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# INFLUENCE OF GEOLOGICAL STRUCTURE ON MICRO-LOCATION OF SUBMARINE KARSTIC SULPHUR SPRINGS NEAR IZOLA (SW SLOVENIA)

# VPLIV GEOLOŠKE STRUKTURE NA MIKROLOKACIJO PODMORSKIH KRAŠKIH ŽVEPLENIH IZVIROV PRI IZOLI (JZ SLOVENIJA)

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**Abstract** UDC 546.22:551.435.85(497.4Izola)
***Boštjan Rožič & Petra Žvab Rožič: Influence of Geological Structure on Micro-location of Submarine Karstic Sulphur Springs near Izola (SW Slovenia)***
In the Slovenian part of the Gulf of Trieste/Trst, submarine springs occur as funnel-shaped depressions in the Holocene sandy-silt marine sediment that forms the seafloor. These springs exhibit both elevated temperatures (up to 29.6 °C) and sulphur content. Based on their location, they are divided into three groups: the Izola group (three springs), the Bele skale group (two springs), and the Ronek group (seven springs). Previous investigations linked these springs to the Izola anticline, characterized by its limestone core and flysch limbs, but no detailed explanation was provided. We propose that: A) sulphur groundwater springs from the limestone (karstic aquifer) at the stratigraphic boundary with the flysch and B) springs occur in the nearshore area, where the sedimentary cover of Quaternary deposits is thin enough to be penetrated by spring waters and washed out. According to existing data, the anticline axis is NW-SE directed, and the Izola group lies approximately on the seaward extension of the axis. Therefore, this interpretation fits perfectly for the Izola group, while the Ronek and Bele skale groups are off-axis extensions and require reinterpretation. In order to resolve the micro-locations of the Ronek and Bele skale groups, we conducted a sedimentological logging of the flysch deposits and detailed geological mapping. The investigations revealed that: A) limestone outcrops occur only in the town of Izola, B) two prominent calciturbidite megabeds that occur in the flysch enable very detailed geological mapping, and C) the axis of the Izola anticline is oriented in the WNW-

**Izvleček** UDK 546.22:551.435.85(497.4Izola)
***Boštjan Rožič & Petra Žvab Rožič: Vpliv geološke strukture na mikrolokacijo podmorskih kraških žveplenih izvirov pri Izoli (JZ Slovenija)***
V slovenskem delu Tržaškega zaliva se v holocenskem peščeno-meljastem sedimentu, ki tvori ravno morsko dno, pojavljajo podmorski izviri v obliki lijakastih kotanj. V teh izvirih so opazni povišane temperature (do 29,6 °C) in vsebnost žvepla. Glede na njihovo lokacijo jih lahko razdelimo v tri skupine: skupina Izola (3 izviri), skupina Bele skale (2 izvira) in skupina Ronek (7 izvirov). Že predhodno so te izvire povezali z Izolsko antiklinalo, ki jo označujejo apnenčasto jedro in flišna krila, vendar natančnejše razlage niso podali. Predvidevava, da žveplene vode izvirajo iz apnenca (kraškega vodonosnika) na stratigrafski meji s flišem, in sicer v bližini obale, kjer je pokrov kvartarnih sedimentov dovolj tanek, da ga lahko izvirske vode izperejo. Glede na podatke naj bi bila os antiklinale v smeri SZ–JV in skupina Izola bi potemtakem ležala na protimorskem podaljšku osi. Takšna interpretacija torej povsem ustreza skupini Izola, preostali dve skupini pa padeta povsem izven podaljškov antiklinalne osi, zaradi česar je potrebna ponovna interpretacija. Da bi razložili mikrolokacije skupin Ronek in Bele skale, smo posneli sedimentološke značilnosti profilov flišnega zaporedja in izvedli natančno geološko kartiranje. Raziskave so pokazale, da a) se izdanki apnencev pojavljajo le na območju mesta Izola, b) dve kalciturbiditni veleplasti, ki se pojavljata v flišu, omogočata zelo natančno geološko kartiranje in c) je os Izolske antiklinale orientirana v smeri ZSZ–VJZ. Prav ta zmerna rotacija antiklinalne osi v nasprotni smeri urnega kazalca razloži mikrolokacije vseh izvirov. Skupini Ronek in Bele skale

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ESE direction, and this moderate anti-clockwise rotation of the anticline axis explains the micro-locations of all springs. The Ronek and Bele skale groups are located on the southern side, and the Izola group is on the northern side of the limestone core of the Izola anticline.
**Keywords:** sulphur, karst springs, Adria foreland, Izola anticline, geological mapping.

sta na južni strani, skupina Izola pa je na severni strani apnenčastega jedra Izolske antiklinale.
**Ključne besede:** žveplo, kraški izviri, Jadransko predgorje, Izolska antiklinala, geološko kartiranje.

## 1. INTRODUCTION

Topographic mapping of the Slovenian part of the Gulf of Trieste/Trst revealed a relatively flat seafloor composed of Holocene fine clastic marine sediments (Kolega & Poklar, 2012; Slavec, 2012). Before early Holocene transgression, the area was part of a Po River floodplain characterized by alluvial and eolian sedimentation (Correggiari et al., 1996; Trobec et al., 2017; Brunović et al., 2020). Post transgression Holocene sediments, usually several meters thick, overlie Pleistocene deposits and in the near-shore area, also a Paleogene rock basement (Ogorelec et al., 1991, 1997; Romeo, 2009; Trincardi et al., 2011a, 2011b; Trobec et al., 2017, 2018, Novak et al., 2020). The most prominent topographic features that stand out in relief from the present-day sea bottom are a current-related elongated depression near Piran, a small reef near Cape Ronek, remains of pre-transgression river channels, sand dunes, and unusual funnel-shaped depressions of more than 10 m deep (Figure 1) (Slavec, 2012; Orlando-Bonaca et al., 2017; Trobec et al., 2017, 2018; Novak et al., 2020). An initial dive into these depressions revealed that they are submarine springs, above which the Quaternary sediment is almost completely eroded, but the walls as well as the bottoms of these depressions are still composed of fine-clastic Quaternary deposits (Žumer, 2004, 2008). These springs show elevated temperatures (up to 29.6 °C) and sulphur content (Žumer, 2004, 2008; Faganeli et al., 2005; Žvab Rožič et al., 2021; Šušmelj et al., 2022). Morphological and hydrogeological characteristics of these depressions indicate that they correspond to subaqueous pockmarks formed where focused fluids

