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SCIENCE

Morphoneotectonics and lithology of the eastern sector of the Gulf of Trieste (NE Italy)

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ABSTRACT
The paper aims to describe and map the geomorphological and lithological features of the Gulf of Trieste and its eastern coasts and to define its neotectonic behaviour by means of the analysis of the morphoneotectonic evidence. The final map, produced at a scale of 1:30,000, shows the outcome of field investigations carried out along the coast and the sea bottom and a detailed geomorphological classification of the coastline. Published and new data coming from the analysis of archaeological remains, geomorphological and sedimentological sea-level indicators and geophysical researches are discussed in order to provide a complete overview of the study area.

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Coastal geomorphology; geomorphotypes; neotectonic; NE Adriatic

1. Introduction

The Gulf of Trieste is an epicontinental semi-enclosed shallow marine basin in the NE Adriatic Sea, with a maximum depth of 25 m. Marine sedimentation is strongly affected by local inputs of freshwater, fed by the Isonzo and Timavo rivers in the north and some minor rivers in the southeastern sector (Covelli, Fontolan, Faganeli, & Ogrinc, 2006). The eastern side of the gulf is bordered by rocky coasts and dominated by plunging cliffs and shore platforms (Furlani, Pappalardo, Gomez-Pujol, & Chelli, 2014). The surface area of the gulf is about 600 km^2, with the water depth generally shallow, reaching a maximum of about 25 m in the central part of the gulf.

The neotectonic behaviour of the Gulf was first highlighted during the 1980s by many authors, including Cucchi, Forti, and Semeraro (1979), Carulli et al. (1980), Carobene and Carulli (1981), Zanferrari et al. (1982), Cucchi, Forti, and Forti (1983), Slejko et al. (1987), Carulli and Cucchi (1991), Del Ben, Finetti, Rebez, and Slejko (1991).

Over the last decade, the neotectonic behaviour of this area has been investigated using new instrumental data as well as sea-level markers. Braitenberg, Nagy, Romeo, and Taccetti (2005) described the SE–NW tilting of the Karst plateau; Antonioli, Carulli, Furlani, Auriemma, and Marocco (2004), Antonioli et al. (2007, 2009), Furlani et al. (2011), Melis et al. (2012) and Evelpidou, Pirazzoli, and Spada (2015) studied vertical tectonic rates using geomorphological, sedimentological and archaeological markers. Busetti et al. (2010a), employing multichannel seismic surveys, provided the distribution of the main fault systems and the activity in the gulf during the Quaternary.

This paper aims to present a 1:30,000 morphoneotectonic map (Main map) of the rocky coasts of the eastern sector of the Gulf of Trieste together with the lithological features of the sea bottom. The map extends up to 1000 m inland in order to represent landforms and deposits derived from marine, karst, fluvial and gravitational processes. Moreover, a detailed classification of the coastal landscape is provided.

2. Study area

The Gulf of Trieste constitutes the northeastern end of the Adriatic Sea and is bordered to the north by the Friuli Plain, to the east by the Classical Karst plateau, and to the south by the Istrian peninsula. In the Karst and in Istria, a thick carbonate platform sequence outcrops. It spans the time from the early Cretaceous to the early Eocene and is followed by the Eocene flysch (Cucchi, Biolchi, Zini, Jurkovšek, & Kolar-Jurkovšek, 2015; Cucchi, Pirini Radrizzani, & Pugliese, 1987; Jurkovšek, Cvetko Tešović, & Kolar-Jurkovšek, 2013). This carbonate sequence is composed of *Monte Coste Limestone* (350–400 m thick, Aptian-Albian in age), composed of bedded, foraminiferal, dark limestones and layers of breccia. It is overlain by the *Monrupino* fm. (300–700 m, middle-upper Cenomanian in age), composed of light grey and dark grey dolomites, with frequent red-yellowish lenses of bedded dolomites, micritic limestones and calcareous-dolomitic alternations (Colizza, Cucchi, & Ulcigrai, 1989). The sequence

