CSONTOS et al., 1992; CSONTOS, 1995; CSONTOS & NAGYMAROSY, 1998). Mainly neutral–acidic volcanism was related to the stretching, filling the half grabens with lavas and volcanoclastics up to a thickness of 1500 m. A series of partly isolated depocentres scattered along the southern margin of the present Drava depression and along the northern margin of the Sava depression are also remarkable. These occur along the strike of the major longitudinal fault systems along which rifting started in Ottnangian times (TARI, 1994; HORVÁTH, 1995; TARI & PAMIĆ, 1998; HORVÁTH & TARI, 1999; FODOR et al., 1999; PAVELIĆ, 2001). The strong influence of tectonics on sedimentation in the syn-rift phase resulted in a variety of depositional settings and lithofacies. Obviously, 3rd order depositional sequences – not to be discussed here – are tectonically overprinted (cf. BÁLDI et al., 2002).

In the Croatian part of the study area, lithological composition and depositional characteristics of the 1st megacycle are described based on the maps and reports from the INA archives (AVANIĆ et al., 1995[5] and PIKIJA & ŠIKIĆ, 1996[6], 1999[7]). Ottnangian freshwater coarse clastics were found throughout the Drava depression, all around the Slavonian Mts. (Papuk, Krndija and Psunj), and also in the western Sava depression. Karpatian marine sediments were documented in the eastern Drava depression, at outcrops in practically all mountains of northern Croatia and NW of the Mecsek Mts. in Hungary.

At about the Karpatian/Badenian boundary, huge areas became inundated by normal salinity sea water and the former terrestrial depocentres became the loci of the deepest (bathyal) basins. Due to this Early Badenian sea-level rise the majority of the 1st megacycle consists of Badenian rocks. Upper Badenian coastal to shallow marine deposits are found around the coeval basement highs: Lithothamnion and bioclastic limestones prevail in the western part of the study area; conglomerates in the centre and extending to the Slavonija–Srijem depression; while marls are found on the slopes and in the central parts of all the depressions. The youngest part of the 1st megacycle is the Sarmatian, mainly conformably overlying Badenian sediments in many places throughout the study area. The basin was then starved

[5] AVANIĆ, R., PAVELIĆ, D. & KOVAČIĆ, M. (1995): Građa površinskih ekvivalenata formacija Ivanić-Grad, Kloštar Ivanić i Široko Polje.– Unpubl. report, INA–Naftaplin Archive, Zagreb.

[6] PIKIJA, M. & ŠIKIĆ, K. (1996): Stratigrafsko-facijesna interpretacija naslaga miocena (zaključno sa sarmatom) Dravske potoline.– Unpubl. report, INA–Naftaplin Archive, Zagreb.

[7] PIKIJA, M. & ŠIKIĆ, K. (1999): Stratigrafsko-facijesne odlike starijeg i srednjeg miocena Murske depresije i obodnih područja.– Unpubl. report, INA–Naftaplin Archive, Zagreb.

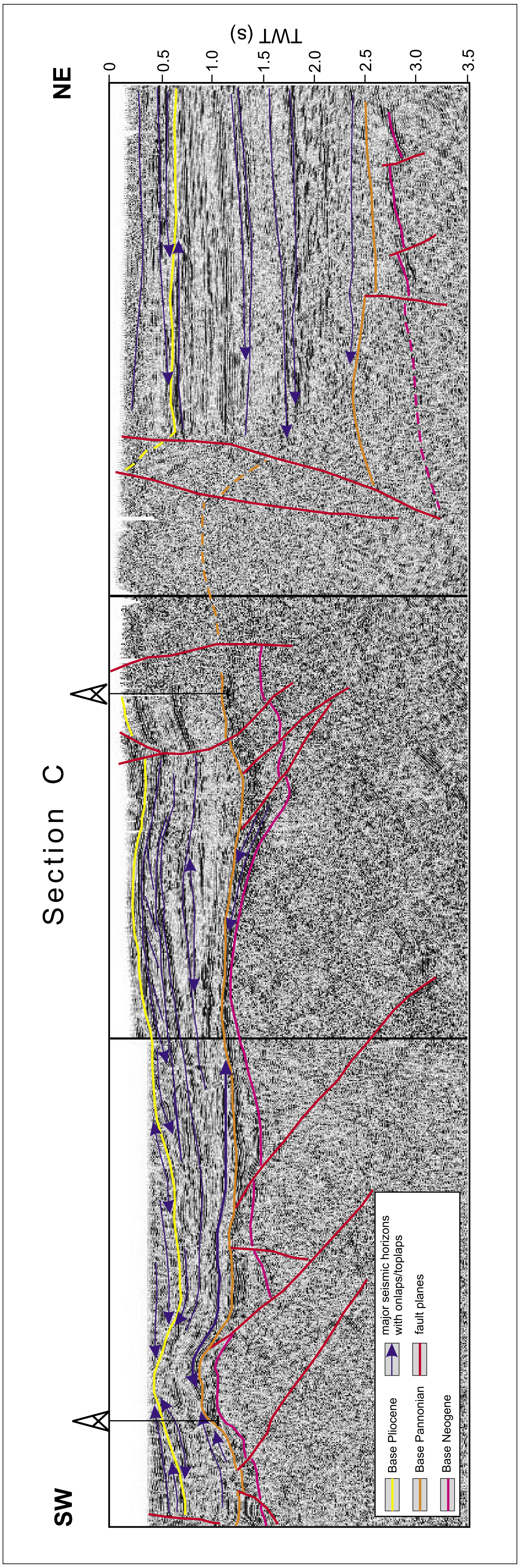

Fig. 8 Section C – Bjelovar sag and Drava depression (location in Figs. 10–13).