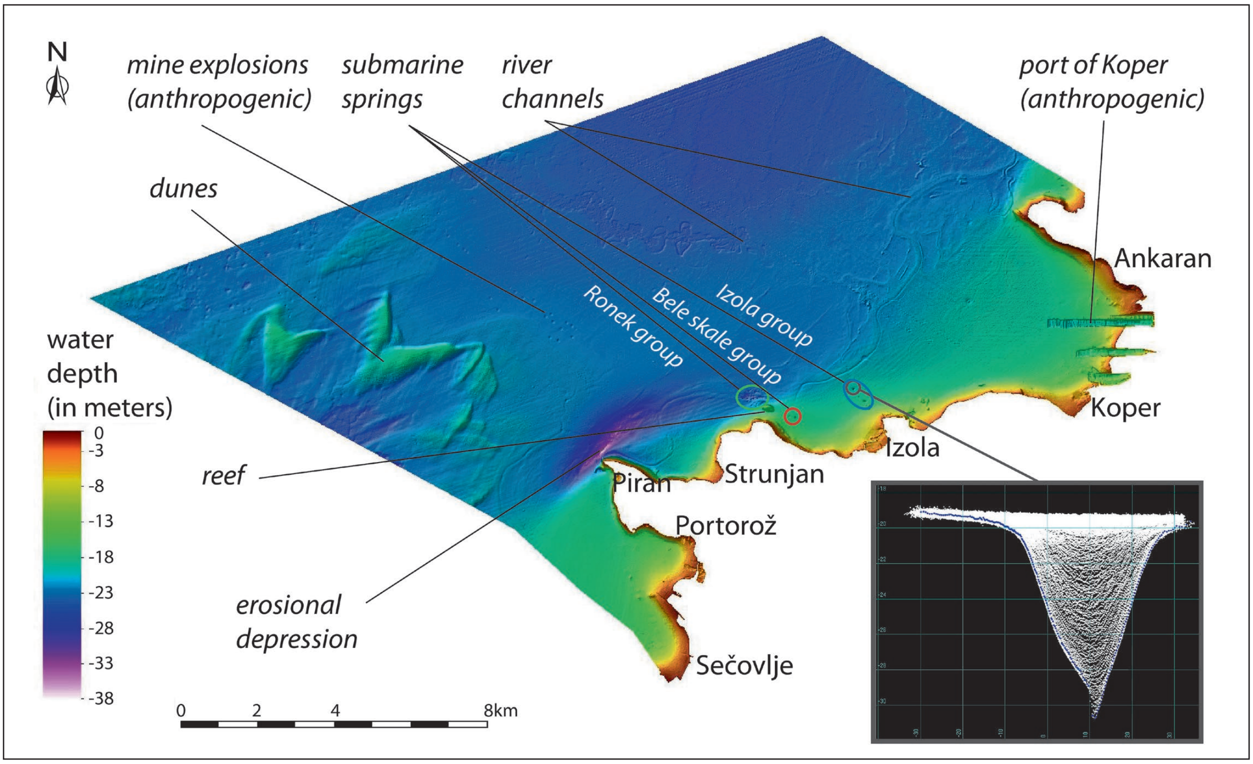


*Figure 1: Digital elevation model of the southern Gulf of Trieste/Trst seafloor with major topographic features that stand out in relief. Submarine sulphur springs are encircled (Ronek group – green, Bele skale group – red, Izola group – green). In the lower right corner is a vertically exaggerated sonar-data cross section of the Izola group's north-western spring (modified from Slavec, 2012).*

migrate through unconsolidated sediments toward the sediment surface (gas seepage, submarine groundwater discharge, hydrothermal vents) (King & Maclean, 1970; Hovland et al., 2002; Judd & Hovland, 2007; Wirth et al., 2020).

Based on their positions, the springs are divided into three groups. The first group (three springs) lies near the town of Izola, while the second (two springs) is located near the Bele skale rockfall between Izola and Strunjan, and the third (seven springs) is near Cape Ronek at Strunjan (Figures 1, 3 and 9).

In the earliest reports, the occurrence of these springs was linked to the geological structure, the Izola anticline (Žumer, 2004). Namely, the entire Slovenian coast is characterized by a thick sequence of Eocene flysch deposits that act as an aquitard. The base of the flysch is an aquiclude composed of transitional marl 50 m thick that acts as a hydrogeological barrier. The only coastal outcropping of the underlying Eocene limestone is found in the core of the Izola anticline. We agree with early proposals that sulphur groundwaters spring from this limestone in the near shore area. The springs are therefore considered karstic in origin. This is supported by a historically documented (now demolished and inaccessible) sulphur thermal spring inside Sveti Peter Cave, which was used for the Izola Spa (Kramar, 2003) and from the 501 m-deep LIV-1/01 borehole (no longer operational) drilled in the Livade part of the town of Izola (Benedik & Rožič; 2002; Lapanje, 2006). Both locations lie within the area of the Izola anticline limestone core (marked in Figure 9). Basic analysis of the borehole water that was obtained during the pumping test showed that the groundwater is fresh and cold near the surface. Deeper, below the two coal layers of limestone-dominated Early Paleocene Liburnia Formation (at depths of approximately 280m and 410m respectively) the water temperature rises of a 1 °C and a sulphur smell appears. A slight increase of Na and Cl was detected particularly at greater depths (Benedik & Rožič; 2002; Lapanje, 2006). Unfortunately, no precise geochemical data is published in these reports. However, interesting evidence of sulphur content comes from the fact that the deeper-level pumping test was halted by the police, because the "smell of rotten eggs (sulphur)" was spreading intensively across the entire Izola area (first author's personal experience). Detailed hydrogeochemical and isotopic studies of the sulphuric waters from submarine springs are in the early stages (preliminary results in Šušmelj et al., 2022) and no

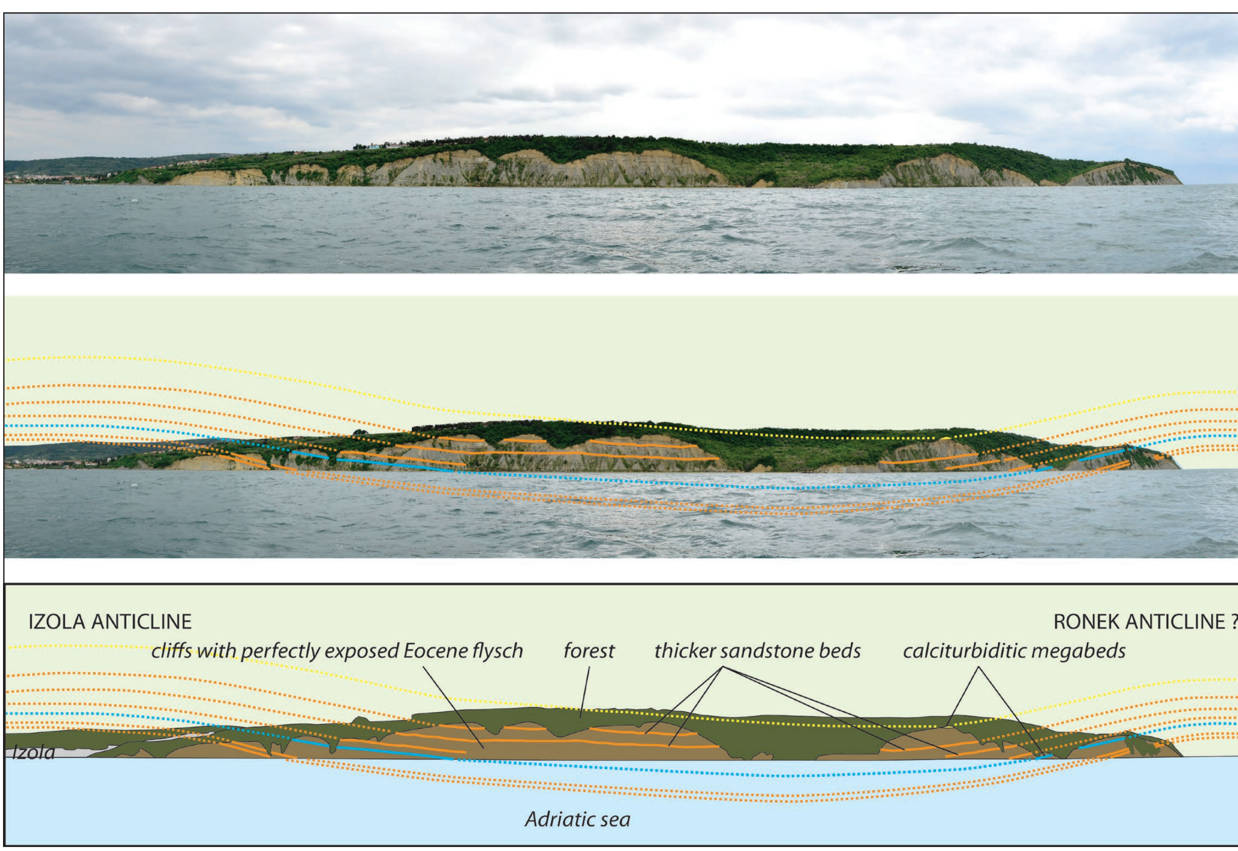


*Figure 2: The geological structure of the cliff between the bay of Simonov zaliv and Ronek cape suggested the existence of a hypothetical Ronek anticline (photo: M. Moškon).*

consistent results are yet available. This is mainly due to the water sampling problem inside the marine depressions, where the mixing with seawater is a rapid process, and at the same time the sampling is dangerous due to the loose, steep walls of the depressions there. However, preliminary results indicate that the spring waters correspond to those from the borehole and are karstic in origin (Šušmelj et al., 2022).

Submarine and sea-level karstic springs are common along the Adriatic coast (Bakalowicz, 2018), including some enriched with sulphur (D'Angeli et al., 2019, 2021; Liso & Parise, 2020). These springs represent cave systems that were flooded after the Holocene transgression and occur along the coastal areas, which are composed entirely of carbonate rocks. In contrast, almost the entire Slovenian coast consists of flysch, with limestone outcrops limited solely to the small area of the town of Izola. In the sea, Holocene sediments cover a rocky basement, and little is known about its continuation below them. Therefore, the geological and hydrogeological factors that determine the exact micro-locations (spatial distribution) of the springs are ambiguous and their explanation is the main goal of this paper.