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continues with the *Zolla Limestone* (200 m, upper Cenomanian-Turonian in age), which is composed of bedded micritic limestones with pelagic fauna and very fossiliferous bioclastic limestones, and the *Aurisina Limestone* (600–1400 m, Upper Campanian-upper Maastrichtian), which is composed of shallow water, fossiliferous limestones. The cretaceous sequence ends with the *Liburnia fm.* (upper Maastrichtian-Paleocene), 80–200 m thick, which includes the Cretaceous–Paleogene boundary (Pirini Radrizzani, Pugliese, & Stocca, 1987; Tewari et al., 2007). The latter is subdivided in two parts: *Liburnia fm. A*, composed of bedded and medium dark-grey, bioclastic, micritic limestones and *Liburnia fm. B*, composed of thin-bedded dark limestones, slightly marly and massive bioclastic and coral algal limestones. The carbonate sequence ends with the *Alveolinid and Nummulitid Limestone* (70–300 m, lower Eocene in age), which is composed of grey, very fossiliferous limestones, rich in macroforaminifers. At the top of the carbonate sequence, an alternation of limestones and marls, the Transitional Beds, 50 m thick and Middle Ypresian-Lower Cuisian in age (lower Eocene) occur (Burelli et al., 2008). The drowning of the carbonate platform is followed by the deposition of the turbidite sediments of the Flysch fm., which is composed of an alternation of silty marlstones and sandstones, dated back to the middle Eocene (Bensi, Fanucci, Pavšić, Tunis, & Cucchi, 2007).

Finally, Quaternary deposits are composed of alluvial deposits, sedimented by small temporary streams, *terra rossa* in the karst area and cemented debris which sometimes cover flysch cliffs.

In the gulf, the same lithologies occur, with the 3–4 km of Cretaceous to Paleogene carbonates overlaid by a wedge of flysch up to several hundred metres thick, draped by Quaternary continental and marine sediment, thickening westward from a few metres at the coast to 1–200 m in the central part of the gulf (Busetti et al., 2010a, 2010b).

From a geodynamic viewpoint, the Karst belongs to the External Dinarides (Figure 1). The latter are characterised by thrusts, reverse faults and high-angle faults, often with a strike-slip movement, NW–SE oriented. The thrusts caused the development of a series of overlaid tectonic units with a SW vergence, tending to the superimposition of the Mesozoic carbonate sequence on the Paleogene turbidite one. Carulli (2011) described the important role that dinaric and anti-dinaric faults played in the formation of the gulf.

The main tectonic structure, which affects the Gulf of Trieste, is the Dinaric frontal ramp system, composed of the NW–SE segments of the Panzano Thrust (Fantoni et al., 2003) and by the Karst Thrust (Bensi, Fanucci, & Podda, 2009), formerly the Trieste Fault (Busetti et al., 2010a, 2010b; Del Ben et al., 1991), with a vertical displacement of about 1400 m (Busetti et al., 2010a, 2010b). Locally, the distal part of the thrusts is displaced by tear-faults, which are strike-slip faults with NE–SW or ENE–SWS orientation (Cucchi & Piano, 2013) (Figure 1).

In the gulf, a system of thrusts related to the inversion of the Dinaric foredeep occurs (Busetti et al., 2010a, 2010b, 2013).

3. Materials and methods

The lithological and tectonic features represented on the map were partly derived from a revision of the Geological Map of the Classical Karst (Cucchi & Piano, 2013; Cucchi et al., 2015) and the models provided by Placer (2008) and Placer, Vrabec, and Celarc (2010). In the offshore area, the tectonic features are derived from Busetti et al. (2010a, 2010b 2013). The geomorphological characteristics of the coastal sector were provided by the CGT Project (RAFVG, 2008a) and were integrated by field surveys and air-photo interpretation that allowed to refine the original data, in particular those regarding the coastal features. The map of the eastern part of the Gulf of Trieste was enhanced by the representation of the sediments covering the sea bottom.

Grain-size results from previous works (Brambati & Catani, 1988; Covelli & Fontolan, 1997; Covelli et al., 2006; Ogorolec, Misic, & Faganeli, 1991) were included in a comprehensive data-set along with those obtained from new sampling, where bottom sediments were collected by means of a grab during fieldwork in 2006.

Sedimentological results report the percentage of sand and pelite (mud) contents where the size limits are from 2 to 0.050 mm (sand) and finer than 0.050 mm (pelite) according to Nota (1958) classification: sand (pelite < 5%), pelitic sand (5% <pelite>30%), very sandy pelite (30% <pelite>70%), sandy pelite (70% <pelite>95%), pelite (pelite >95%).