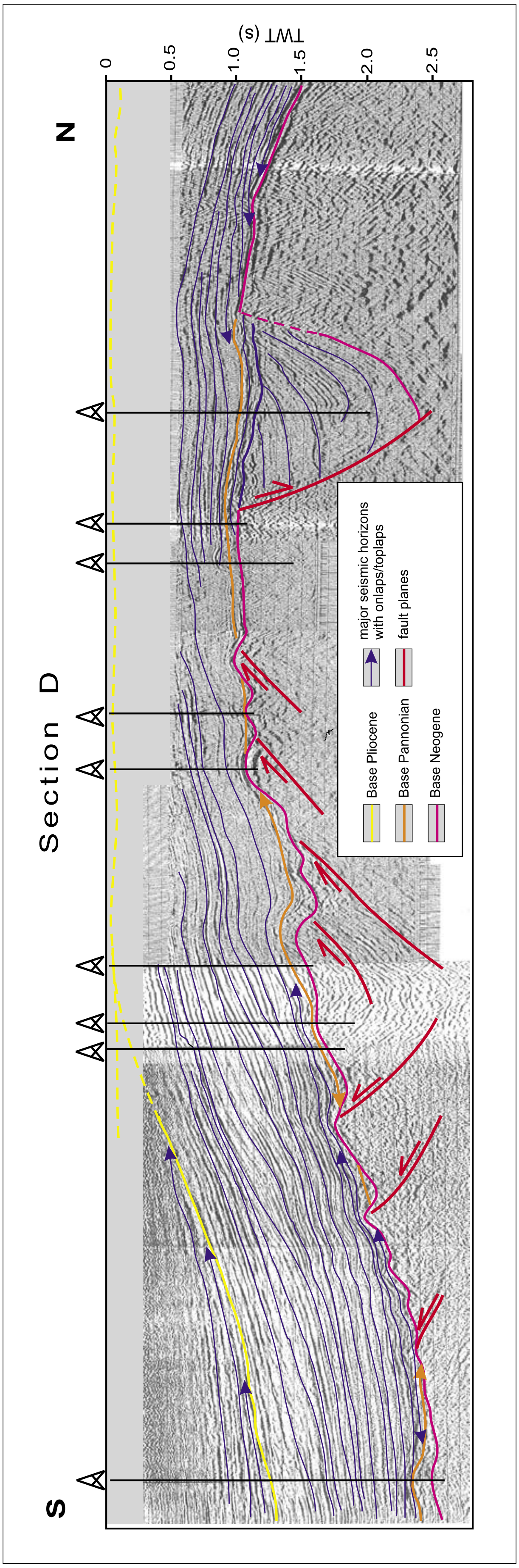

Fig. 9 Section D – northern part of the Drava depression (location in Figs. 10–13).

from the sediment supply and was later strongly eroded on some elevated blocks, so the Sarmatian unit is rarely thicker than 50 m. These layers were mostly deposited in a shelf environment with occasional coastal influence along the southern margin of the Sava depression and NE of Mt. Krndija. The offshore Sarmatian sediments were documented in the southern and western marginal parts of the Pannonian Basin, i.e. NE of Karlovac (“Ka”), W of Krapina (“Kr”), as well as in the eastern part of the Sava depression.

During the Late Badenian very rapid subsidence ceased, only slow post-rift subsidence occurred. At the end of the Sarmatian the first very pronounced compressive event resulted in rejuvenation of former extensional structural elements in a compressive regime (cf. TARI & PAMIĆ, 1998; HORVÁTH & TARI, 1999; CSONTOS et al., 2002). Some basement blocks were uplifted and to a various extent erosion of the syn-rift and early post-rift strata took place (Figs. 6 and 8).

4.2. Lacustrine, deltaic to alluvial deposits (Base Pannonian – top Pontian)

Sediments of the 2nd megacycle were all deposited in Lake Pannon during an interval of thermal subsidence that followed rifting (HORVÁTH & ROYDEN, 1981; ROYDEN & HORVÁTH, 1988; HORVÁTH & TARI, 1999).

As subsidence commenced after the basin inversion, the “lacustrine” transgression quickly inundated both the wide depressions and the basement highs. As a result, a large underfed lake with an inherantly uneven basin floor topography was born (ŠIMON, 1973, 1980; BÉRCZI et al., 1988; KŐRÖSSY, 1989). The thickness of the 2nd megacycle (Fig. 12) varies from 2000 m (western Sava depression) through 3000 m north of the Iharosberény high, to 4–5000 m along the SW margin of the Drava depression. As a rule, the maximum thickness is close to basin margin faults. These are also the places where sandstones of turbiditic origin show their maximum thickness (cf. Fig. 5). Turbidites, accumulating mainly in the deepest depressions, particularly in front of, and on the slopes of basement highs, gradually levelled the basin floor topography.

Above the turbidites deltaic progradation fed from the N, NW occurred. Due to persisting high rates of subsidence coupled with enormous rates of sediment supply, delta front-, delta plain-, coastal plain- to alluvial plain-series accumulated mainly in an aggradational style (Figs. 2–4), resulting in a relatively large uniform thickness. In the northern part of the Drava depression, the top of the successions infilling Lake Pannon were eroded mainly above the previously existing basement highs (Figs. 5 and 9), suggesting rejuvenation of former structural elements again in a reverse sense (cf. CSONTOS et al., 2002). According to the present regional seismic interpretation in the Sava depression (IVKOVIĆ et al., 2000), the entire Pannonian to Quaternary sequence can be subdivided into 6 seismostratigraphic units which start with turbidites, followed by progradation of deep-water deltas gradually shallowing up to the alluvial sediments.

