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"Groundwater Heritage and Sustainability"

EXCURSION GUIDEBOOK

Arboretum Trsteno - Koločep Bay - Ston

25th - 29th September 2017, Hotel Dubrovnik Palace, Croatia

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Excursion: Arboretum Trsteno - Koločep Bay - Ston

Fig. 1 Map of the area with field trip stops

STOP 1: ARBORETUM TRSTENO
STOP 2: KOLOČEP BAY
STOP 3: STON

REGIONAL HYDROGEOLOGICAL SETTINGS OF THE DUBROVNIK - NERETVA REGION

Staša Borović[1] & Josip Terzić[1]

Croatia can, generally, be divided into two very different regions based on their geological settings. The North-eastern part of the country represents the southern margin of the Pannonian Basin System, while the south-western part belongs to the Dinarides. Dubrovnik - Neretva County is the southernmost county in the Republic of Croatia and, in accordance, its structural fabric forms part of the Dinarides. The geological and tectonic settings also dictate the hydrogeological features.

Based on their lithology and age, three dominant types of rocks and deposits can be identified in the area:

1. Carbonate rock complex, encompassing rocks from Upper Triassic, Cretaceous up to Lower Eocene (230 - 40 Ma);
2. Upper Eocene clastic flysch deposits (40 - 34 Ma);
3. Various Quaternary deposits found in karst poljes and the Neretva River delta (<1.8 Ma).

It should be emphasized that carbonate rocks predominate in the region.

The distribution of these deposits reflects the structural and tectonic relationships of the wider area. The regional structural setting is composed of the Dinaric, Epiadriatic and Adriatic structural units of the Dinarides: consecutively positioned from inland toward the shore and islands (Herak, 1991). The current setting is the consequence of the movement of the Adria microplate toward the Dinarides, which resulted in its subduction beneath the Dinarides. In the Dubrovnik-Neretva area, these deposits reach depths of 15-20 km (Aljinović, 1984; Aljinović et al., 1987). On the surface, the Dinaric units are thrust onto the Epiadriatic structural unit. Rock fracturing at the surface is the only manifestation of much greater movements taking place at depth (Prelogović et al., 1999). Hydrogeologically, this area is a typical example of the globally famous karst locus typicus - the Dinaric karst. Geology and tectonics of the Dinaric karst have been described in numerous publications (in addition to those already mentioned see: Prelogović et al., 1995; Vlahović et al., 2005; Korbar, 2009). Due to compressive tectonics dominated by overthrusting and reverse faulting of geological structures, karstification reaches deep horizons in the underground and karstified rock masses are very irregularly distributed. This makes hydrogeological relationships extremely complex; the delineation of catchments is very challenging, and numerical modelling virtually impossible.

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Dubrovnik, Croatia, 25th - 29th September 2017

The Dinaric is the most prominent regional structural unit, composed of thick carbonate deposits. A thrust fault front on the surface consists of Triassic dolomites, upon which there is a continuous sequence of Jurassic and Cretaceous deposits, predominantly composed of limestone. The Dinaric unit was thrust onto Epiadriatic fine-grained flysch deposits. The thrust fault front is a regionally prominent geomorphological feature; visible as a carbonate escarpment reaching maximum heights of 500 m. Sub-horizontal tectonic movements are estimated to be up to 10 km (Marković, 1971), which caused the Epiadriatic flysch deposits to be either completely thrust under the Dinaric unit, or eroded. Their extent on the surface of the terrain rarely reaches 1 km in width.

The regional structural unit of the Adriatic comprises carbonate rocks situated to the south of the flysch deposits. A carbonate rock mass comprising the coastal area and the Pelješac peninsula generally represents a monocline structure of dinaridic strike (NW-SE), dipping toward the NE. Dip angles are mostly between 20° - 50°, but can be up to 70° on the Pelješac peninsula. Geological structures on the islands are characterized by their “Hvar” strike (W-E). Carbonate rocks are folded, and small karst poljes were formed in the synclinal parts of the structures.

Seismic activity in the area proves that tectonic movements have not ceased in the neotectonic phase. Maximum expected intensity is 9-10° on the MCS-scale, while 7.5 is the maximum predicted magnitude on Richter scale (Kuk et al., 1987).

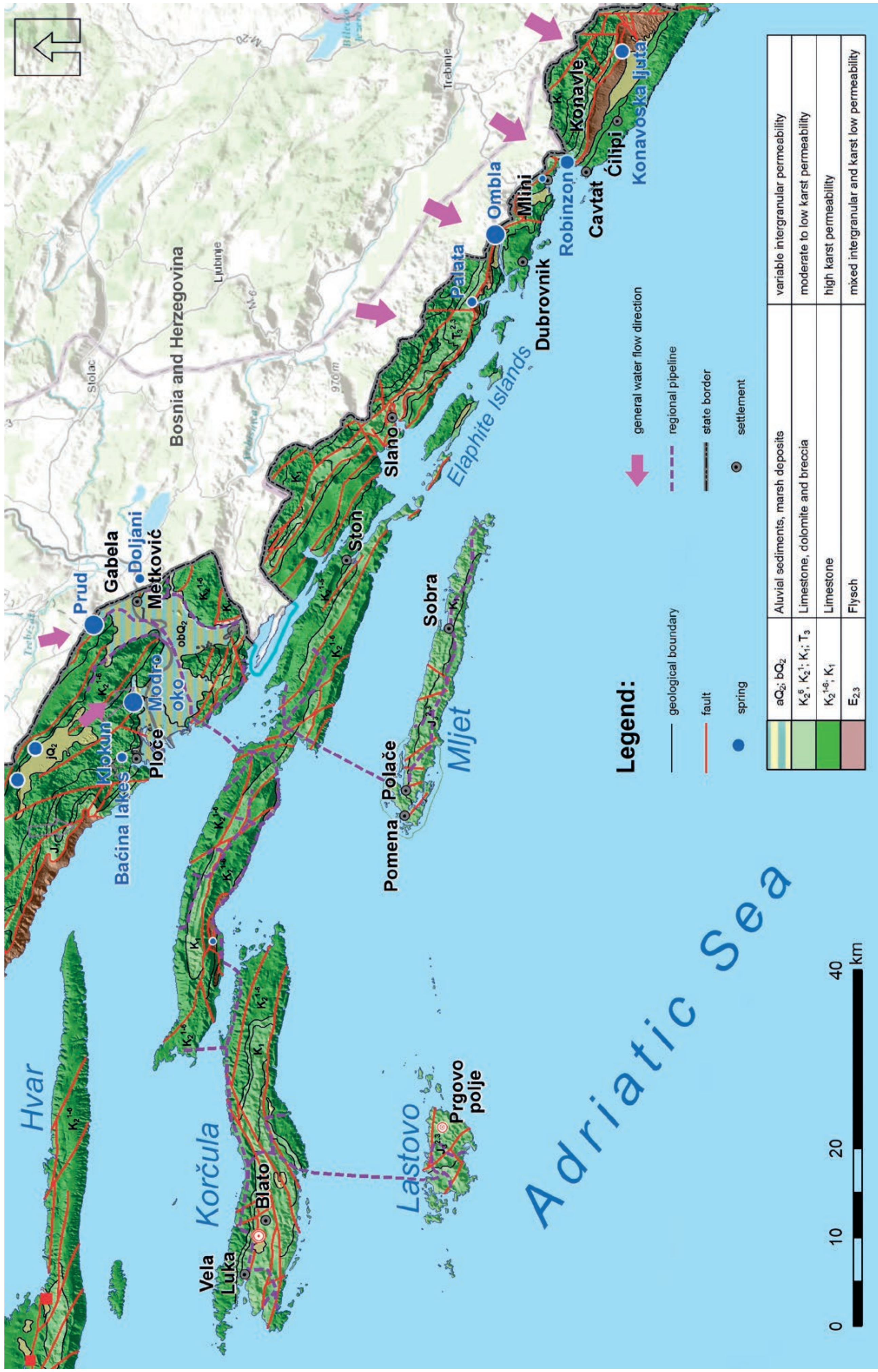

Fig. 2 Hydrogeological map of the area

Deposits in the area can be classified according to their hydrogeological properties into three basic categories: high permeability deposits, low permeability deposits and impermeable deposits.