Field mapping and symbols convention have been performed according to the guidelines of the Geological Survey of Italy (Gruppo di Lavoro per la Cartografia Geomorfologica, 1994). The resulting map of the Gulf of Trieste consists of two main sections:

(1) the main geomorphological map at a 1:30,000 scale. It includes the lithological map of the sea-bottom and the related legend;
(2) a morphoneotectonic sketch map of the Gulf of Trieste (upper right side of the map), draped over a Digital Terrain Model (DTM).

3.1. *Lithostratigraphical units*

The coastline is mainly composed of sandstones belonging to the Flysch fm., because marlstones have been partly removed by erosion, from *Costa dei Barbari* (Italy) to *Debeli Rtič* (Slovenia), while limestones belonging to the upper part of Aurisina Limestone, to Liburnia Formation and to Alveolinid-Nummulitid Limestone occur in the northwestern sector of the gulf, from Sistiana

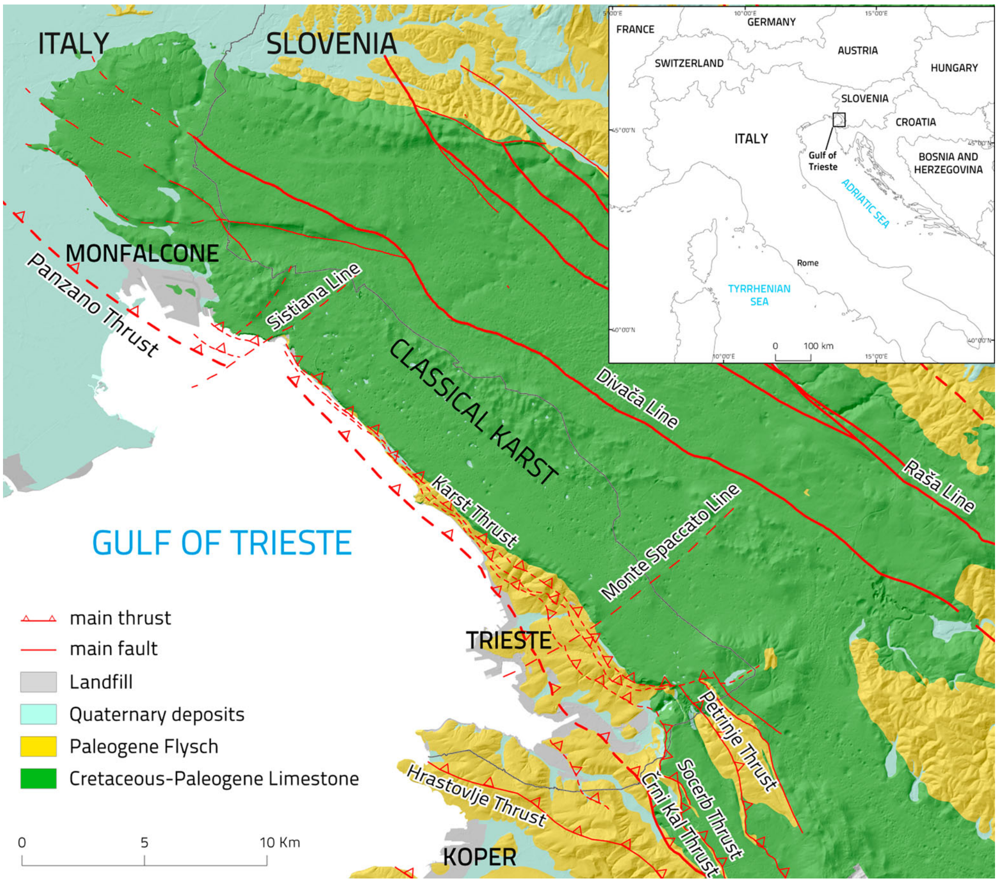

Figure 1. Tectonic sketch of the study area (redrawn from Placer et al., 2010).