4.3. Inversion-related lacustrine to fluviatile deposits (Base Pliocene – surface)

Sediments of the 3rd megacycle are found only in those depressions which are situated between the most elevated basement units. They begin with lacustrine deposits and marshes in the remnants of Lake Pannon in Pliocene times. Fluvial beds become more frequent in the Pleistocene (in the Drava river valley) and Holocene (Sava river valley). The end of the cycle is marked by gravels, loess and unconsolidated surface layers (Figs. 2–4). As illustrated in Fig. 13, the thickness of this unit is negligible in Hungary (below 200–300 m), but reaches well over 1000 m in several places to the south. Local thickness variations can be quite abrupt, producing differences in relatively closely spaced seismic sections (compare the NE end of Section C in Fig. 8 with the southern end of Section D in Fig. 9). In the central part of the Sava depression, over 1500 m were drilled and the sequence reaches 1800 m in the central Drava depression between the Slavonian Mts. and the Mecsek–Villány Mts. Contacts with underlying rocks are frequently marked with onlaps (Section A, Fig. 6; Section D, Fig. 9), and there are regions where these sediments cover all the older Neogene rocks and directly overlie Palaeozoic rocks (N and W slopes of Mt. Moslavačka gora). As a rule, in comparison to the previous megacycle the depocentres are shifted in a southerly direction (western Sava) or to the SE (Bjelovar sag and central Drava depression). Different relationships were determined in the eastern part of the study area where areas of the maximal thickness of the 2nd and 3rd megacycles either overlap each other (eastern Drava and Slavonija–Srijem depression), or there is a local shift of the depocentre in a westerly direction (eastern Sava – S of Mt. Psunj).

5. HYDROCARBON POTENTIAL

5.1. Source rocks within the Neogene basin fill

Studies of hydrocarbon source rocks in the Pannonian basin were intensified in the last two decades of the 20th century. A number of papers were published both in Croatia and in Hungary by the joint efforts of organic geochemists and petroleum geologists (BARIĆ & RADIĆ, 1988; DANK, 1988; HORVÁTH et al., 1988; KŐRÖSSY, 1988, 1989; BARIĆ et al., 1989; PUTNIKOVIĆ et al., 1989; RADIĆ et al., 1989; ALAJBEG et al., 1990; SZALAY & KONCZ, 1991; CLAYTON & KONCZ, 1994; HERNITZ et al., 1995a; HORVÁTH & TARI, 1999).

Neogene source rocks with type II and III kerogen content were deposited as marine or lacustrine clays