According to existing data, the Izola anticline is either a dome (Pleničar et al. 1969, 1973) or an elongated anticline with a NW-SE directed axis (Placer et al., 2010). Because the Izola group of springs lies approximately on the north-western (seaward) prolongation of the anticline axis (extension of the dome), this interpretation fits for this group. At the same time, the other two groups are completely off-axis (or dome) extensions, and our knowledge of the geological structure requires adequate reworking. The observation of flysch beds on the cliff between Izola and Strunjan led to the working hypothesis that predicted the existence of another anticline near Cape Ronek, which would run parallel to the Izola anticline (Figure 2), but the limestone core would be completely covered by Quaternary deposits. The existence of such a structure would explain the micro-location of the Ronek spring group, whereas the position of the Bele

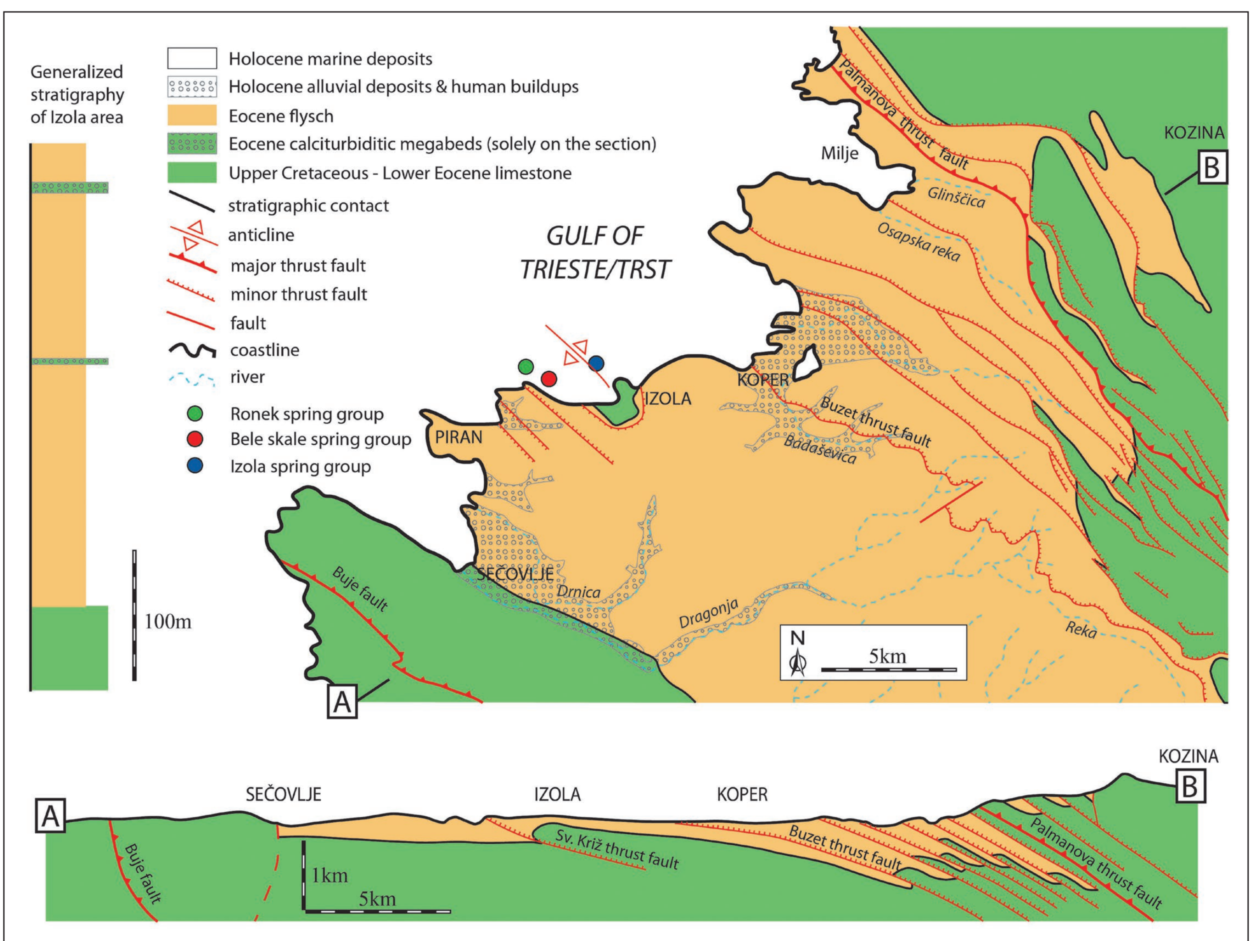


*Figure 3: Geological map and cross-section of investigated area – (simplified from Pleničar et al., 1973 and Placer et al., 2010) with generalized stratigraphic column. Note that lithology colours also mark their hydrogeological characteristics, where limestone and calciturbiditic beds (green) are karstic aquifers and flysch (yellow) generally acts as a groundwater barrier (aquitard, aquiclude).*

skale spring group would still remain debatable (maybe related to buried pre-Holocene river channel).

In order to address the problem, we conducted sedimentological logging of the flysch deposits along the coastal cliffs and made detailed geological map of the adjacent mainland. We present another solution that challenges our working hypothesis and provides a minor but persuasive alternative of the geological structure. With the extrapolation of newly obtained mainland geological data on the sea (below Quaternary deposits), we are able to explain the micro-locations of all of the spring groups.

We emphasise that the main goal of this paper is to provide an explanation of the spatial distribution of the Izola submarine springs. This will serve as the basis for on-going hydrogeochemical research, which will provide further insight into the hydrogeological characterisation and dynamics of the sulphur springs between Izola and Strunjan.

## 2. GEOLOGICAL SETTING

Structurally, the investigated area is part of the External Dinaric Imbricated Belt, which is characterized by SW-directed structural shortening (Placer, 2008; Placer et al., 2010). The coastal area forms its external part known as the Istria-Friuli Underthrust Zone and shows minor internal tectonic deformations, like the small-scale Buzet Thrust Fault and Izola anticline, and was also considered to be an undeformed Adria Foreland (Figure 3). The area is confined by the Buje Fault to the SW and towards the NE by the Palmanova (Črni kal) Thrust Fault, with the latter accompanied by several smaller thrust faults (Placer, 2005, 2007; Placer et al., 2010).

The entire stratigraphic succession of the study area is divided into four main units. The basal unit is formed by Upper Cretaceous to Lower Eocene limestones of the Dinaric/Adriatic Carbonate Platform (Pleničar et al., 1969, 1973). The second unit is represented by Eocene Flysch, which consists mainly of alternating marl and turbiditic sandstone beds. Calciturbidites also occur, mainly as thin/medium-bedded, graded calcarenites, but several calciturbiditic megabeds are also interstratified (Pavšič & Peckmann, 1996; Placer et al., 2004; Vrabec & Rožič, 2014). Along the southern part of the Gulf of Trieste/Trst the coast consists mainly of Eocene Flysch, while in its southern part along the Istra Peninsula, in the core of the Izola anticline and north of the city of Trieste/Trst, limestones are found.

In river valleys and especially on the sea floor, Cretaceous to Paleogene rocks are overlain by Pliocene to Quaternary deposits, which can be divided into two units. The lower unit (third in the overall succession) consists of the Pliocene-Pleistocene alluvial deposits (mainly silty clay, and subordinate sand and gravel) occasionally interrupted by marine and brackish sediments. The uppermost unit is represented by Holocene marine deposits that cover most of the present-day sea floor. These are fine-grained clastic sediments (sandy silt, clayey silt, silt, and silty sand) with frequent foraminifera, bivalve, and gastropod shells (Ogorelec et al., 1987, 1991, 1997). The transgression is dated using the radiocarbon method at 8.270±50 BP to 9.160±120 BP (Ogorelec et al., 1981; Covelli et al., 2006). The thickness of the marine sediment cover varies from zero (in coastal areas) to ten meters (Romeo, 2009; Slavec, 2012; Vrabec et al., 2013; Trobec et al., 2018). At the same time, the Holocene is still characterized on the mainland by alluvial deposits covering valley bottoms with brackish environments at river mouths (Pleničar et al., 1973), and by specific subrecent sedimentary environments in Sečovlje and Strunjan Salinas (Ogorelec et al., 1981; Kovač et al., 2018).

## 3. METHODS

Geological mapping was performed on the topographic base map at a 1:5000 scale, combined with a shaded digital elevation model with a spatial resolution of 1 m taken from a lidar scan in 2014–2015 (available from ARSO – Environment Agency of the Republic of Slovenia). For the elaboration of the detailed geological map (see supplement material), we used a combination of two mapping approaches: A) all outcrop analysis (including the description of lithology and structural elements) and B) the tracing of geological boundaries, the latter particularly for the calciturbiditic megabeds within the flysch. The orientation of beds is graphically represented using Steronet11 software (for details see Allmendinger et al., 2011; Cardozo & Allmendinger, 2013).