High permeability deposits are karstified limestones of different ages and they represent the most important aquifers (Fig. 2). Their hydrogeological properties, along with the monocline geological structure and tectonics (which were of paramount importance for the formation of underground flow systems), enabled the formation of large watersheds and high-yield springs in these hydrogeological units.

The carbonate complex also encompasses dolomites in the form of lenses or layers of different thickness. Due to their lithological features, their permeability is lower than that of the limestones. Dolomite zones therefore represent a modifier capable of redirecting groundwater flow within the carbonate complex, which is often called the dolomite barrier.

A narrow coastal zone of impermeable (at the regional scale) flysch deposits is locally very thick (up to 500 m). In the coastal area between Slano and Konavle it represents a total hydrogeological barrier to karst groundwater flow, although some lithological members within the flysch can be permeable. Such a continuous flysch belt effectively disables scattered outflow of fresh water from karst aquifers in the hinterland into the sea. This explains why the majority of discharge occurs through a few large karst springs and there are no significant vruljas (submarine fresh water springs). The most important springs in the area are: the Ljuta spring in Konavle (providing the water supply of the Grude area, used for water bottling and acting as a strategic groundwater reserve), the Robinzon spring in Duboka Ljuta/Plat (for the water supply of Župa Dubrovačka, Kupari, Cavtat, Ćilipi and the surrounding area), the Zavrelje spring at Mlini (acting as the water supply for Mlini and a small hydroelectric power plant), the Slavjan spring in Brgat (previously used for the water supply of Dubrovnik - an aqueduct led to Onofrio's fountains in the town), the Ombla spring in Komolac (providing the current water supply of Dubrovnik with the possibility of hydroelectric power plant construction), the Palata spring in Mali Zaton (for the water supply of Zaton, as well as the Elafite islands off the coast), together with springs in Orašac, Trsteno, Slano, and dozens of smaller springs with intake structures supplying smaller settlements.

From Slano to the NW, the flysch barrier tectonically disintegrated so the majority of the groundwater discharge from the hinterland occurs in the form of small coastal springs and vruljas, which results in their low potential for utilization in larger-scale water supply systems. The most significant discharge area is in the Kuti bay in the internal part of the Ston bay, and in Bistrina bay (Bojanić & Ivičić, 1984). The constant inflow of fresh water is lowering the salinity of the bay which, combined with the sparse population and the lack of industrial facilities (i.e. low pollution levels), has enabled ideal conditions for growth of clams, so the aquaculture of mussels and oysters is a significant source of income in the area.

The Neretva River delta downstream from Metković is a marshy cultivated area, suitable for fruit and vegetable production. Both the surface and shallow subsurface deposits are composed of medium and low permeability clastic deposits. On the surface, clayey silt and clayey sand rich in organic materials predominate, while in the lower horizons gravels with conglomerate intercalations are present. There are three identifiable aquifers along the depth of the Neretva River alluvium (Vidović, 1968). The total thickness of the alluvium is 120 m, and it is underlain by carbonate rocks. The water supply of the town of Neum comes from two drilled wells close to Gabela, north of Metković (Slišković et al., 2002).

On the left bank of the Neretva River a number of springs appear: the Doljani spring (providing the water supply for Metković), as well as the Mlinište, Mislina, Bađula, Bili vir and other smaller springs. These are ascending springs in which water upwells through fractures and forms small lakes on the surface. These springs drain the water from a large carbonate watershed extending as far as Popovo polje with the swallow holes in the Trebišljica River Valley and waters from the compensation basin of Hutovo, built for the Čapljina hydroelectric power plant.

On the right bank of the Neretva River the most significant springs are the Klokun (near the Baćina Lakes, providing the water supply of Ploče), the Modro oko (for the water supply of Desne village) and the Prud (supplying both Metković, and the extensive regional water pipeline NPKL: Neretva River - Pelješac Peninsula - Island of Korčula - Island of Lastovo).

In the NE part of Jezero polje there are a number of contact springs, with the largest ones being the Butina, Stinjevac and Lukavac springs. Only the Butina is used for water supply. The Pelješac peninsula has a few sources of water supply. The Ston area receives its water supply from the Studenac spring in the Ston polje. The rest of the peninsula uses small local pumping sites such as Žuljana, Trpanj and Orebić, or water from the regional NPKL pipeline. The Eastern part of Korčula Island also gets its water supply from the regional pipeline, while the central and western parts of the island use the Blato pumping site with dug wells (Terzić, 2006). Lastovo and Mljet islands use desalinated water from boreholes in the Prgovo polje (Lastovo) and blatinas (specific karst lakes on Mljet).

Acknowledgement: The overview of regional hydrogeological settings was written as a review on the basis of published and unpublished materials listed in reference list and the authors would like to thank all colleagues who contributed.

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STOP 1: ARBORETUM TRSTENO

Ivana Turalija[2]

The Trsteno Arboretum is located in the surroundings of Dubrovnik, in the small municipality of Trsteno, and covers an area of 25.5 ha (63 acres) (Fig, 3 & 4). It was established by the end of the fifteenth century as a park and summer residence of the patrician family Gučetić. It has been the property of the Croatian Academy of Sciences and Arts since 1948, when it was donated. The Arboretum reserves a very special place among the old Ragusan, Dalmatian and Mediterranean parks due to its five-century-long continuous development from Gothic-Renaissance, Renaissance-Baroque and Romantic forms to the present. It includes a Gothic-Renaissance park surrounding the fifteenth-century summer residence, which is a monument of garden architecture, and the nineteenth-century neoromantic park at Drvarica. Its collection of exotic and decorative trees and shrubs includes over 300 species and cultivars.

On October 2 and 3, 1991, the Yugoslav Army launched a series of gunboat and air attacks and set the Arboretum ablaze. Most of the Arbore-tum was destroyed by the fire. Fortunately, how-ever, the summer residence and the oldest part of the Arboretum were only partially damaged.