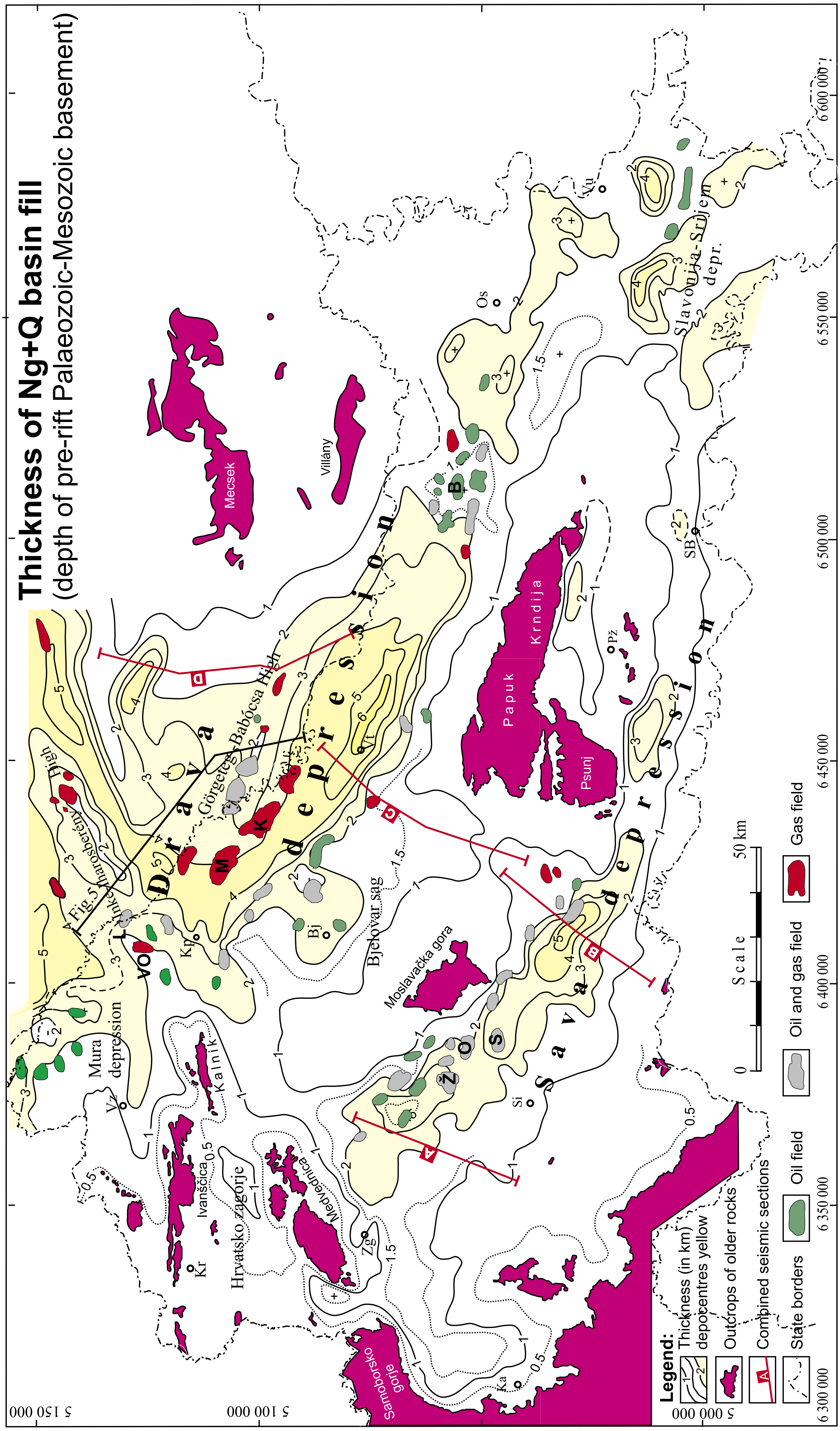

Fig. 10 Isopach map of the entire Neogene to Quaternary sequence with HC accumulations.

and marls. The source rocks are dark grey to black marls, calcareous marls, clayey limestones, siltstones and shales. In these sediments the organic matter usually appears uniformly dispersed in the matrix, but it can also be found in the form of lenses, bands or as centimetre to millimetre thick laminae. These source rocks were deposited during the 1st and in the beginning of the 2nd megacycle – mostly between the Base Neogene and the Lake Pannon turbiditic successions. They were formed mainly during the Karpatian and Badenian, and a minor portion during the Sarmatian and Early Pannonian (Figs. 3 and 4).

According to SZALAY & KONCZ (1991), in the Hungarian part of the basin, the oil generation window is situated between 2.4–4.3 km, while TOC averages 1–2 wt.% (up to 5 wt.%). There are type II and III kerogens, thus both oil and gas generation have occurred. In the southern part of the study area (in Croatia) there is a local variation in composition of organic matter. Two main types appear – either the hydrogen-rich kerogen type II (liptinite) mixed with some type I (alginite), or kerogen type III (vitrinite). Both types originate from the bacterially altered marine algal–lipid matter more or less mixed with terrigenous matter and deposited in the dysoxic–anoxic environment of the bottom waters. The source rocks are mostly mature, because they reached the conditions for expulsion at depths exceeding 2000 m and temperatures of over 100ºC. Oil–Source correlation determined that the C^{13}/C^{12} isotope ratio of the above source rocks has the same value in oils of the area, which means that the analysed hydrocarbons really originate from the described source rocks (PUTNIKOVIĆ et al., 1989; RADIĆ et al., 1989; HERNITZ et al., 1995a). When compared to the produced quantities and the total HC reserves, the Middle Miocene source rocks are evaluated as being thick enough and having a very good generation potential.

The situation in the western part of the Drava depression in Croatia is different because of the presence of large gas and gas condensate fields (Fig. 10). These are the deepest reservoirs of the Pannonian basin in Croatia. According to BARIĆ et al. (1992) the sediments rich in organic matter are found there in two intervals. The older one is of Early Miocene age (Fig. 3) and contains siltstones and mudstones at a depths of 3200–4500 m. Hydrogen indices are significantly reduced – this is the kerogen type III, and rocks are presently in the phase of increased thermal maturity (mature to over-mature) and capable of generation of dry and wet gas and gas condensate. It was found that part of the source rocks from this interval has generated only dry gas, which is thermally highly altered. The younger interval of source rocks in this area is formed of Badenian sediments and Pannonian fossiliferous calcareous marls at a depth of 2000–3000 m. Optical analyses of the maceral composition of kerogen, revealed predominance of vitrinite and debris of wood structure, as well as sporadic concentrations of exinite which, of course, originate from the land, but which were deposited in lacustrine anoxic conditions. These rocks are presently situated within the oil window.

There are also older, pre-Neogene source rocks in the nearby parts of the Pannonian basin. In the Hungarian Zala basin, in the NW part of the study area, two–three types of oils were identified by isotopic, chemical and biological signals, which indicate that the Upper Triassic black shales (Kössen Marl) were the main source rocks, and that Miocene source rocks produced only minor amounts. Oil generation and expulsion both from Triassic and Miocene source rocks began during the Late Miocene extension (CLAYTON & KONCZ, 1994). In the Drava basin this Kössen Marl cannot be found in the pre-Neogene basement, therefore the main source rocks must be of Neogene age, but that does not mean that similar future findings can be ruled out, especially in the contact zone of the Dinarides and Eastern Alps. In the same area, there are the remnants of the Slovenian Trough with lots of flysch sediments and also Cretaceous–Palaeogene flysch sediments under the most western part of the Sava depression – but this is beyond the scope of this paper.

5.2. Main petroleum reservoirs

Matured hydrocarbons migrated along the major unconformities and fault zones from the deepest parts of the depressions towards the structural traps situated usually above the basement highs or in en-echelon folds in the vicinity of the most faulted margins of the depressions. Neogene sand beds in folded and compacted anticlines over basement highs are the most obvious hydrocarbon traps (KRANJEC, 1972; DANK, 1988). Occasionally the fractured basement together with the generally overlying basal conglomerates bears hydrocarbons. Stratigraphic traps are difficult to find and only minor occurrences of this type have been discovered.