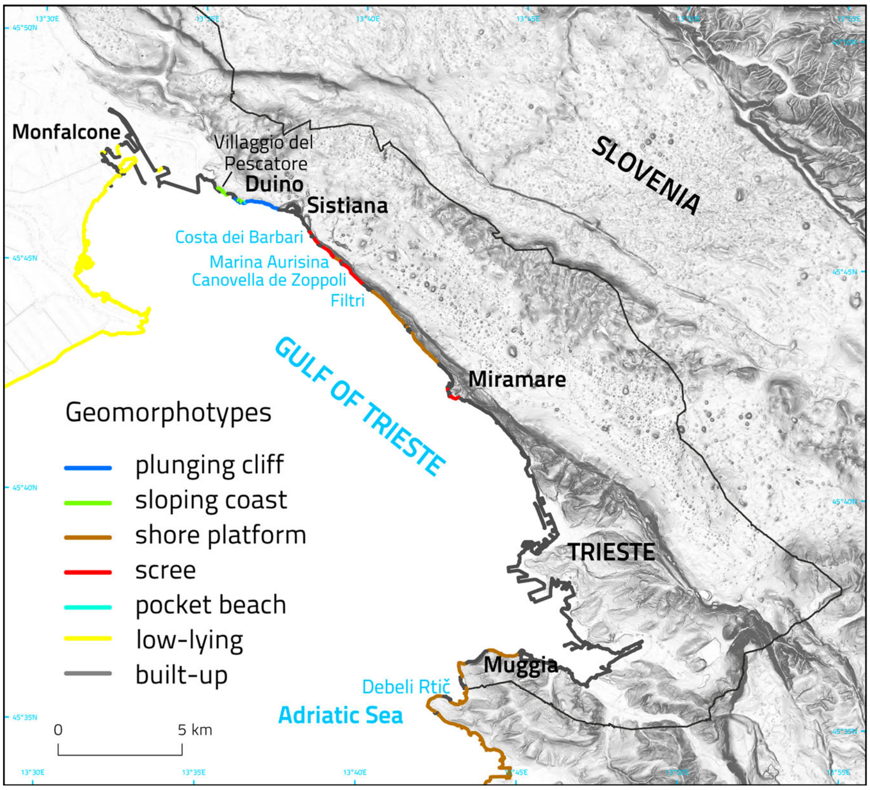

Figure 2. Geomorphological classification of the coastline.

to Duino. Locally, collapsed limestone blocks outcrop at *Costa dei Barbari*, *Canovella de Zoppoli* and Marina Aurisina and at Miramare, the latter as olistoliths. The altitude of limestone-flysch contact decreases from the south (300–400 m) to the north (−1.5 m a.s.l. at Sistiana; Furlani, Biolchi, Cucchi, Bensi, & Burelli, 2009), following the aforementioned tilting direction. Small sections of the studied coast, at the mouth of small rivers, have Quaternary alluvial deposits, such as in the Bay of Muggia. These sectors are completely urbanised.

3.2. *Geomorphotypes and coastal landforms*

The coastal geomorphotypes are defined by peculiar topographical, lithological and geomorphological characteristics, as suggested by Furlani et al. (2014). In the Gulf of Trieste, seven classes have been identified, following Biolchi et al. (in press): plunging cliff, sloping coast, shore platform, scree, pocket beach, low-lying and built-up coast (Figure 2).

Plunging cliffs, up to 70 m high, occur in the northern sector between Sistiana and Duino (Figure 3(a)). The depth, at the submerged foot of the cliff, ranges between −0.5 and −7 m m.s.l. Cliff faces are intensely conditioned by the tectonic structures, which cross them in the NW–SE as well as in the N–S direction (Figure 4(c)).

Sloping coasts can be observed only in the northwestern sector of the gulf, between *Villaggio del Pescatore* and Duino (Figure 3(b)), where limestone beds dip about 35° seaward.

South from Sistiana, such as at Marina Aurisina, *Filtri* and Santa Croce, and in the southern part of the gulf, between Muggia (Italy) and Debeli Rtič (Slovenia, Figure 3(c)), the alternation of sandstone and marlstone has allowed the development of *shore platforms*. Locally they may be covered by pebble and gravel beaches, which have been locally managed for tourism. They extend for some tens of metres offshore. Due to the late Holocene sea-level change, shore platforms also occur below sea level (Furlani, 2003; Furlani et al., 2011).

Figure 3. Coastal geomorphotypes: (a) plunging cliff (Sistiana-Duino, Trieste, Italy); (b) sloping coast (Duino, Trieste, Italy); (c) shore platform (Debeli Rtič, Koper, Slovenia); (d) scree (Costa dei Barbari, Trieste, Italy); (e) pocket beach (Duino, Trieste, Italy).

Figure 4. (a) Sandstone beds forming a shore platform covered by pebbles with a wall behind that hides the natural cliff (between Grignano and Santa Croce, Trieste); (b) marine cave (Duino, Trieste); (c) structural constrain on the coastal landscape (Duino, Trieste).