Fig. 3 Arboretum Trsteno

[2]conTres, Zagreb, Croatia

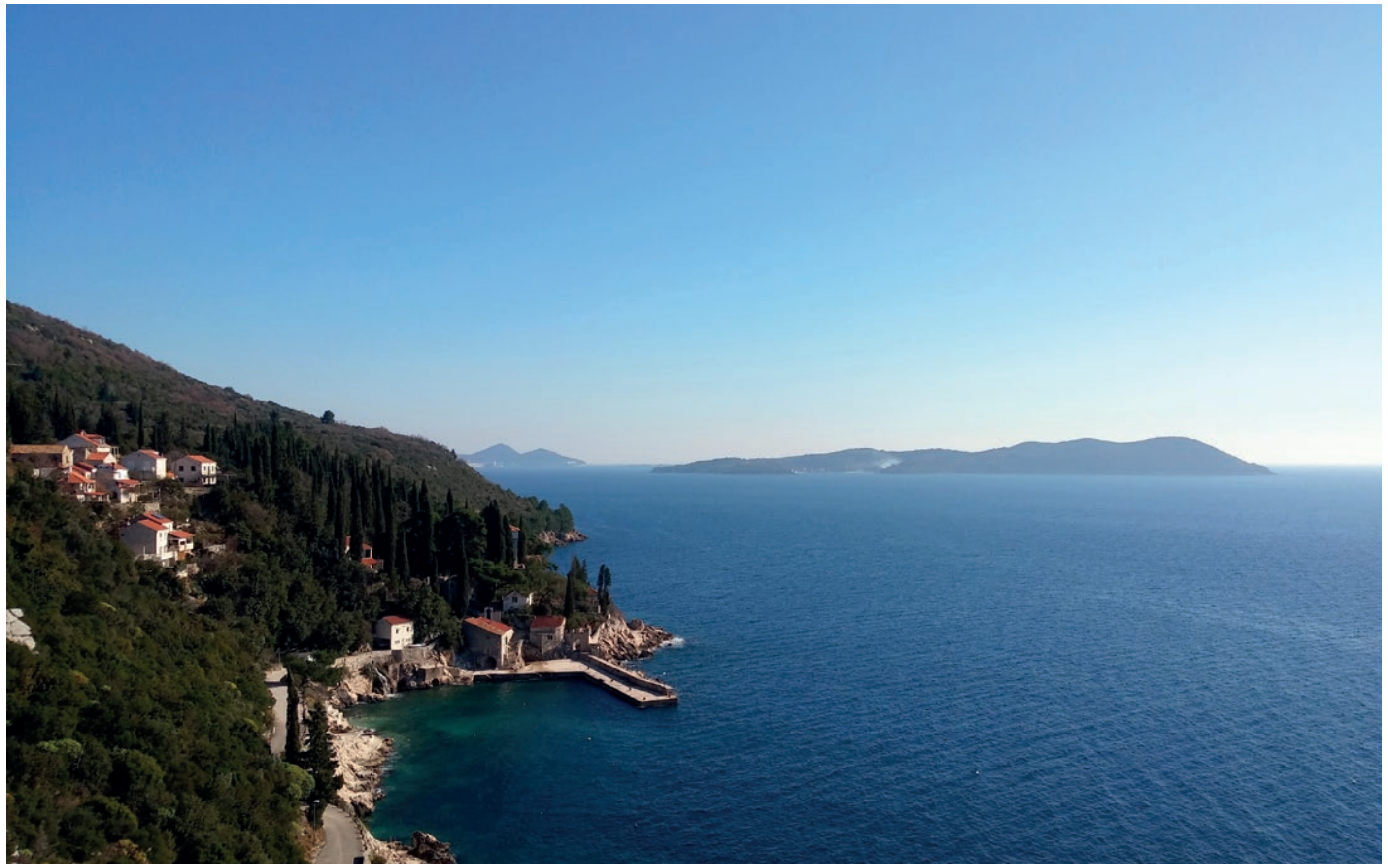

Fig. 4 Panoramic view of Arboretum Trsteno

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Dubrovnik, Croatia, 25th - 29th September 2017

STOP 2: THE KOLOČEP CHANNEL

Dragana Šolaja[1], Slobodan Miko[1]

Introduction

The Koločep channel is a sea channel between the coast and Elafiti islands in the Dubrovačko-neretvanska County. The average with of the channel is 1.5 km. The distance between the mainland and the island of Koločep is about 1 km at the narrowest part of the channel.

In the geographic sense, the area represents part of the South Dalmatian region, which is included within the larger region of the South Croatian littoral zone. It comprises Konavle, the Dubrovnik littoral zone, Elafiti islands and the peninsula of Pelješac. This peninsula is the only part of the South Croatian littoral zone without its own hinterland and, immediately behind the coastline, hinterland turns into the Herzegovian karst (Šundov, 2012).

The Elafiti islands are a group of South Dalmatian islands consisting of: Koločep (locally Kalamota), Lopud, Šipan, Jakljan and Olipa, together with the islets and reefs of Tajan, Crkvina, Goleč, Kosmeč, Mišnjak, Ruda, Sutmiho, Sv. Andria, Large and Little Skupio and Grebeni. The surface area of the islands is 27, 13 km^2. According to surface area, Šipan is the largest island, followed in decreasing size by Jakljan, Lopud and Koločep. The islands stretch from the NW to the SE over a length of approximately 26 km. Šipan, Lpud and Koločep are constantly inhabited (Šundov, 2012). In the 2001 census, the population of Koločep island was 163 (Magaš et al., 2001).

[1] Croatian Geological Survey, Zagreb, Croatia

Geology

The area of the field trip is located in what was the southeastern part of the Adriatic Carbonate Platform (AdCP) which belongs to the circum Mediterranean Mesozoic carbonate platform and is now integrated into the Alpine orogenic belt and the collision zone of the African and European plates (Fig. 5, Prtoljan et al., 2007). The AdCP deposits crop out in Italy, Slovenia, Croatia, Bosnia and Herzegovina, Serbia and Montenegro, and Albania (Fig. 6, Vlahović et al., 2005). These deposits comprise a major part of the entire carbonate succession of the Croatian part of the Karst (External or Outer) Dinarides, which is very thick , with a stratigraphic range from the Middle Permian to the Eocene (Vlahović et al., 2005). The Dinarides comprise two genetically different parts: the Outer (Karst or External) Dinarides along the Adriatic Sea, composed mostly of relics of the carbonate platform and its basement, and the Inner (or Internal) Dinarides, situated between the Outer Dinarides and the Pannonian Basin, composed of passive and active continental margin rocks including ophiolites (Pamić et al., 1998). The AdCP deposits currently form the eastern coastline of the Adriatic Sea. The Adriatic Sea is elongated in a NW-SE direction, and is the most northern basin of the Mediterranean.