Most of the reservoirs are within the 1st and 2nd megacycles – Ottnangian breccias, Karpatian, Badenian or Pannonian basal conglomerates and Lake Pannon prodelta turbiditic lobes, sand sheets, slumps, delta front mouth bars and delta plain channel fills have the most favourable reservoir characteristics (Figs. 3 and 4). The seals are usually provided by the associated intralobe mudstones or interdistributary clays. The most important lithostratigraphic units are illustrated in Fig. 2, details can be found in the works of ŠIMON (1973) and KŐRÖSSY (1989). The oldest coarse-grained clastic member of the Ivanić Grad Formation – **IVA Sandstones**, contains 30% of the total discovered HC reserves in Croatia. Most thoroughly investigated in the Sava depression (VRBANAC, 2002b), it was deposited in a deep basinal, prodelta environment. This finding can be extrapolated in other sub-basins. More detailed descriptions can be found in the works of ĐUREKOVIĆ (1995), KOVAČEVIĆ (1996), LARVA (1996) and MATASOVIĆ (1996) and also the first part of this paper. The most important characteristic for HC accumulation in this unit is that porosity varies from

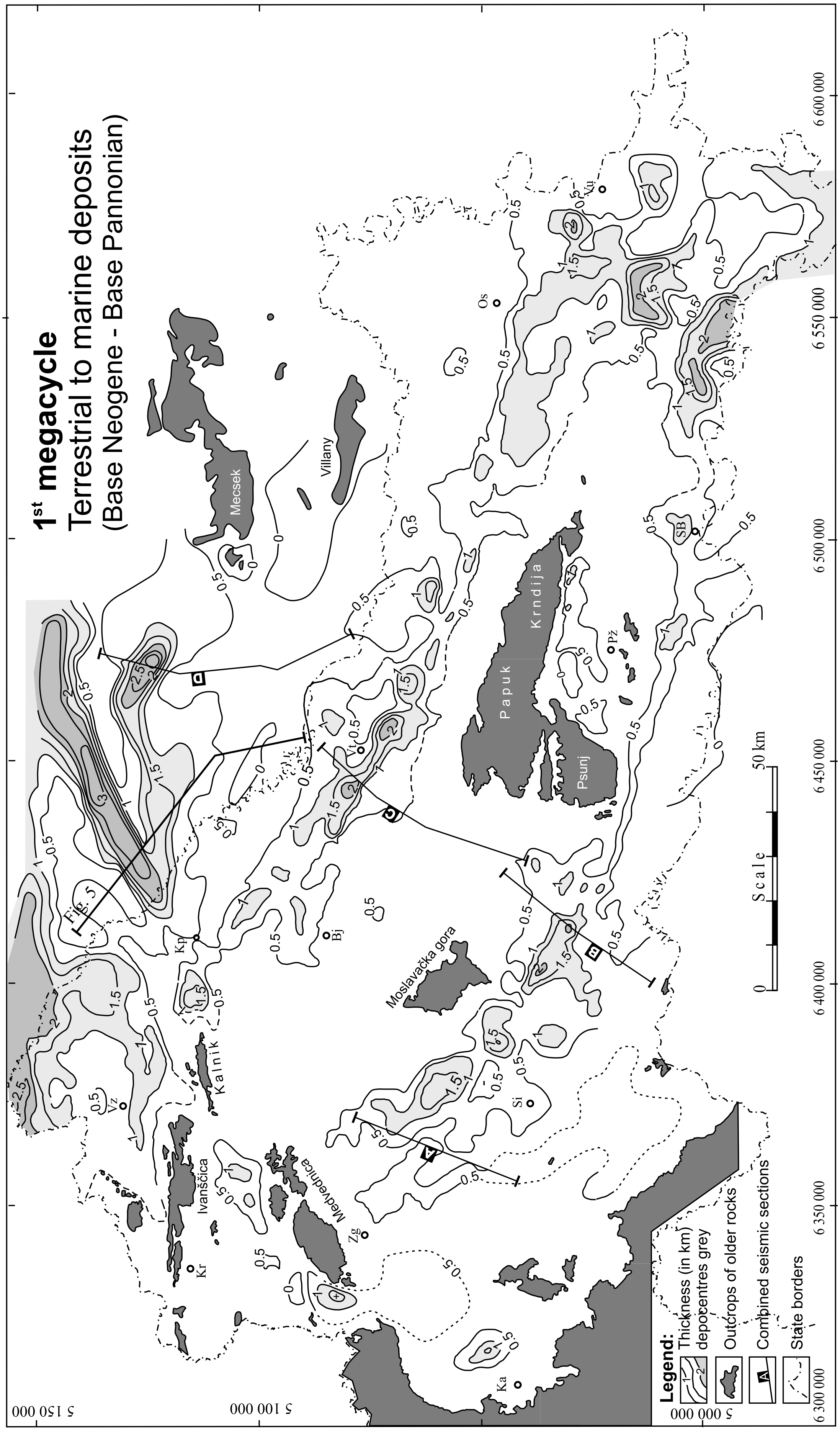

Fig. 11 Isopach map of the 1st megacycle.