Sedimentological logging was performed precisely bed-by-bed, and all beds thicker than 1 cm were measured and are presented in sections (Figures 6 and 7). The sections were logged at different locations but could be compiled into two separate logs (for locations see supplement material and descriptions below).

# 4. RESULTS

## 4.1. *LITHOSTRATIGRAPHIC UNITS*

The description of lithostratigraphic units is made using a combination of data from previous research (general descriptions, biostratigraphy) and our observations obtained during the mapping and sedimentological research. This is particularly valid for the flysch deposits that were logged in detail in several composite sections.

The stratigraphically lowest outcropping succession is found solely in the town of Izola and belongs to the Alveolinid-Nummulitid Limestone Formation. This formation was described in detail on the Kras (Karst) Plateau by Jurkovšek et al. (2013, 2017), where it documents a progressive deepening of the sedimentary environment. Namely, it passes from alveolinid limestone characterized by an inner/middle ramp, through nummulitid limestone characteristic of the middle ramp, to the outer ramp limestone rich in discocyclinids, orbitolitids, and flat forms of nummulitids (Jurkovšek et al., 2013). As evident in the large discoid foraminifers, the topmost part of the formation in the Izola anticline is outcropping (Fig-


*Figure 4: a) a panoramic view towards the NW of the Izola area with encircled limestone outcrops, and their seaward extrapolation due to anticline structure, with locations of the submarine sulphur springs, b) limestone in the coast of the town of Izola, c) close-up of the limestone with large benthic foraminifera, d) the uppermost part of the transitional marl between Alveolinid-Nummulitid Limestone Formation and flysch deposits.*


*Figure 5: a) Cape Kane with duplex structure and three beds (3B) used for correlation with the Cape Ronek outcrops, b) three beds (3B) used for correlation with Cape Kane succession near Izola, c) flysch succession exhibits characteristics of a basin plain - distal fan sedimentary environment with thin, laterally continuous turbiditic beds, d) calciturbiditic bed at 88 m of the Strunjan section showing entire Bouma sequence (Ta-e), e-g) thickest calciturbiditic bed at 207 m of the Strunjan section below the Sveti Križ viewpoint with (e) lower graded part, (f) middle part with wash-out marl plasticlasts (encircled), and (g) topmost part composed of calcareous marl.*

ures 4a-c). In the Kras Plateau, the formation is dated to the Ypresian stage (Ilerdian) (foraminiferal biozones SBZ 5 to SBZ 8) (Jurkovšek et al., 2013). In Istria (including the Izola anticline), the formation is younger and the topmost part is Lutecian in age (foraminiferal biozone SBZ 14) (Pavlovec, 1985; Drobne et al., 2009).

The limestone is overlain by an interval of transitional calcareous marl several tens of meters thick, known as Globigerina marl (also as beds with crabs) (Figure 4d). This unit outcrops poorly, and its exact thickness is hard to determine, but based on the geological map it probably does not exceed 50 meters. The age of these beds is already Lutetian (nanoplankton biozone NP 14 in Pavlovec & Pavšič, 1986; and NP 15/16 in Pavšič & Peckmann, 1996).

Upwards, turbiditic sandstone beds start to occur within the marl, and the succession gradually changes to typical flysch facies (Figures 5a-c). It is composed of alternating marl and thin- to medium-bedded sandstone, which exhibits a partial Bouma sequence. In most of the beds, Tb-Tc parts of the sequence are present, but rarely show the full sequence. Calciturbidites also occur, and in the mapped area form beds from 10 cm to 9 m thick (Figures 5d-g). The entire flysch succession is more than 600 m thick (Pleničar et al., 1973) and is Lutetian in age (nanoplankton biozones NP 16; in Pavšič and Peckmann 1996).

## 4.2. DETAILED SEDIMENTOLOGY OF MAPPED PART OF THE FLYSCH

A detailed logging of the flysch was performed to produce a lateral tracing of the particular turbiditic beds between Izola and Cape Ronek and the position of the particularly thick calciturbiditic beds within the complete flysch succession. A total of 264 meters of the flysch was logged, and sections cover almost the entire succession between the transitional marl interval and the top of the thickest calciturbiditic bed.

The basal part of the flysch was logged in the Simonov zaliv section at a thickness of 51 m (start N 45°31'54'', E 13°38'38'', end N 45°31'60'', E 13°38'22'') (Figure 6). Our fieldwork observations indicate that the section starts just above the transitional marl interval. It consists of three subsections that are stratigraphically positioned one above the other, but an exact lateral stacking of particular beds (as in the Strunjan section) was not possible. Nevertheless, we consider the logged succession to be nearly continuous. The first subsection (22 m) starts above the beach at the Simonov zaliv bay and was logged towards the west up to the part of the cliff covered by vegetation and tuffa. The second subsection (24.5 m) continues on the other side of the covered cliff until the

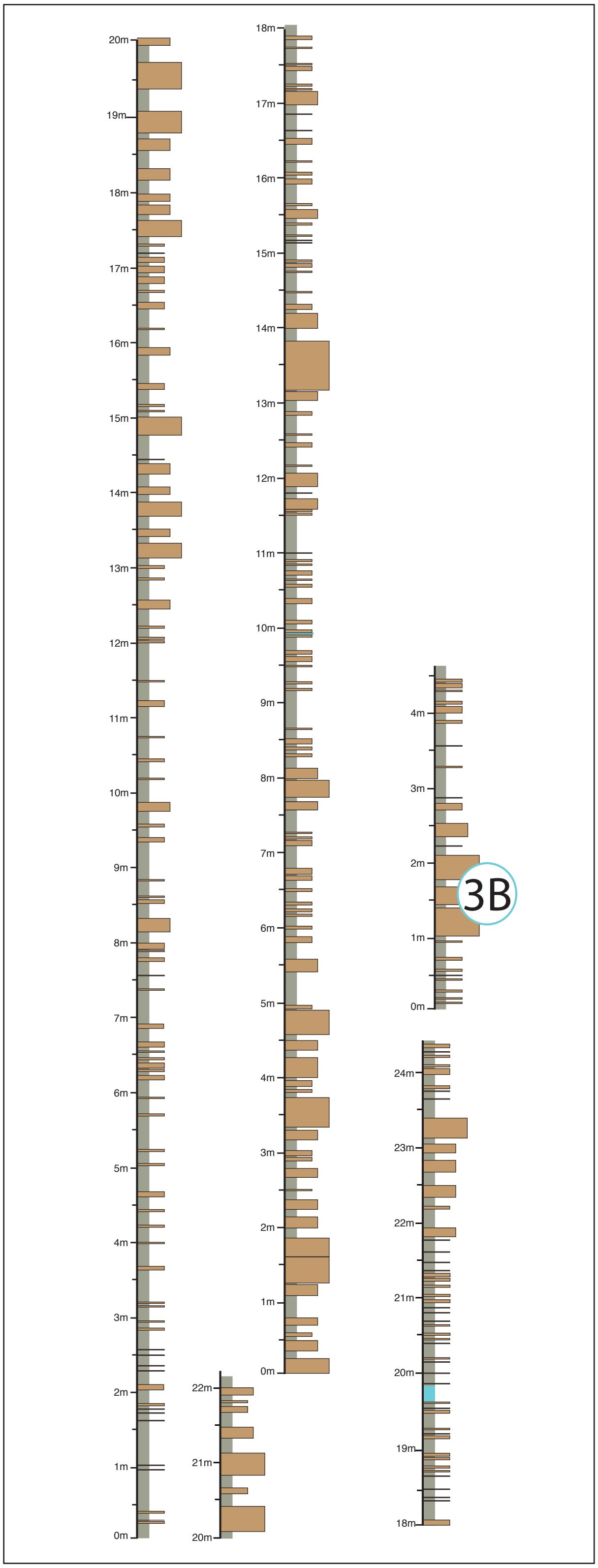


*Figure 6: The Simonov zaliv section is compiled from three subsections that represent stratigraphic continuation (Sign 3B marks the stratimetric position of the three beds used for correlation with the Strunjan section – for details see text).*