The coastal sectors classified as *scree* are characterised by the presence of limestone or cemented scree deposit blocks overlapping flysch, such as (from N to S) at *Costa dei Barbari* (Figure 3(d)), Marina Aurisina, *Canovella de' Zoppoli* and *Filtri*. At Miramare these carbonate blocks are olistoliths and they are included in the sandstone–marlstone beds of the flysch. These have played a crucial role in the coastal development, as they have significantly reduce local cliff retreat (Furlani et al., 2009), producing a promontory.

A *pocket beach* occurs at Duino, in the NW sector of the gulf and it is represented by carbonate pebbles and gravels (Figure 3(e)).

The southeastern coasts of the gulf, from Grignano to Muggia, have been classified as *built-up*, because they are completely modified by human activities (Figure 4(a)). Furlani (2003) suggested that this tract was originally composed of cliffs and shore platforms.

A sea cave is located close to the harbour of Duino (Figure 4(b)). It develops in late Cretaceous limestones and is 7 m wide and 10 m long, while its maximum depth is −5 m below sea level. The bottom is characterised by sand and rounded carbonate pebbles (Furlani, Cucchi, & Biolchi, 2012).

A submerged tidal notch outcrops continuously in the northwestern sector, where it developed on the limestone plunging cliff, in correspondence with the collapsed limestone blocks (Figure 5(a)) and to the Miramare olistoliths (Furlani et al., 2011). Abrasional features, which are due to wave action, occur on sandstones and breccias (Figure 5(b)).

3.3. *Sediment supply and its distribution*

The main sediment supply into the Gulf of Trieste comes from the Isonzo River, whose catchment area extends for 3430 km^2 within both Italy and Slovenia. The coastal marine area near the Isonzo River mouth is dominated by carbonate sediments, while the southeasternmost sector is characterised by significant amounts of quartz–feldspathic material due to ephemeral terrigenous inputs from two small rivers, the Rosandra and the Rižana (Brambati, 1970).

Grain-size variability in the sediments is strictly connected to the sedimentary load from the Isonzo River, seabed morphology and meteomarine conditions.

The Isonzo River produces a microtidal, low-energy and fine-grained deltaic system. It is affected by long periods of low-medium discharges and short peaks of intense riverine flow, associated with high suspended sediment load, following heavy rainfall (Covelli, Piani, Faganeli, & Brambati, 2004). Coarse sediments, mainly medium to fine sands and pelitic sands, are dispersed as bed-load by longshore currents both eastward to Grado and westward to the Gulf of Panzano, respectively. In the first case, fluvial sediments mix with residual deposits of similar grain-size belonging to the *Mula di Muggia* sandbank, whereas in the second case they accumulate in front of the Quarantia channel. Both features are related to Isonzo's ancient delta fronts (Brambati, Catani, & Marocco, 1982). When a strong Bora wind blows from E-NE in association with river flood events, the fluvial plume cannot expand symmetrically and is diverted and stretched NE–SW with sediments carried away southwestwards along the coast. Conversely, when winds from the SE and SW (locally called the *Libeccio* and *Scirocco*) are dominant, riverine suspended load is trapped in the Gulf of Panzano where fine particle settling is completed over several days (Covelli, Faganeli, Horvat, & Brambati, 2001). The distribution pattern of fine deposits is therefore related to the decrease in river flow, and the sediments progressively become finer, from very sandy pelites not far from the river mouth, to pelites in the mid-gulf and at depths greater than 6–7 m in Panzano Bay.

3.4. *Structural elements and tectonic data*

In the Gulf of Trieste, landforms are strongly influenced by Dinaric (NW–SW) and anti-Dinaric (NE–SW) structures. The Dinaric system is responsible of the shape of the coast (Carulli, 2011), of the stratigraphical boundaries' alignment, the karst features' alignments and the topographical setting.

The most important Dinaric structures are the Panzano and Karst Thrusts (Figure 1). The latter occurs along the coast and is represented by a system of sub-parallel fault strands onland displaced by strike-slip faults. According to the geophysical data, the same features occur nearshore, even if, due to the poor distribution of geophysical data, their correlation along the coast is difficult.

The occurrence of a thrust northwestward of the Panzano Thrust is inferred from seismic investigations acquired in the area of the Roman-aged baths of Monfalcone by Mosetti, Ambrosi, Nicolich, Lavenia, and Cescon (1970).