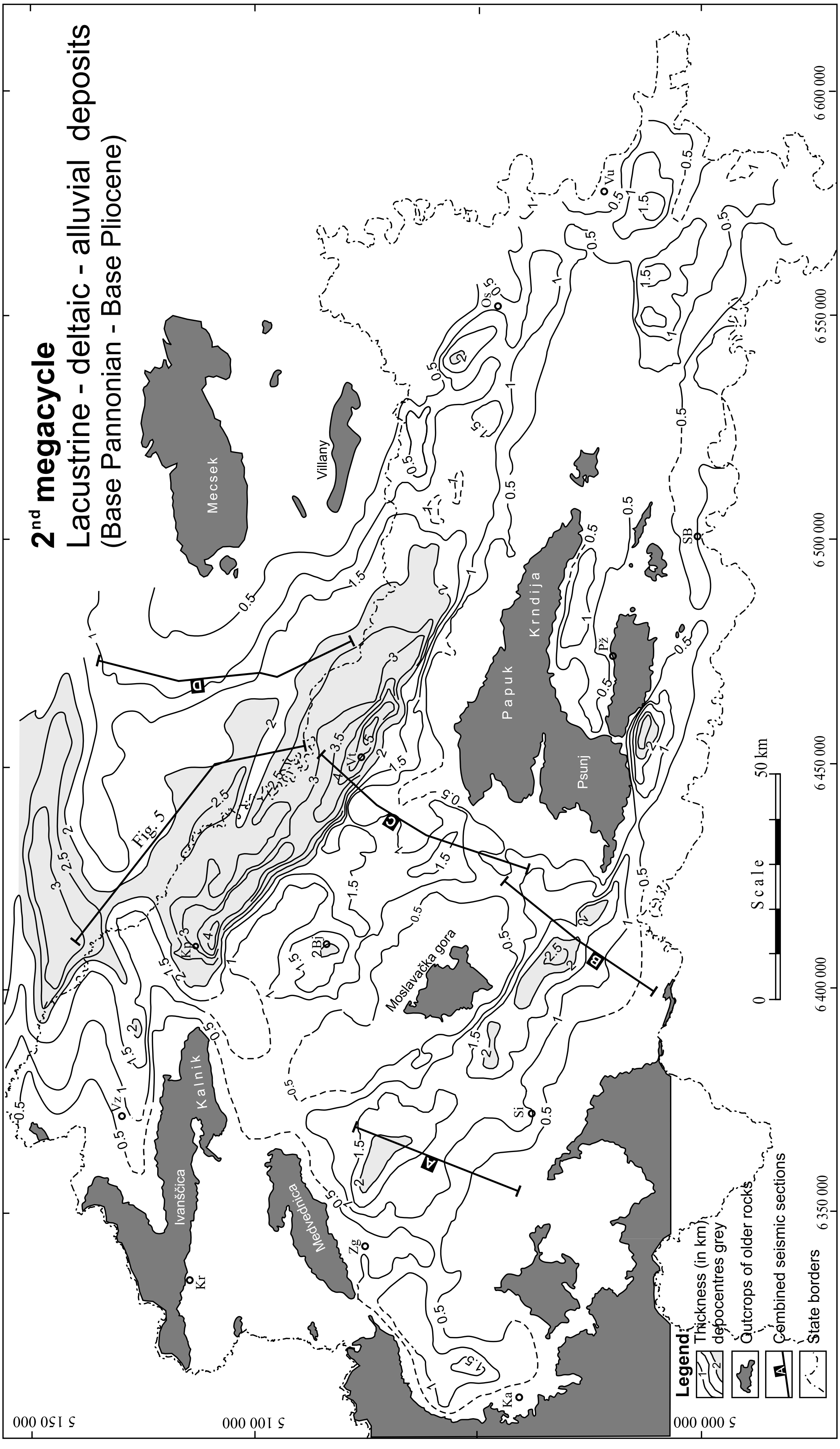

Fig. 12 Isopach map of the 2nd megacycle.