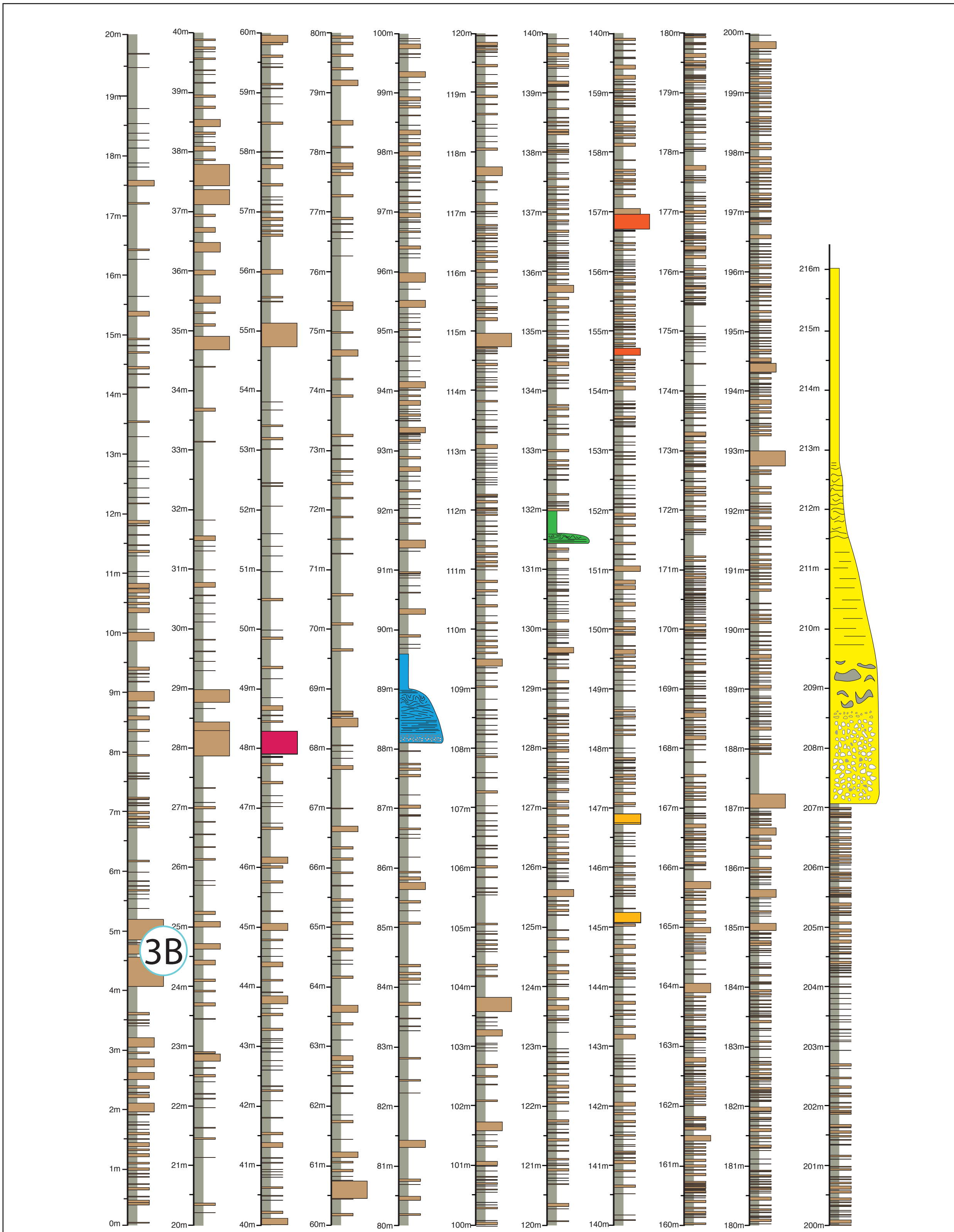


*Figure 7: Strunjan section is dominated by siliciclastic turbidites (brown), whereas calciturbidites (other intense colours) are sporadic but can stand out. Beds at 88m (blue) and 207m (yellow) were laterally traced during detailed geological mapping. 3B marks a stratimetric position of 3 beds used for correlation with the Simonov zaliv section.*

end of the cliff outcrops. The third subsection (4.5 m) was logged at Cape Kane.

The Simonov zaliv section begins with alternations of thin sandstone beds and marl (lower part of the first subsection). In the middle part of the section (upper part of the first subsection and lower part of the second subsection), several medium-sized beds (up to 36 cm thick) are present. Above, thin beds again prevail, with the exception of a 65-cm-thick bed at 35.5 m of the section (13.5 m of the second subsection). The top of the section (third subsection) is characterized by three medium-sized sandstone beds (33, 24, and 38 cm), which contain large marl mud-chips (marked as 3B in Figures 5a, 6 and 9). These clasts are washed out on the weathered surface, which gives it the appearance of a void. Just above these three beds a large-scale duplex structure (Figure 5a) of Cape Kane is positioned and is either tectonic or synsedimentary (our preference) in origin (Vrabec & Rožič, 2014). We note that these three beds are also repeated due to a minor thrust.

The rest of the flysch was logged in the 216-meter-thick Strunjan section (Figure 7). It is compiled from three subsections that represent a direct stratigraphic continuation of the flysch. The lower subsection (0-89 meters of the section) was logged on the cliff east of Cape Ronek (start N45°32'24" E13°36'60", end N45°32'14" E13°37'13") (A lateral tracer to a base of the middle subsection was the first prominent calciturbidite megabed). The middle sub-section was logged in the Mesečev zaliv bay from 88 to 187 meters of the section (start N 45°32'18" E13°36'44", end N 45°32'15" E 13°36'26") (A lateral tracer to a base of the upper subsection was a turbiditic bed with a thick marl top). The upper subsection from 187 to 216 meters of the section was logged at the base of the cliff below Sveti Križ towards Cape Punta, and included the thickest calciturbiditc megabed (start N 45°32'16" E 13°36'18", end N 45°32'13" E 13°36'07"). The latter was additionally logged at the top of the cliff on the Sveti Križ viewpoint (Figure 5d).

The Strunjan section (Figure 7) represents the direct stratigraphic continuation of the Simonov zaliv section, which is deduced from the fact that the basal part of the Strunjan section (on the Cape Ronek) contains three medium-sized sandstone beds (50, 16, and 35 cm) with large, mostly washed-out marl mud-chips (marked as 3B in Figures 5b, 7 and 9). Based on these characteristics, the stacking pattern of under/overlying successions, and an analysis of the entire cliff outcrop we suggest that these three beds are the same as those from the topmost part of the Simonov zaliv section. We attribute the minor variations in the thickness of particular beds to the variability of lateral thickness.

Above, approximately 200 m of the flysch is completely exposed. This succession shows typical distal-fan development with numerous, thin- to medium-bedded, laterally continuous siliciclastic turbidites (coloured brown in Figures 6 and 7). The majority of these beds are less than 10 cm thick, medium-sized beds are sporadic, and in the lower part of the section they occur at a distance marginally greater than 10 meters, whereas in the upper part of the section they are virtually absent (just a few siliciclastic turbiditic beds are 25 cm thick).

Calciturbiditic beds start to occur in the upper part of the Strunjan section (intense colours in the Figure 7). The first bed (at the 48 m of the section) still exhibits a high siliciclastic content, whereas upwards these beds become almost pure limestones. Two calciturbiditic (mega) beds stand out for their thickness: the first occurs at the 89 m of the section, showing the full Bouma sequence, and is 1.45m thick, with the Te part (marl top) 60 cm thick (Figure 5d). The thickest bed forms the top of the Strunjan section (Figures 5e-g). It exhibits the full Bouma sequence and is 9 m thick. In the transition from the Ta to Tb part of the Bouma sequence, large marl mud-chips are present. As with the siliciclastic beds, they are washed out and give the typical appearance of a void (Figure 5f). The marl top (the Te part of the Bouma sequence) is approximately 4 m thick. These two megabeds were also used as lateral tracers for detailed geological mapping. Between these two megabeds, five other calciturbiditic beds occur. These beds are thinner (10 to max. 60 cm) and exhibit base-cut Bouma sequences (Tc-Te, Td-Te parts).