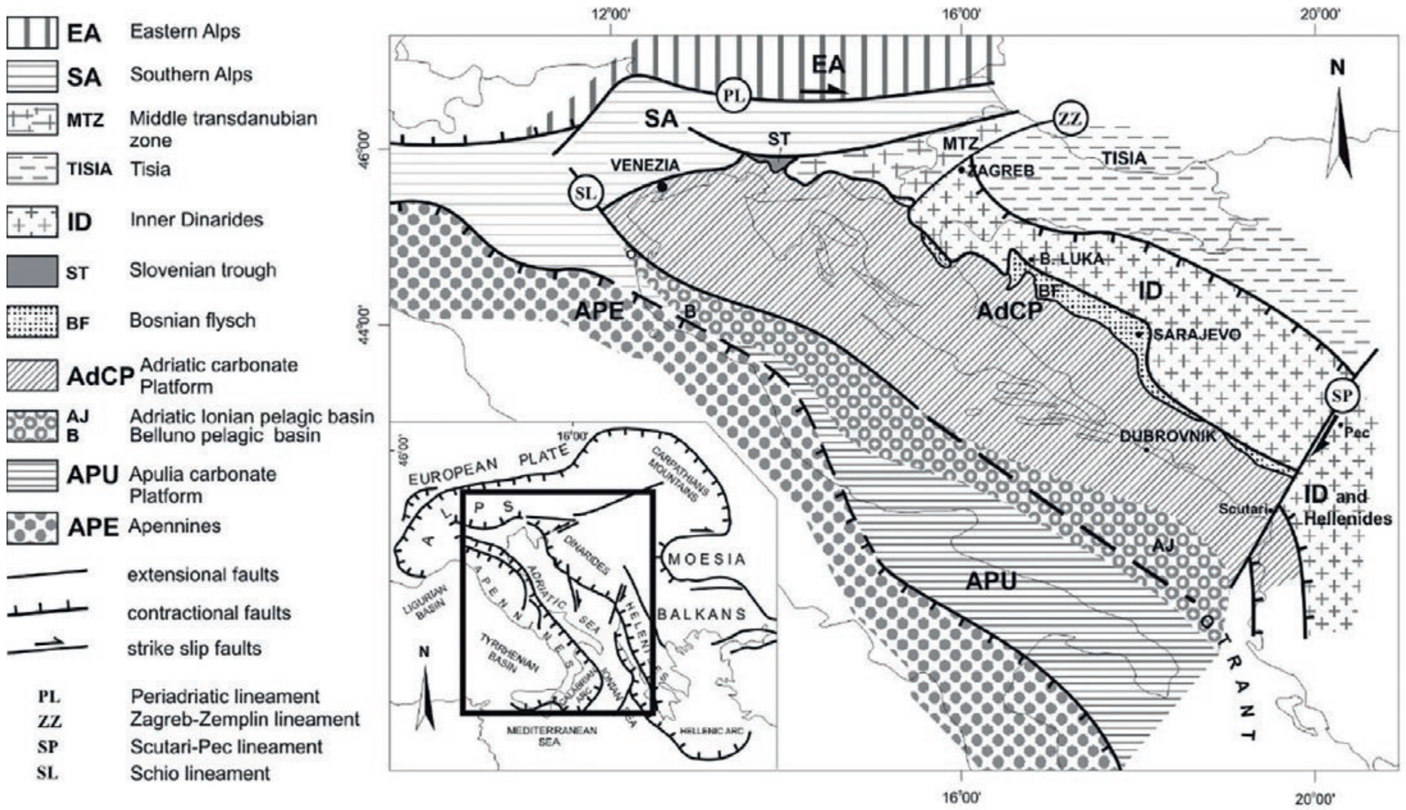

Fig. 5 Tectonostratigraphic unit of the AdCP in the Alpine - Mediterranean region (Prtoljan et al., 2007)

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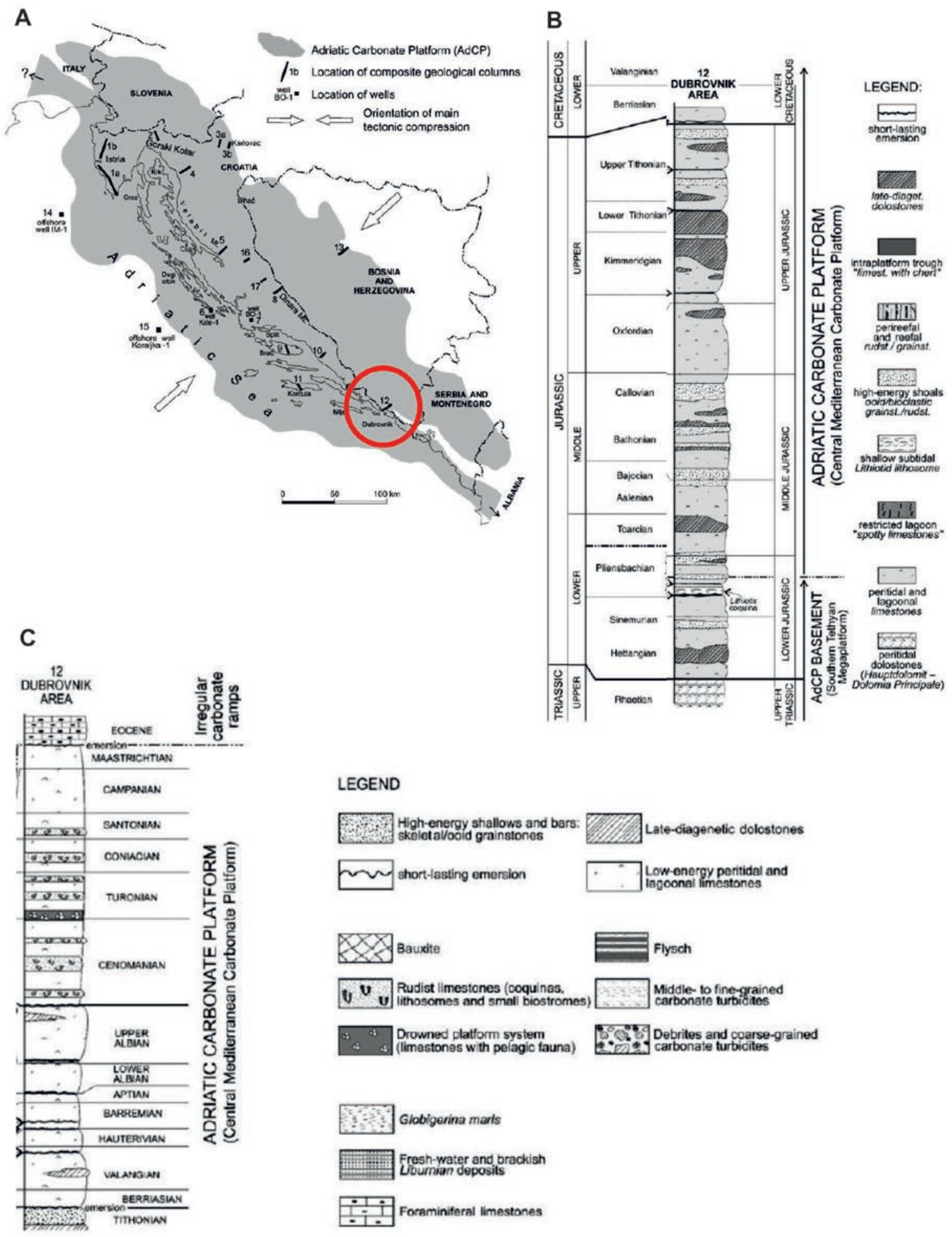

Fig. 6 A) Location map showing the recent distribution of the Adriatic Carbonate Platform (AdCP).
B) The main facies types of Jurassic deposits in the Croatian part of the AdCP in the Koločep channel (Dubrovnik area).
C) The main facies types of the Cretaceous deposits in the Koločep channel area (Dubrovnik area). (Modified figure from Vlahović et al., 2005)

The eastern Adriatic coast is a high and rocky coast, with deeply fractured carbonate structures that may have been karstified since the Miocene, while the recent coast has been shaped by the last (Late Pleistocene-Holocene) sea-level rise, when the folded, faulted, and karstified relief was partially submerged (Pikelj & Juračić, 2013).

The consequence of this sea-level rise is the steep, rocky, and primarily transgressional coastline, where coast-parallel anticlines (analogous to inland mountains) have formed island chains, while coast-parallel synclines (analogous to inland depressions) have become bays and channels and this coast is termed the Dalmatian coast type (Pikelj & Juračić, 2013).

The littoral area of the Koločep kanal (Koločep channel) covers part of a high karst Dinaric geotectonic unit. Limestone and dolomite prevail over clastic sediments. More than 90 % of the entire surface area consists of Mesozoic carbonate formations. The depth of soluble and karstified rock exceeds 3000 m. A small part of the area is composed of Triassic dolomite. These sediments play an important hydrogeological role, particularly if they are situated in the anticline cores. They are composed of the modification of white to light-colored stromatolytic early-diagenetic dolomites and darker early-diagenetic dolomicrites which transcend partially into the large crystalline late-genesis dolomite. The total thickness of these deposits ranges from 300-800 m (Lukšić et al., 2008). The Jurassic carbonate formations are not significant over the entire area. They represent the carbonate complex with dominant light to white grainy limestone and late-genesis dolomite with a maximum thickness of up to 150 m (Lukšić et al., 2008). Cretaceous sediments are the most strongly developed stratigraphic unit. Cretaceous limestone with interlayers and zones of dolomite are continuous over the area. The total thickness of the deposits may exceed 1000 m (Lukšić et al., 2008). Both Jurassic and Cretaceous limestone and dolomite, including Triassic sequences, have been (locally) affected by karstification down to great depths. The Eocene flysch does not represent a significant lithostratigraphic formation, but according to its hydrogeological role and location along the reverse faults within the autochthon, in the many karst fields, it has a huge effect on karst aquifers, at both local and regional scales (Milanović, 2006). The most significant zone is along a great dislocation which divides the high Karst tectonic unit from the area of the para-autochthon. Lithologically, the Miocene flysch is composed of marl, sandstone, marly-limestone, conglomerate and breccia with very low permeability. Locally, the permeability is related to subsurface layers and to carbonate inclusions and lenses. The deposits are eroded and tectonically reduced with very different thicknesses from 1 to a maximum of 200 m. According to the tectonics, these deposits act as an underground barrier for waters from carbonate hinterland (Bojanić & Goatti, 1985). The youngest deposits in the area are the Quaternary deposits. They can be observed as small, relatively thin isolated phenomena of a very different genetic origin. They are represented by terra rossa, sand and diluvium-proluvium deposits (Lukšić et al., 2008).