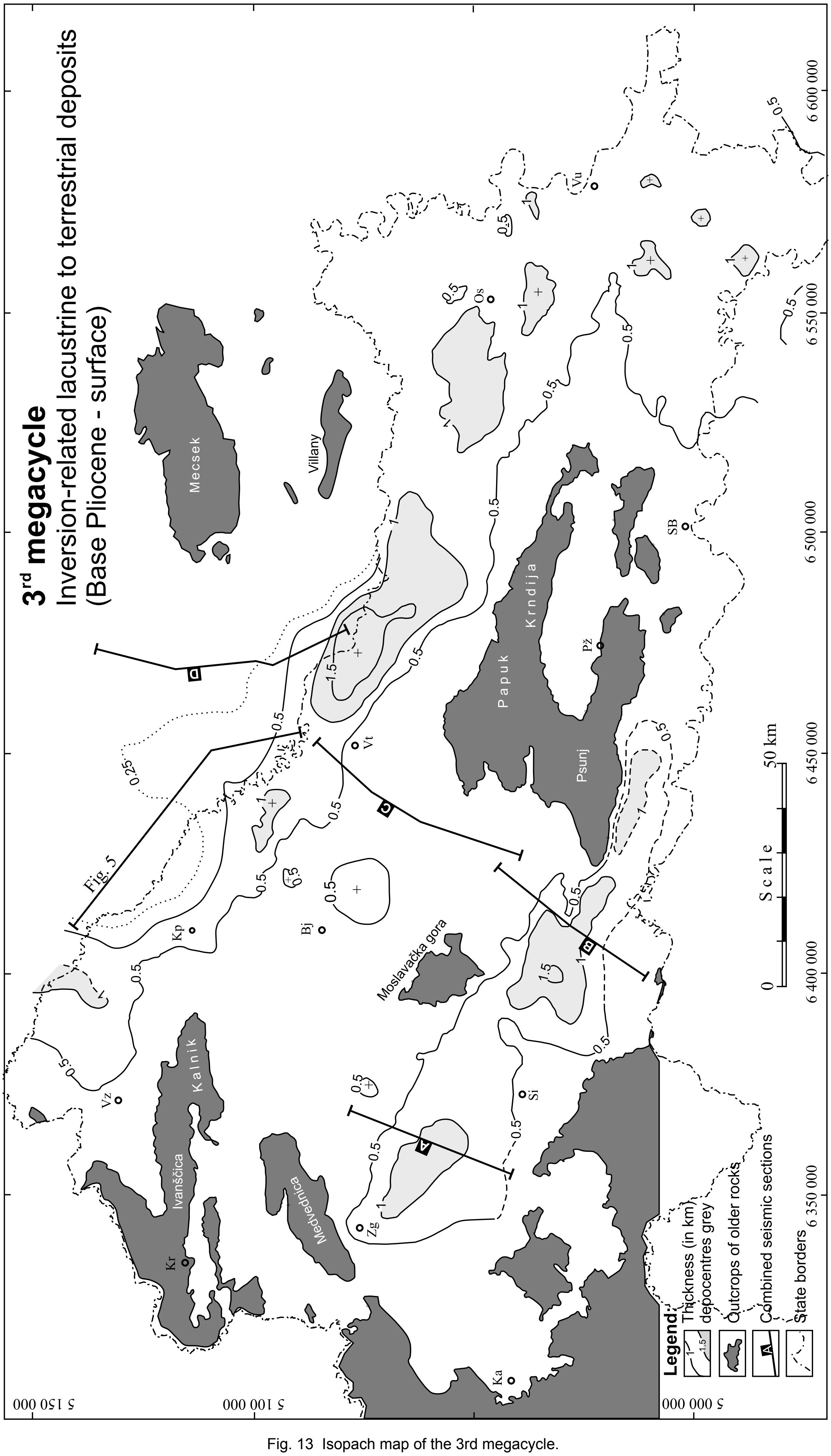

Fig. 13 Isopach map of the 3rd megacycle.

11% to 25% and even 30%. It was also determined that porosity declines with depth, mainly because of compaction and because the ratio of the silt-sized grains increases in this direction. The horizontal permeability was also measured on cores and it is between $0.1x10^{-3}m^2$ and $380x10^{-3}m^2$. Reservoir characteristics usually vary over relatively short distances, which must be precisely defined in order to obtain a better recovery ratio, especially in the phase of secondary production (injection of water or gas) or in the planned tertiary production methods.

The **Drava depression** is both the largest and the deepest sub-basin in the study area. The deepest part lies between Virovitica and Slatina ("Vi" and "Sl" in Fig. 10), where the thickness of Neogene and Quaternary sediments can reach 7000 m. In the Croatian part of the Drava depression, 30 gas and oil fields were discovered, of which 23 are presently producing oil, gas condensate or gas. In the western part of the Drava depression, the HC traps are within conglomerates and sandstones of the Lower and Middle Miocene (1st megacycle) and Pannonian sandstones (basal part of the 2nd megacycle). Above, the Lower Pontian sandstones also have good reservoir properties. Nevertheless, the most valuable hydrocarbon accumulations are in the fractured Palaeozoic and Mesozoic rocks with secondary porosity; the reservoirs at Molve and Kalinovac ("M" and "K" in Fig. 10) are the largest gas and gas condensate fields in Croatia. In the eastern part of the Drava depression, the largest HC accumulation is the Beničanci oil field (marked with "B", where more than $18x10^6m^3$ of oil has been produced since 1972). Here the reservoir rocks are Middle Miocene basal carbonate breccias with excellent petrophysical properties (HERNITZ et al., 1995b). According to TIŠLJAR (1993), the Beničanci reservoir is composed of wedge-shaped bodies of rockfall and debris breccias, formed by the accumulation of large masses of dolomite detritus from the shore zone. The cliffs of the steep shoreline were situated along the margins of the faulted dolomite massif that was gradually uplifted. In this unit there are also thinner bodies of breccias, conglomerates and sandstones built up by detritus of coral reefs (VELIĆ et al., 2000). They were also deposited in the shoreline zone during the Early Badenian sea-level rise and subsequent Late Badenian transgression.

On the Hungarian side of the Drava depression two basement highs are of primary interest: the Inke–Iharosberény high at the north-western part of the basin and the Görgeteg–Babócsa high to the south (Fig. 10). Görgeteg is also a historical place, because the first well log measurements in Hungary were carried out here in 1935. In this area both oil and gas bearing rocks are confined to Lake Pannon turbiditic sand sheets and in one example to a delta plain channel-fill sandstone. The excellent reservoir quality sandstones of the delta front and delta plain hardly ever contain traps because there are no good seals in the extremely thick wave-reworked, delta-front successions. Not far from Görgeteg a minor oil pool was also found in the Badenian Leitha (Rákos) Limestone, and north of the high, minor indications of oil reservoirs were detected in Badenian (tuffaceous) sandstones, and conglomerates of shallow marine origin. South of the main Görgeteg high, a minor anticline was found, in which gas reservoirs are situated at the top of the Palaeozoic basement and in the overlying Badenian transgressive coarse clastics. At the Inke high small isolated sand bodies of Badenian to Lower Pannonian are producing minor amounts of gas. In addition, occasionally the top of the fractured Triassic carbonates is a CO_2–CH_4 reservoir. Between the two major highs, the Somogyudvarhely–Gyékényes depression is found, which acted rather as a source area; here both the fractured crystalline basement and the overlying Karpatian to Badenian sandstones contain indications of oil and CO_2 (KŐRÖSSY, 1989).