### 4.3. GEOLOGICAL MAP

The entire mapped area shows minor structural deformations. The Sveti Križ Thrust represents a major structural discontinuity that occurs in the western part of the mapped area and which outcrops in the Mesečev zaliv bay below the Sveti Križ viewpoint. The displacement is assessed to 80 meters and is particularly visible due to the movement of the upper megabed. The thrust plane dips towards the NW (Placer et al., 2010; Vrabec & Rožič, 2014) and the orientation was measured at the coast to 62°/21°. Towards Strunjan, i.e. in the footwall of the Sveti Križ Thrust, several folds are visible in the cliff. On the cliff at Cape Kane near Simonov zaliv bay a complex duplex structure is perfectly exposed (Figure 5a). Several indices, such as strongly folded beds, thick marl cover with practically absent sandstone beds, and partly visible overlying continuous sandstone beds indicate its synsedimentary (slump) origin. Laterally, the rather chaotic folds seen at Cape Ronek could indicate the same synsedimentary soft sediment deformation. Several other minor folds and thrusts of more univocal tectonic origin are seen in the cliff between Izola and Strunjan (e.g. see description of the Simonov zaliv section). Some normal faults with only minor displacement (usually less than a meter of displacement) are also present in the area (see also Vrabec & Rožič, 2014). Placer et al. (2010) mention a bedding – a parallel thrust zone in the transitional marls, but this structure was not detected during our geological mapping.

The major structure of the mapped area is an Izola anticline (Figures 8 and 9). In the core of the anticline an Alveolinid - Nummulitid Limestone Formation is outcropping, with outcrops limited to the area of the town of Izola and surrounded by a rim of poorly exposed transitional marl. The rest of the mapped area is composed of flysch. The anticline is reflected also in the outcrops of the two calciturbiditic beds that were traced across the entire area. The upper (thicker) megabed shows almost continuous outcrops from the Sveti Križ viewpoint to the south-easternmost point of the mapped area near Baredi. Similarly, the lower megabed can be traced in the area between Izola and Semedela (Koper suburbs), whereas it is discontinued in the Bele skale area and sinks below the sea, and in the area of Jagodje (Izola suburbs) due to the settlement.

Measurements of the orientation of beds revealed a uniform azimuth in the anticline SW limb between Mesečev zaliv bay and Šared village (grey lines in Figure 8), which are generally oriented towards the SSW (mostly between 190° and 210°), and dip mostly between 15° and 25°. Between the village of Šared and the Segadici hill the azimuth changes towards the south (around 180°) with similar dips (blue lines in Figure 8). In the eastern part of the mapped area between the Segadici hill and Izola Hospital the dip becomes almost horizontal (from 5° to 10°), but the azimuth gradually shifts towards the east (orange lines in Figure 8). In the north-eastern corner of the mapped area, north of the Izola Hospital, the azimuth changes towards the NNW (around 30°) with a dip of 10° (green lines in Figure 8). From the compiled data we conclude that the Izola anticline is asymmetric, with steeper dips in the SW limb; it has a very poorly expressed half

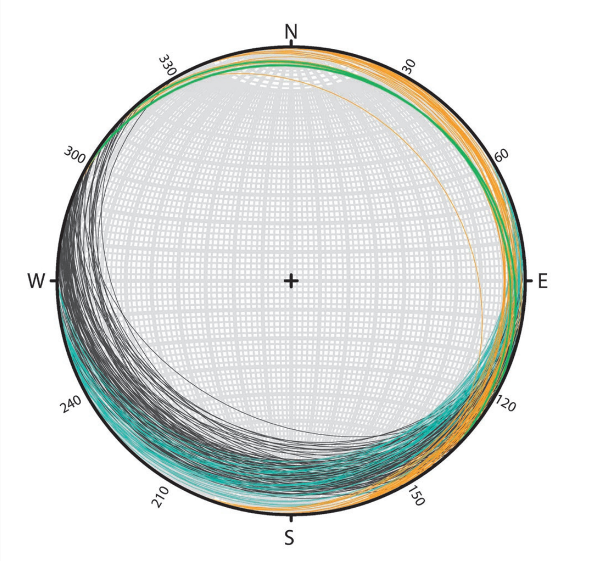


*Figure 8: Steronet diagram of the dips of beds in the Eocene flysch indicates a WNW – ESE oriented axis of the Izola anticline with poorly expressed dome at the ESE part of the mapped area; grey lines - area between Mesečev zaliv bay and village of Šared, blue – area between village of Šared and Segatici hill, orange lines – area between Segadici hill and Izola Hospital, green lines – area north of Izola Hospital.*

dome shape in its ESE part and the axis of the anticline is oriented in the WSW-ESE direction. The Izola anticline architecture generated from our research generally corresponds to previous geological maps but brings minor yet important modifications. The dome proposed by Pleničar et al. (1973) is only partly recognised in the ESE part of the anticline. From the town of Izola towards the WNW, limbs (at least the outcropping SW limb) shows a rather uniform dip of the beds all the way to the last outcrops in the Strunjan area. The axis of the anticline is therefore moderately rotated anticlockwise compared to the previously drawn NW-SE orientation (Placer et al., 2010).

## 5. DISCUSSION

Much of the Slovenian coast is marked by a thick sequence of Eocene flysch deposits. Only in the core of the Izola anticline does the underlying Eocene limestone outcrop. It is surrounded by a rim of transitional marl succession (seen in and around the town of Izola). But neither the dome structure (Pleničar et al., 1973) nor the NW-SE oriented Izola anticline (Placer et al., 2010) can successfully explain the micro-locations of the Ronek and Bele skale spring groups. Furthermore, as revealed by our research, there is no additional anticline in the Cape Ronek area, and an azimuth as well as a dip of beds remains rather constant between Izola and Strunjan. The supposed Cape Ronek anticline is therefore only the result of a simple rule of V's on the slightly curved coastline. This contradicts our working hypothesis and another solution need to be proposed and assessed.

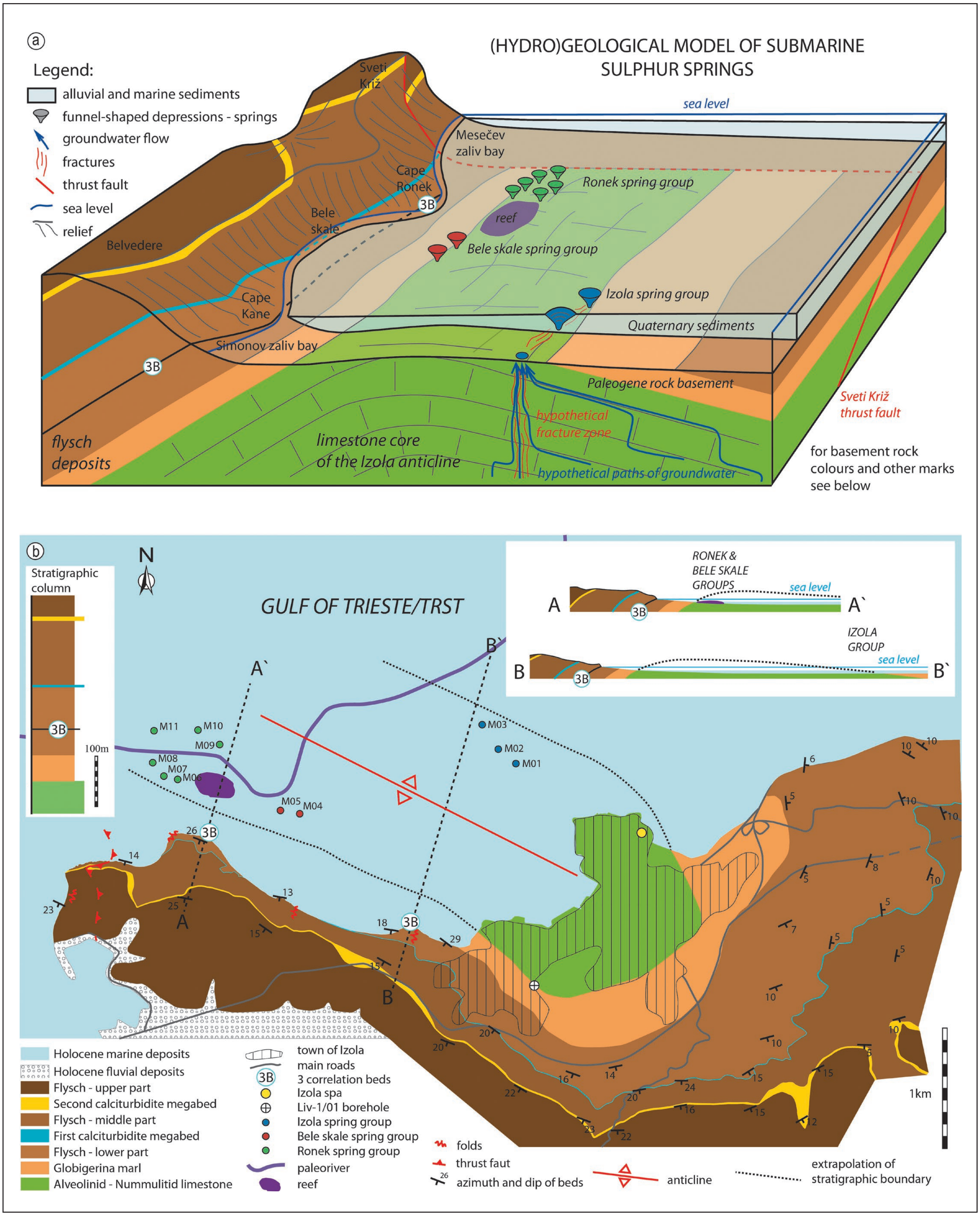


*Figure 9: a) Schematic presentation of the geology including proposed hydrogeological conceptual model (frontal view – for better presentation, Quaternary sediments are presented in a step behind front view) of the area between Izola and Strunjan, and b) simplified geological map, stratigraphic column and cross section of the Izola area: Izola anticline has a dome structure on the SE part and is WNS–ESE oriented, which explains the position of all springs – the Izola group is located at the northern margin of the anticline limestone core, and Ronek and Bele skale at the southern margin.*