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Structural geology and seismisty

The wider area is distinguished and can be divided into three major tectonic units: the External (closest to the Adriatic Sea), Central and Inner Dinarides. The basic structural characteristics of this area correspond to the basic tectonic elements of the External Dinarides, namely the domination of folded structural elements, the distinct linearity of the structures, the direction of the Dinaric dip, and the dense network of faults (Fig. 7). Formation of this area is connected to the Mediterranean geosyncline basin activity (Milanović, 2006). The most important fault assembly is the Ploče - Dubrovnik one (1) (Fig. 8). It is represented by a zone of predominately parallel faults. In a couple of places along the trace, the relief has prominent cliffs. In the main fault zone, Triassic and Jurassic rocks are separated from Cretaceous and Paleogenic rocks. The fault zone is of variable width up to 1.5 km wide. The fault inclination is between 45° and 82°. The second most important feature of the structural assembly is the Pelješac - Dubrovnik fault (4) (Fig. 8). It is represented by a zone of parallel faults which are 1.5 - 4.5 km wide (Šundov, 2012).

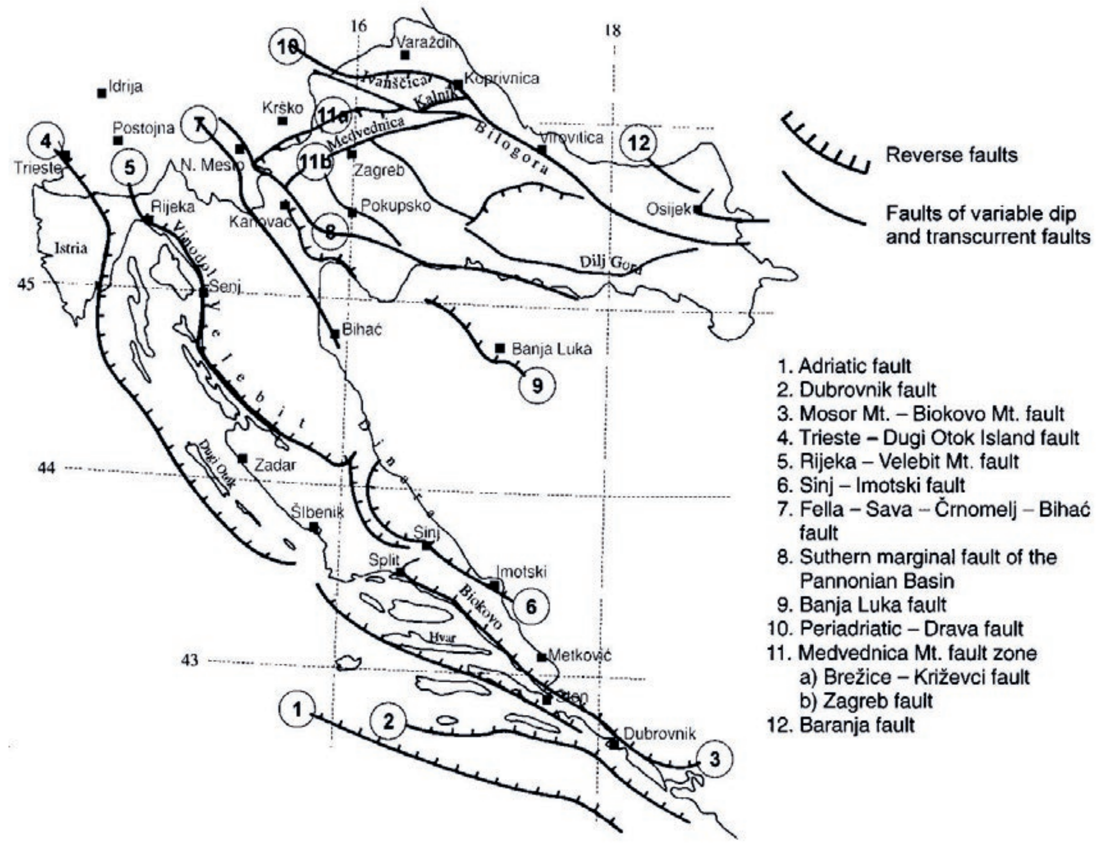

Fig. 7 Map of the most important seismogenic faults in Croatia. (Stevanović et al., 2012)

Most of the earthquakes in this area are caused by slip along the faults in the Dubrovnik and Adriatic fault zones. The historical records list 8 earthquakes of intensity IX or X - MCS in the 15th, 16th, and 17th, centuries, of which the most important is the great Dubrovnik earthquake of 1667, (I=X - MCS).

The earthquake foci concentrations depict the strongest activity in the zone that is associated with the Ploče-Dubrovnik fault, but there are also some active faults within the Adriaticum unit. Particularly increased activity is observed along the Adriaticum - Dinaricum contact, in the fault zones parallel to Mljet Island and the Pelješac peninsula (Fig. 8). The locations of earthquake foci show that this is actually a single area of seismic activity, which means that there is extensive compression in this area. The significant subduction of the Adriatic micro-plate, which reaches 40 km inland from the coastline must also be emphasized. As a consequence, there is activity in the carbonate complex basement and there are reverse-overthrust displacements on the faults within the Adriaticum, together with formation of a broad active zone marked by deformations of structural fabric and the permanent occurrence of earthquakes (Kuk et al., 2000).