The **Mura depression** is in the NW part of the study area. The most valuable hydrocarbon reservoirs in the southern part of it occur in breccias, conglomerates and sandstones of the Early and Middle Miocene, and Lake Pannon sandstones of different depositional facies. Reservoir rocks were deposited in a variety of depositional settings, ranging from the subaqeous slumps and turbidites (Ottnangian–Badenian) to flood plain and slope lithoarenites and biocalcarenites, mixed with siliciclastic detritus that were formed in the vicinity of patch reefs (mostly Badenian). The described sediments form HC reservoirs of several smaller and two larger fields – Veliki Otok and Legrad ("VO" and "L" in Fig. 10) which, according to the cumulative production, are amongst the 10 largest gas fields in Croatia. Similarly to the Hungarian part of the Drava depression, quite large, but CO_2-rich gas accumulations were recently discovered in the Triassic basement highs in the very NW corner of the study area, close to the border with Slovenia.

The **Slavonija–Srijem depression** in the SE corner of the study region is relatively shallow and covers the smallest area. Only the western part lies in Croatia, where the entire Neogene–Quaternary sedimentary and volcanic succession has a maximum thickness of 4000 m (Fig. 10). Three HC fields were discovered in this area, with relatively shallow reservoirs (approx. 1000 m) formed of the fractured and weathered Palaeozoic and Mesozoic rocks together with overlying Lower and Middle Miocene clastics (1st megacycle).

The **Sava depression** lies along the SW margin of the Pannonian basin and the thickest sequence of the Neogene–Quaternary sediments (over 5000 m) can be found in its central part, S of Mt. Moslavačka gora (Fig. 10). The most important reservoir rocks are Pannonian and Pontian sandstones which start with the transgressive locally sourced sandstones, soon pass into turbidites and end with large masses of deltaic sediments (mostly sandstones). There are HC reservoirs also in the weathered and fractured Palaeozoic granite and gneiss of the covered western slopes of Mt. Moslavačka gora, but the most important fields are in Neogene reservoirs – Stružec, Žutica and Okoli fields (marked with “S”, “Ž” and “O” in Fig. 10).

6. CONCLUSIONS

1) In the Neogene sedimentary succession three depositional megacycles can be identified in the SW part of the Pannonian Basin. Each encompasses rocks deposited during 2nd order cycles influenced mainly by the structural evolution of the basin. The megacycles are separated by major unconformities – the Base Neogene, the Base Pannonian and the Base Pliocene unconformities, which usually separate the onlapping deposits of the younger cycle from uplifted, tilted and eroded older rocks. These uplifts interrupting basin subsidence reveal compressional events in association with inversion tectonics. Such a subdivision is suitable for the subsurface geological data, in the sedimentary record the actual syn-rift/post-rift boundary is identified as the prominent unconformity in the base of the Late Badenian sediments. Even a fifth, Quaternary unconformity exists, as the reflection of the youngest uplift of the mountainous areas.
2) The 1st megacycle is composed of Early to Middle Miocene syn-rift and early post-rift sediments. Terrestrial sandstones, subordinate coal seams, coastal talus breccias, conglomerates and sandstones are overlain by shallow to deep marine marls and shales of varying carbonate content and with thin sandy intercalations, while biogenic and bioclastic limestones were formed in the nearshore zone. The end of the megacycle is characterised mostly by fine-grained deposition in the starved brackish-water basin.
3) The 2nd megacycle is connected to the thermal subsidence of the Late Miocene Pannonian basin, thus is built up by the post-rift sediments of Lake Pannon. Apart from local variations due to pre-Pannonian topography the sedimentary succession begins with littoral limestones and a nearshore transgressive lag overlain by hemipelagic calcareous and clayey marls basin-wide. The deepest depressions were filled by lacustrine turbidite lobes and channel fills of considerable thickness, thus the initial basin floor topography gradually became levelled. Turbiditic successions are overlain by shale-prone delta slope and sandy delta front to coastal plain sediments. The northern part of the Drava depression was filled to lake level and the youngest deposits of this megacycle were formed in fluvial environments. To the south, deposition continued on the delta front and in the prodelta region respectively.
4) The 3rd megacycle was formed during Pliocene to Quaternary basin inversion resulting in subsidence in the deepest zones, associated with uplift and erosion of the most elevated blocks. At that time Lake Pannon occupied only the southern part of the study area where basin fill up to fluvial deposits continued in a similar manner as previously occurred.
5) The main source rocks with type II and III kerogens are Middle Miocene marine clays and marls and Upper Miocene hemipelagic marls of Lake Pannon. They generally occur in the oil generation window or in the wet and dry gas zone depending on their present-day position in the basin.
6) The main hydrocarbon reservoirs are above structural highs in the studied basins, either in the fractured Neogene basement, associated with basal conglomerates and sandstones, or in the Neogene sedimentary succession. Lower to Middle Miocene coarse clastics – rockfall breccias composed mostly of Mesozoic dolomite fragments, conglomerates and sandstones accumulated in the coastal to shallow marine zones during the Badenian, form reservoirs with good characteristics. The most important reservoirs, however, are sandstone bodies of different (turbiditic or deltaic) origin within the Upper Miocene 2nd megacycle. Their reservoir characteristics are highly variable.

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