Our research points to minor yet crucial differences in the structure of the investigated area. Firstly, it revealed that the dome structure (cf. Pleničar et al. 1969, 1973) of the Izola anticline is present, but is very mildly expressed in the outcropping part, i.e. in the ESE part of the anticline. Second, a more important structural alternation is the anticlockwise rotation of the Izola anticline axis that is not oriented in the NW-SE direction (cf. Placer et al., 2010), but exhibits the WNW-ESE orientation (Figure 9). The SW limb of the anticline, which is well exposed on the surface, shows uniform azimuth (around 200°) and a relatively steep (up to 29°) dip of beds in a large part of the mapped area between the village of Šared and Strunjan. The opposite limb of the anticline is exposed solely in the NE corner of the mapped area. Measurements are scarce because the area is anthropogenically changed (it is already part of the town of Koper), but they reveal an approximately opposite azimuth (around 30°) and less dipping of beds (10°). This indicates an asymmetric anticline, which is in accordance with the previously established origin of the Izola anticline, which was interpreted as a thrust-propagating fold that originated with the anticlinal bending of the beds in the hanging wall of the Sveti Križ Thrust (Placer et al., 2010, Vrabec & Rožič, 2014). Such origin is also evident from the subsurface data from the Gulf of Trieste/Trst (Busetti et al., 2010a, 2010b). We note that the azimuth and dip of the Sveti Križ Thrust (62°/21°), measured at the coast in Mesečev zaliv bay, does not perfectly match this model (the azimuth should be around 20° to 30°). This can be explained either by the local bending of a thrust plane or, alternatively, with thrusting that post-date or predate folding. In the second scenario, the thrust plane was primarily oriented like the other Dinaric thrusts (dipping towards NW, i.e., 45°), and was rotated slightly towards the east due to younger folding that created the Izola anticline. A similar post-deformation inclination was proposed also for the duplex structure at Cape Kane (Vrabec & Rožič, 2014). In this scenario, the top of the limestone core would be lowered westwards of the Sveti križ Thrust (as shown in Figure 9a). However, exact geotectonic interpretation extends beyond the scope and focus of this paper and encourages further detailed structural and geophysical analysis of the area under discussion.

The described alteration of existing structural data provides a simpler but hydrogeologically consistent explanation of the spatial distribution of all spring groups. It is based on a hydrogeological conceptual model (Figure 9a – frontal view) that predicts the following: A) water springs from the limestone aquifer (core of Izola anticline) at the stratigraphic boundary between the limestone and the overlying siliciclastic succession (groundwater barrier), B) springs are located in the near-shore area, where the sedimentary cover of Quaternary deposits is thin enough to be washed out, and C) as is evident from the elevated temperatures, sulphur mineralization, and similarities with the LIV-1/01 borehole (Benedik & Rožič; 2002; Žumer, 2004, 2008; Faganeli et al., 2005; Žvab Rožič et al., 2021; Šušmelj et al., 2022), groundwater originates from well buried limestone formations, below the coal-rich Liburnia Formation. We predict that the groundwater is recharged by a deep hypogenic loop from the NE (Kras Plateau) and/or SW (Istra Peninsula). Upward, the water penetrates the coal layers (internal hydrogeological barriers within the thick limestone sequence) at various, supposedly structurally governed points, and rises to the surface along karstified (fracture) zones. In areas where it meets the stratigraphic contact, it flows along it and finally springs at the margin of the Izola limestone core.

Combining the proposed hydrogeological conceptual model and a moderate anticlockwise rotation of the previously described (Placer et al., 2010) Izola anticline axis leads to the solution of micro-locations for all submarine sulphur springs. Namely, if we prolong the stratigraphic contact between the limestone and the overlying siliciclastic beds into the sea (below Quaternary deposits) parallel to the newly established axis orientation (Figure 9), we see that all spring groups fall along the margin of the Izola anticline limestone core. The Ronek and Bele skale groups are located on the southern side, and the Izola group on the northern side of the limestone core of the Izola anticline. The grouping of springs into the three areas can be attributed to the minor structures within the limestone, such as faults and associated fracture zones, which either act as local barriers or increase the permeability of the rocks (Šušteršič et al., 2001; Šušteršič, 2006; Čar, 2018). This is particularly evident in the NW-SE linear distribution of the Izola group.

Alternatively, the position of springs can be connected to the variable thickness of the overlying Quaternary sediments above the particular segments of the Izola anticline limestone core. The latter is indicated in the area of the Cape Ronek group. In this area, small-scale bioconstructions (reef) exist (Falace et al., 2011; Lipej et al., 2016; Orlando-Bonaca et al., 2017). We propose that the reef formed above the topographically elevated area, which existed in the area of the Eocene limestone outcrops and would somehow represent a small-scale equivalent of present day Izola. During the transgression, such a topographic height would provide a hard substrate appropriate as a habitat for the Holocene reef community. Our speculation is supported by both the position of this reef as well as geological data. The following is considered: A) three thicker sandstone beds (3B in Figures 4, 6, 7 and 9) that outcrop on the coast and form the base of the duplex structure in Cape Kane are the same as the sandstone beds outcropping along the coast of Cape Ronek, B) the thickness of the siliciclastic succession below these three beds is the same at both locations (assessed to 120 m), and C) the calculated horizontal seaward distance between the three beds and the limestone outcrops, based on the dip of beds at approximately 300 meters. The reef and first springs of the Ronek and Bele skale groups are positioned at precisely such a distance from the coast, which proves the existence of limestone below the reef as well as the surrounding springs. The upper surface of this limestone might be elevated and the Quaternary sedimentary cover consequently thinner, at any rate enabling the groundwater to spring on each side of the reef area. This is already visible in the general map indicating the thickness of the Holocene marine sediment inside the entire Gulf of Trieste/Trst (Trobec et al., 2018), but further, more detailed geophysical research of this particular area would be useful and well serve to better frame our proposal.

The absence of springs further to the west is explained either by thicker Quaternary deposits that disable the spring waters to penetrate through them or by the termination of scantly buried limestone due to the Sveti Križ thrust plane (Figure 9a). The latter is possible, if we consider a measured dip of the thrust plane (62°/21°) from the Mesečev zaliv bay as characteristic for the entire thrust plane.

## 6. CONCLUSIONS

The submarine sulphur karstic springs in the Slovenian part of the Gulf of Trieste/Trst near the town of Izola, are divided into three groups: the western Ronek group, the intermediate Bele skale group, and the eastern Izola group. Previous investigations already linked the position of the springs to the geological structure characterized by the NW-SE-oriented Izola anticline, which has a limestone core and flysch limbs. However, based on pre-existing geological data, only the position of the Izola group was successfully explained by such interpretation. Our detailed sedimentological logging and geological mapping, and the extrapolation of the geological basement beneath the seafloor (below the Quaternary deposits) provided a structural solution that explains the micro-locations of all spring groups in question.

We demonstrated that the Izola anticline has a slightly different orientation than previously suggested, namely it is oriented in the WNW-ESE direction. We propose that springs occur A) at the stratigraphic boundary between the limestone (aquifer) and flysch (aquiclude, aquitard), B) in the near-shore, where the sediment cover of the Quaternary deposits is thin, and C) the Izola spring group is located on the northern limb, and the Ronek and Bele skale groups on the southern limb of the Izola anticline limestone core. Our research provides an explanation for the spatial distribution of the submarine sulphur springs, moreover on-going hydrogeochemical studies will provide further insights regarding the specific characteristics, dynamics, and sulphur origin of the springs.