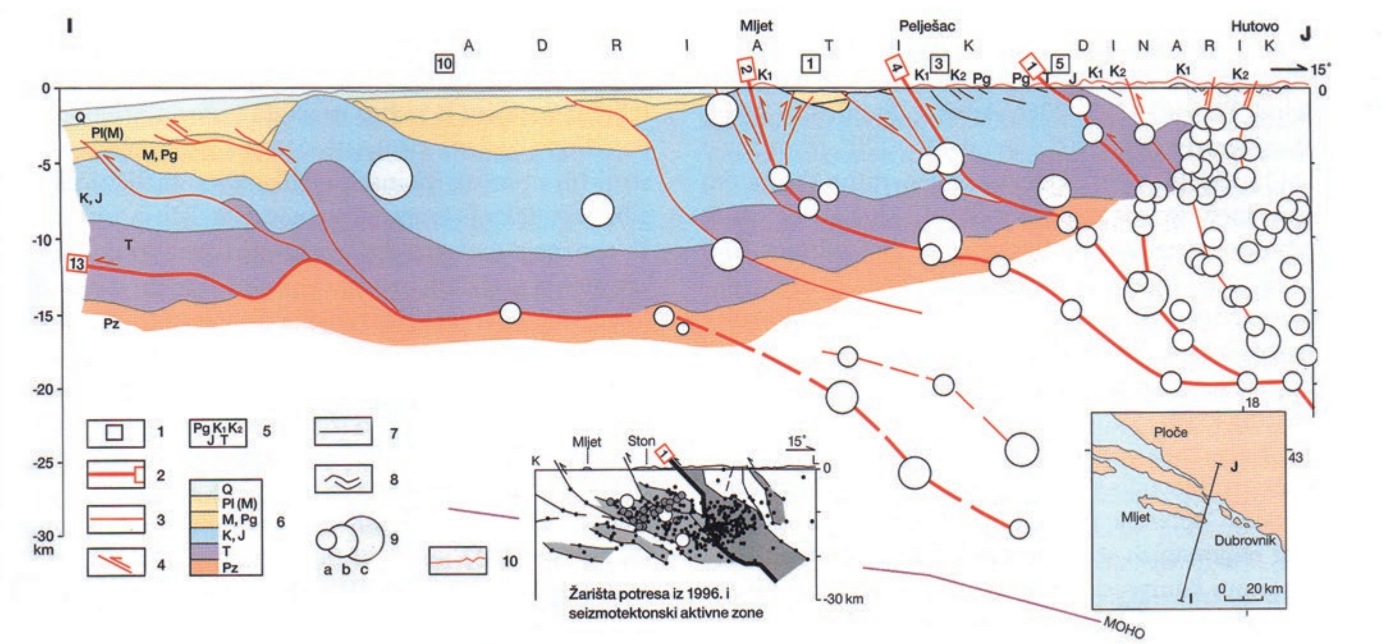

Fig. 8 Seismotectonic cross-section I-J.

(Legend: **1 - Structural units:** South Adriatic (10), Vis - Lastovo - Mljet (1); Pelješac - Elafiti - Cavtat - Molunat (3); Opuzen - Hutovo - Orahov Do (5); **2 - Main faults:** Vis - South Adriatic (13); Ploče - Dubrovnik (1); Pelješac - Dubrovnik (4); Vis - Lastovo - Mljet (2); **3 - Faults**; **4 - direction of hanging wall**; **5 -Stratigraphy and lithology on the surface:** Pg - limestone and flysch (Eocene), K2 - limestone (upper Cretaceous), K1 - limestone and dolomite (lower Cretaceous), J - limestone and dolomite (Jurassic), T - dolomite and limestone (Triassic); **6 - Stratigraphy and lithology under the surface:** Q (Quaternary) - clay, sand, sandstone and marl, PLM (Pliocene and upper Miocene) - clay, sand, sandstone and marl, M, Pg (Miocene, Paleogene) - marl, sandstone, limestone and flysch, K,J (Cretaceous, Jurassic) - limestone and dolomite, T (Trias) - dolomite, limestone and clastic rocks, Pz (Paleozoic) - clastic evaporate, carbonate and metamorphic rocks; 7 - Stratigraphic horizons; 8 - Layers of Mesozoic and Paleogene rocks on surface; 9 - Earthquake epicenters with magnitudes: a) <4, b) 4-5, c) >5; 10 - relief. (Prelogović, 2001, Šundov, 2012).)

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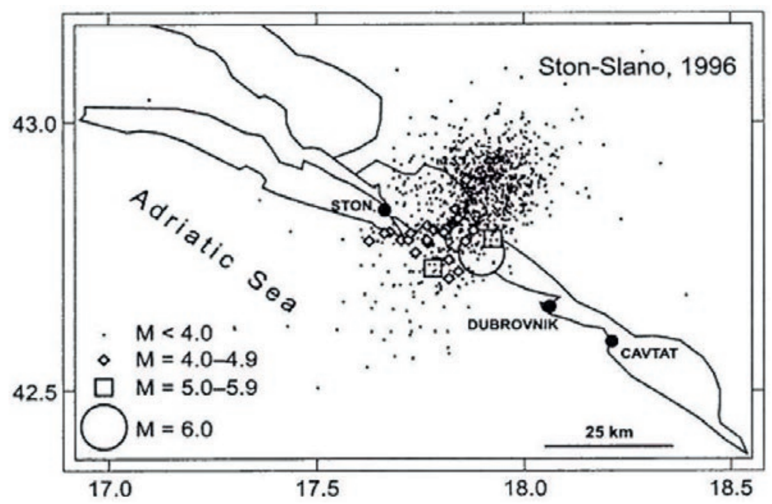

Fig. 9 Epicentral map of the greater Ston region. White circle is the epicenter of the 1996 main shock (ML = 6.0) (Markušić et al., 1998)

The most frequent earthquake concentrations are in the area between the Neretva Delta, Slano and Stone, and in particular around Dubrovnik and Boka Kotarska. It is pointed out that seismic calculations include the explored area (besides the western part of Pelješac) in the zone of a possible earthquake with a magnitude of 7.0. This confirms directly the presence of an above –average and intensive seismic and tectonic activity (Šundov, 2012).

The last significant earthquake occurred near Ston in 1996. It had a magnitude 6.0. The focus of the main earthquake and of the subsequent ones are shown in Fig. 8. The spatial concentration of earthquakes in the area of the zone of seismotectonic activity described above is easily discerned. Numerous earthquake foci (Fig. 9) enable the more detailed separation of minor zones connected with some of the faults (Kuk et al., 2000).

Hydrogeological characteristics

Hydrogeological features of the area are determined by the basic rock masses, their hydrogeologic relationships and karst processes. Dolomite with water permeability belongs to the first rock group which forms a hydrogeological collector. These rocks represent (with to respect to water permeability and hydrogeologic functions), collectors for conductors of atmospheric precipitation, which are filtered into the underground and partly evaporate. Plateaus, which are formed on the Dinaric do not have surficial water courses, but the drainage function was taken over by underground courses. Through intensive karst processes, a peculiar underground channel and cavity networks was formed giving these rock complexes a special feature. On grounds of the colors it was determined that the general orientation of the movement direction of underground water is NE-SW. This orientation was primarily effected by tensional deformation forms within the diagonal and reverse fault and longitudinal fault of Ploče Dubrovnik, the NW-SE direction separating the Adriatic from the Dinaric, faults stretching from the Slano area towards the hinterland and Popovo polje and the fault zone around the Ombla source.

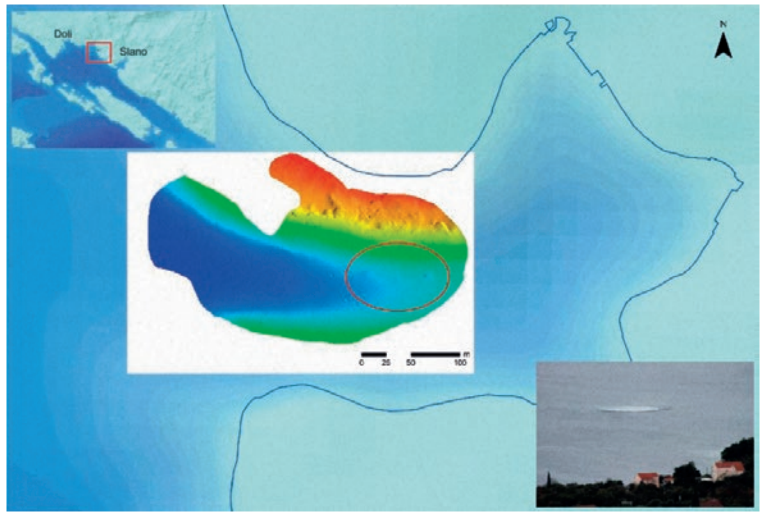

Fig. 10 Vruljas (submarine spring) - offshore at Banići and multibeam bathymetry showing the location of the vruljas (red circle) at 50 m below level. (Photo: O. Hasan)

The second rock group represents practical water permeability and waterless flysch rocks covered by a complex of an entire series of limestone and dolomites of the Dinaric unit. Basically, they are hydrogeological isolators which due to their spatial position act as hydrogeological obstacles for underground waters from the Dinaric unit (Šundov, 2012). Due to the lithological composition of both groups their rock mass fabric and their tectonic position on the thrust contact zone as a result of the described hydrogeological relation, vrela, springs and vruljas (submarine springs) appear, having a significant capacity over the years. Vruljas are recorded in the channel of Mali Ston, Bistrina bay and the areas of Doli – Banići (Fig. 10), Mali Zaton, Župa Dubrovačka, Plat and Konavle. Scattered appearances of vruljas show a partly syphonal movement of underground waters (Fig. 11).

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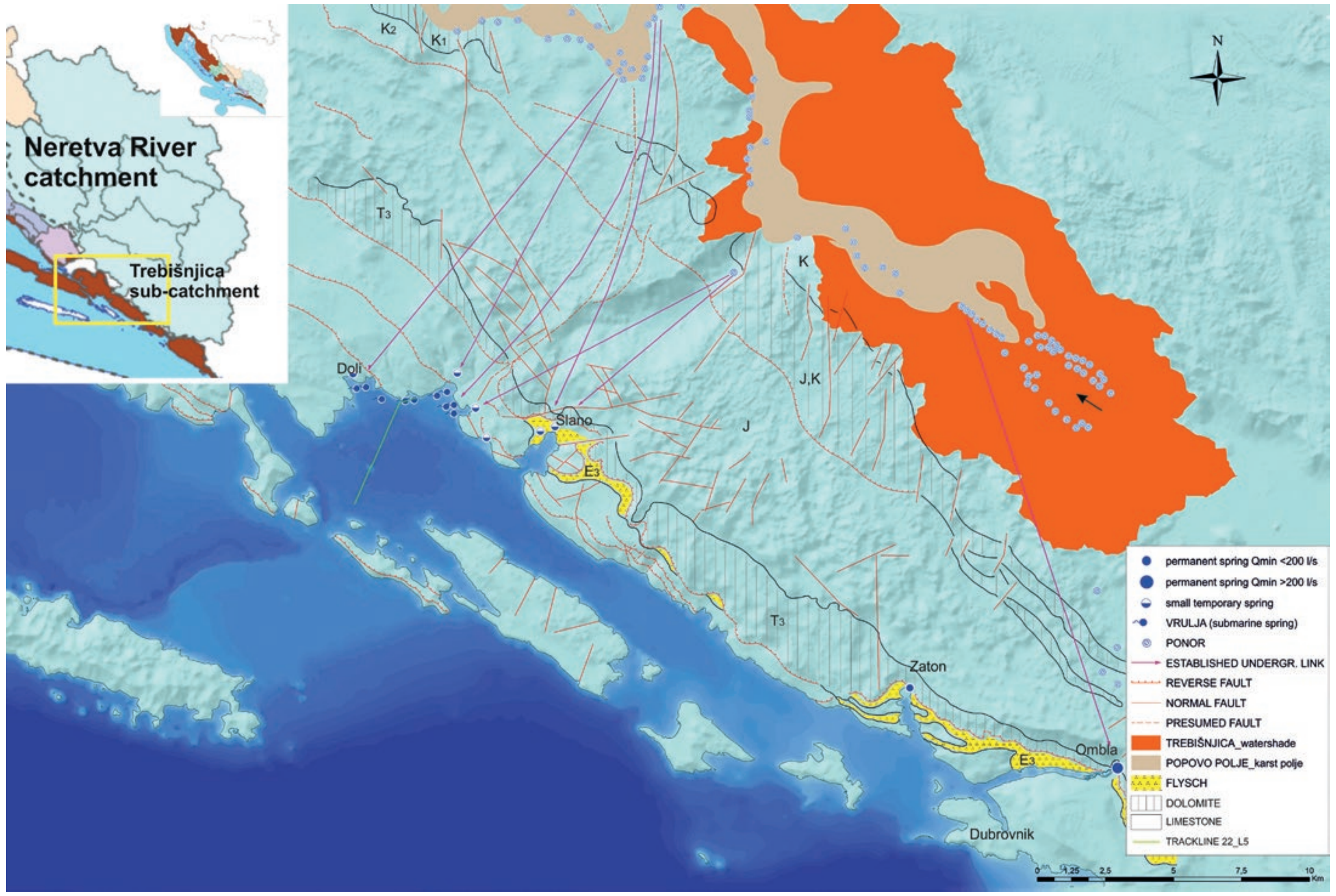

Fig. 11 The Popovo Polje and part of the Dubrovnik littoral (after Natević & Petrović, 1964-1965; Marković et al., 1971; Raić et al., 1980; Stevanović, 2012)

The third group of rock masses consists of individual rocks or loose and semi–loose rock masses of the first and second group. These are predominately slope (deluvium, proluvium, koluvium, slides) sediments. These layers represent hydrogeological collectors with different degrees of porosity and unevenness in which a compact type of outcrop is formed with a variable depth (Šundov, 2012).

The surface and groundwater of the Dinaric karst belongs to two main catchments. The area of the External Dinarides belongs to the Adriatic catchment (a small part to the Ionian Sea), while the Internal (Inner) Dinarides are part of the Sava (i.e. Danube and the Black Sea) catchment area (Fig. 12).

Fig. 12 Major catchments and river basins in the Dinaric region (Stevanović et al., 2012)

Over the area vruljas and springs are defined that can be related to the underground flows of the rivers Trebišnjica (BiH) and Neretva (HR). Based on the ponors from the Popovo Polje on the western side of the Trebišnjica watershed (Fig. 11), we can define groundwater flows with the coastal springs Jansko and Budim, and vruljas Slano and Doli (Vranješ et al., 2000). Under natural conditions, dewatering of the Popovo polje was only possible through the underground karst channels. More than 500 ponors, estavelles and temporary springs have been registered in the Popovo polje (Fig. 11), (Milanović, 2014). Trebišnjica is the largest European sinking river located in Herzegovina. Of the total river length of 90 km, 28 km is permanent. During the dry season, the permanent flow terminates downstream from Trebinje town to Dražin. In wet periods, flow continues to the end of Popovo Polje (Milanović, 2006). According to Milanović (2000), in the Dinaric karst region there are approximately 130 poljes. Drainage of the karst polje is through ponors located along the polje perimeter and at the polje floor within unconsolidated sediments or exposed carbonates. The ponors are frequently located in the polje areas nearest to the erosion base. The Adriatic Sea is an example of regional erosional bases which have a cascade system of poljes (Fig. 13). Poljes become flooded as the spring or recharge capacity of the ponor becomes lower than the inflow quantity of water. Natural plugging of ponors may also lead to faster flooding and longer duration of floods (Stevanović et al., 2012).

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017
HGI HRVATSKI GEOLOŠKI INSTITUT CROATIAN GEOLOGICAL SURVEY
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Over the area vruljas and springs are defined that can be related to the underground flows of the rivers Trebišnjica (BiH) and Neretva (CRO). Based on the ponors from the Popovo Polje on the western side of the Trebišnjica watershed (Fig. 11), we can define groundwater flows with the coastal springs Jansko and Budim, and vruljas Slano and Doli (Vranješ et al., 2000). Under natural conditions, dewatering of the Popovo polje was only possible through the underground karst channels. More than 500 ponors, estavelles and temporary springs have been registered in the Popovo polje (Fig. 11), (Milanović, 2014). Trebišnjica is the largest European sinking river located in Herzegovina. Of the total river length of 90 km, 28 km is permanent. During the dry season, the permanent flow terminates downstream from Trebinje town to Dražin. In wet periods, flow continues to the end of Popovo Polje (Milanović, 2006). According to Milanović (2000), in the Dinaric karst region there are approximately 130 poljes. Drainage of the karst polje is through ponors located along the polje perimeter and at the polje floor within unconsolidated sediments or exposed carbonates. The ponors are frequently located in the polje areas nearest to the erosion base. The Adriatic Sea is an example of regional erosional bases which have a cascade system of poljes (Fig. 13). Poljes become flooded as the spring or recharge capacity of the ponor becomes lower than the inflow quantity of water. Natural plugging of ponors may also lead to faster flooding and longer duration of floods (Stevanović et al., 2012).