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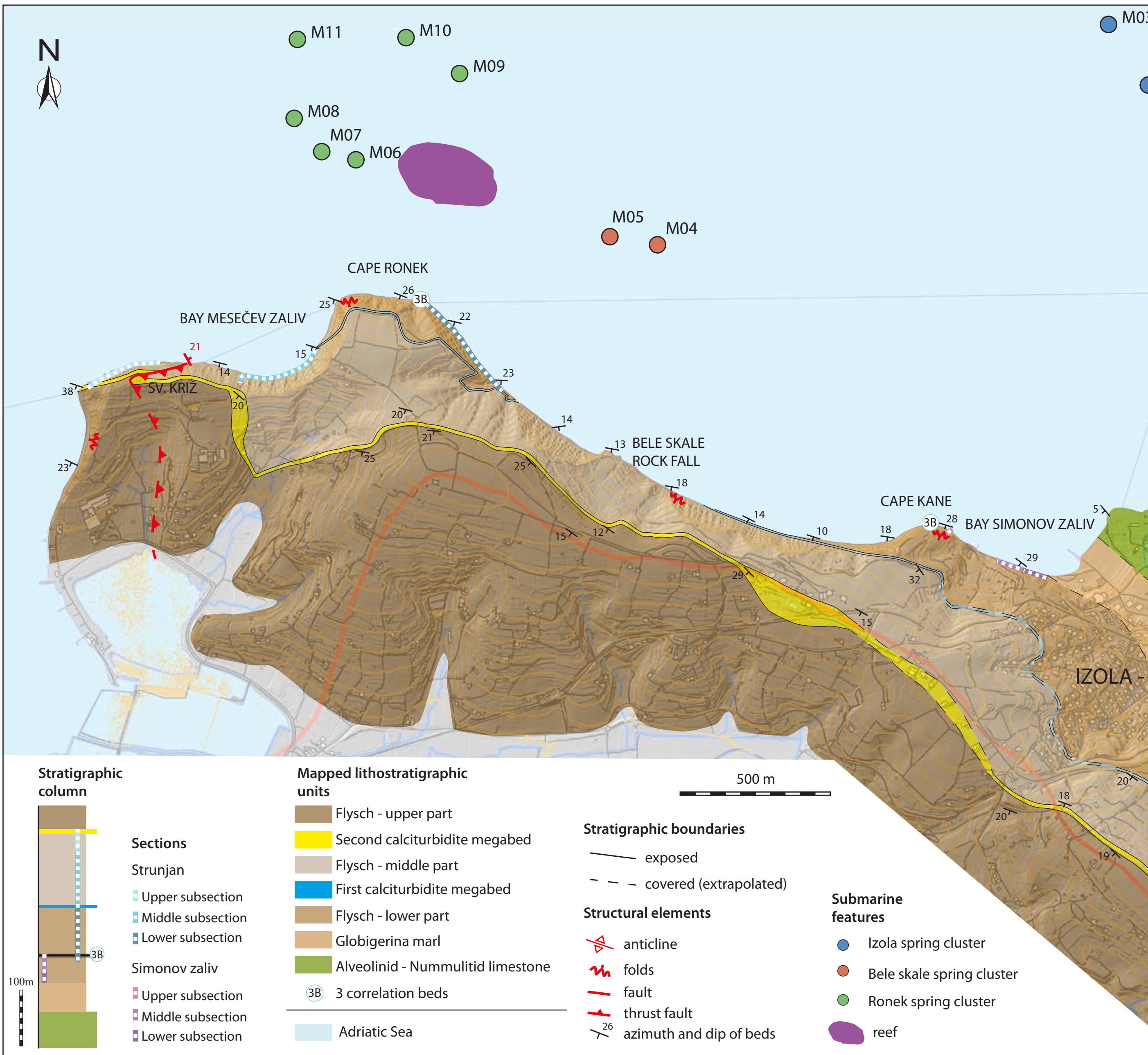
# SUPPLEMENT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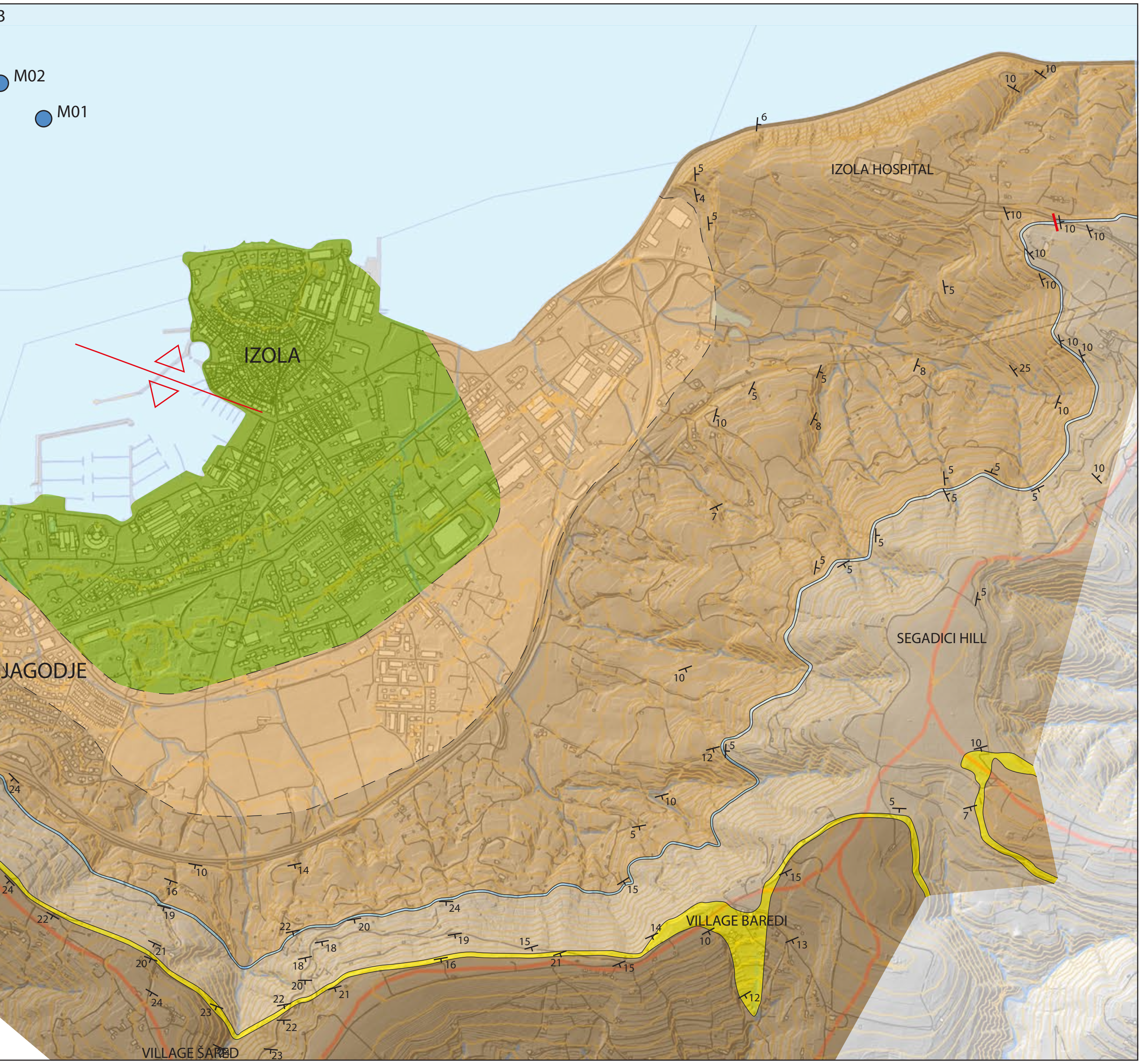
Sections
Strunjan
Upper subsection
Middle subsection
Lower subsection
Simonov zaliv
Upper subsection
Middle subsection
Lower subsection
100m
Mapped lithostratigraphic units
Flysch - upper part
Second calciturbidite megabed
Flysch - middle part
First calciturbidite megabed
Flysch - lower part
Globigerina marl
Alveolinid - Nummulitid limestone
3B 3 correlation beds
Adriatic Sea
500 m
Stratigraphic boundaries
exposed
covered (extrapolated)
Structural elements
anticline
folds
fault
thrust fault
azimuth and dip of beds
Submarine features
Izola spring cluster
Bele skale spring cluster
Ronek spring cluster
reef


M02
M01
IZOLA
IZOLA HOSPITAL
JAGODJE
SEGADICI HILL
VILLAGE BAREDI
VILLAGE ŠARED