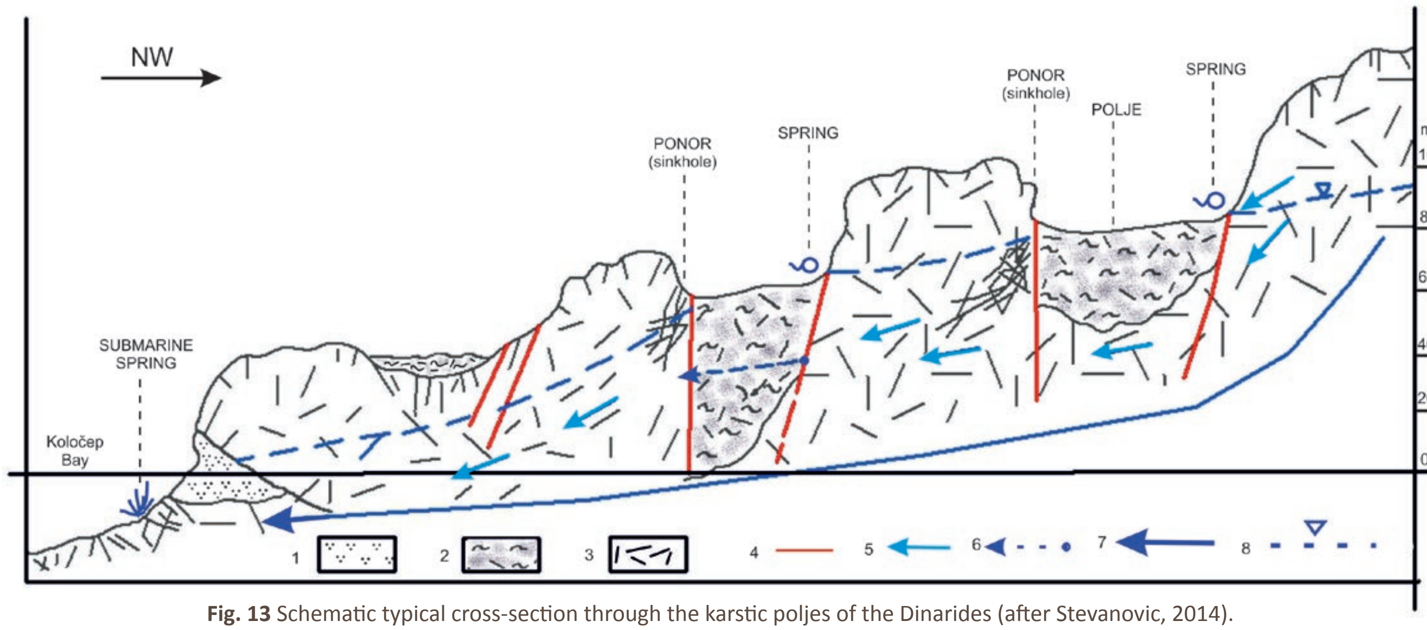

Fig. 13 Schematic typical cross-section through the karstic poljes of the Dinarides (after Stevanovic, 2014).

(Legend: 1. Neogene; 2. alluvium; 3. karstified limestone; 4. fault; 5. groundwater flow; 6. direction of flow around the barrier; 7. regional flow; 8. groundwater table)

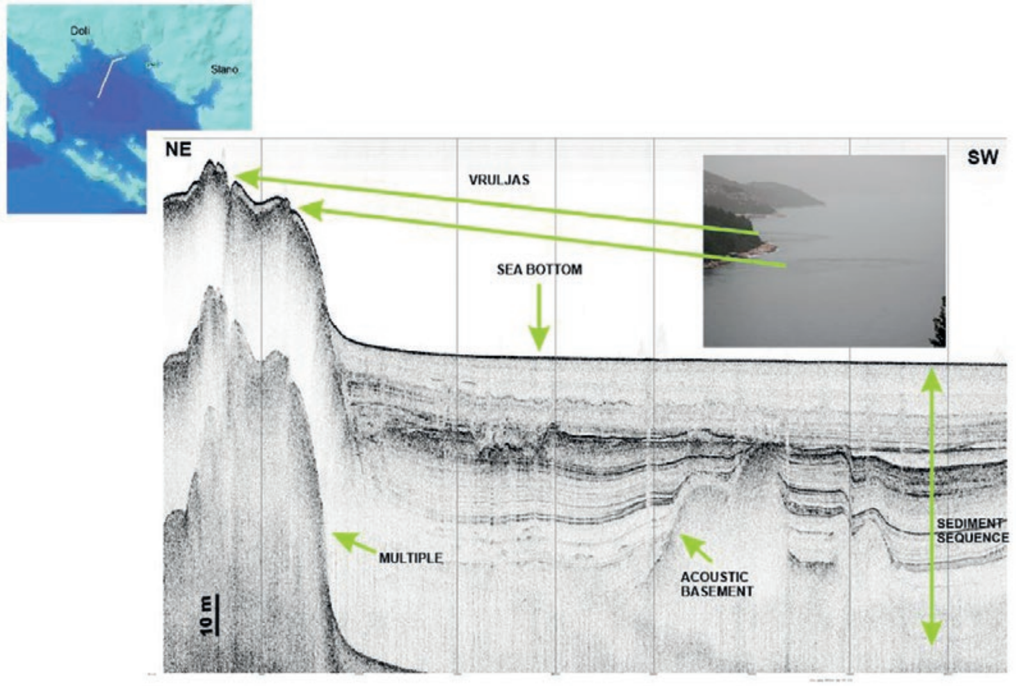

Fig. 14
Vruljas (submarine springs) - Doli. Visible on the acoustic profile showing vruljas along the karstified coast in the Doli area. (Photo: O. Hasan)

Fig. 15
Drainage basins and Veliki Vratnik channel with sea lever under -50 m during the MIS 3 and MIS 4 when acoustic unit B deposited as lake sediments

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44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017
HGI HRVATSKI GEOLOŠKI INSTITUT CROATIAN GEOLOGICAL SURVEY

STOP 3: STON

Ivana Turalija[2]

Ston is a small town in the Dubrovnik area, located at the south of the Pelješac peninsula. Ston lies only 59 kilometres (37 miles) from Dubrovnik.

The whole Pelješac peninsula has about 2500 dwellers whereas only 600 inhabitants live in Ston. Ston was a military fort of the Ragusan Republic whose defensive walls are among the most famous in the world: there is a 900 metre (3000 feet) long town wall and a 5 km (3 miles) Great Wall outside the town. The walls extend to Mali Ston (Little or Small Ston), a smaller town on the northern side of the Pelješac isthmus and the end of the Mali Ston bay.

It is noteworthy to mention that the Ston walls are the second longest defensive walls in the world, second only to the Great Wall of China (Fig. 16).

Fig. 16 Ston - city walls and saltwort (https://split-excursions.com/day-tours-from-split/culture-heritage-group-tours/dubrovnik-group-tour/)

[2]conTres, Zagreb, Croatia

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44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017

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