The offshore Dinaric structures which occur from *Punta Sottile* to the Isonzo rivermouth are structural highs within the Flysch fm. sequence (Busetti et al., 2010a, 2010b). The gulf represents the Dinaric foredeep, with the same carbonates that outcrop in the Karst, at the depth of more than 1200 m inshore, and is filled by the turbidite succession. Due to the progressive westward migration of the Dinaric compression, the foredeep was inverted, with the

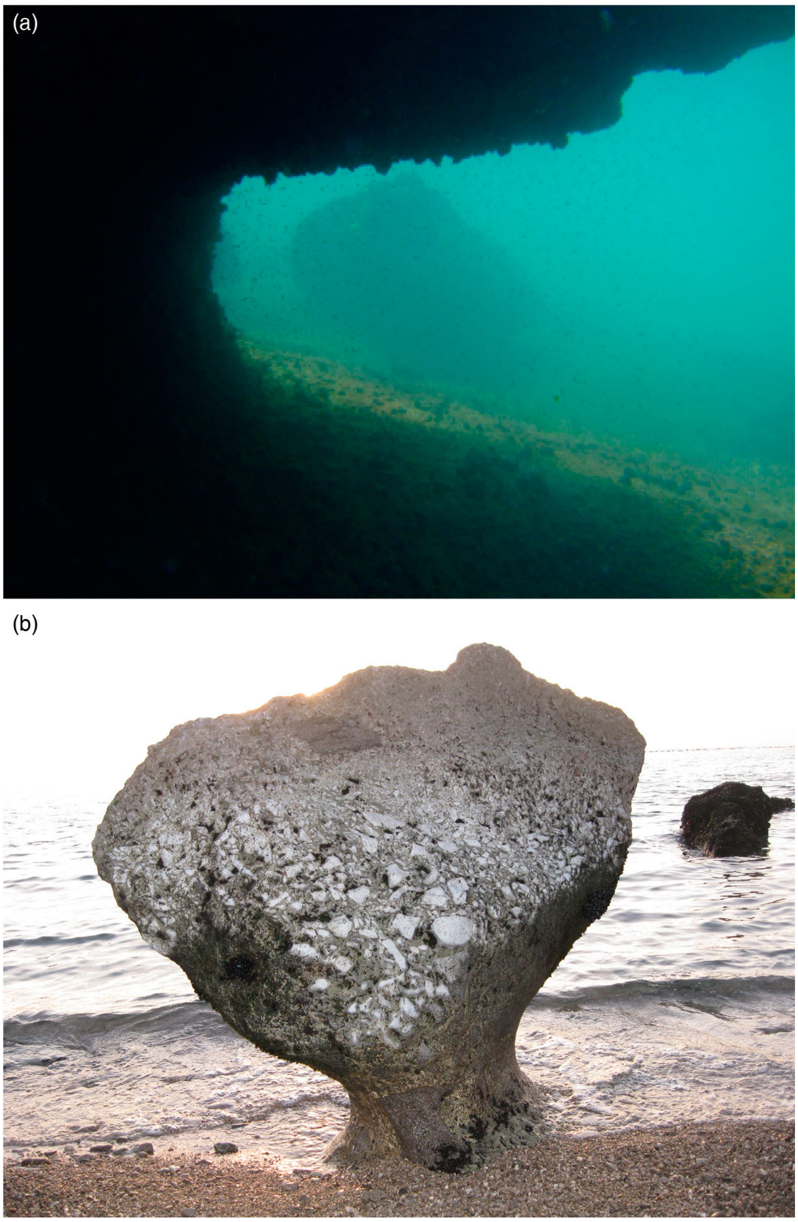

Figure 5. (a) Submerged tidal notch; (b) abrasion notch (Marina Aurisina, Trieste).

consequent formation of folds and thrust-folds (Busetti et al., 2013). The thrusts, which are represented on the map border, are on the southwestern side of the structural highs. The fault strands of these highs displaced the unconformity at the top of the flysch, which is an erosional surface due to subaerial exposure from the Messinian to the Early Quaternary (Busetti et al., 2010a, 2010b, 2013).

The morphoneotectonic sketch placed in the right upper part of the Map summarises all published data. In the northwestern sector, some faults are supposed to be responsible for the downlifting of the submerged tidal notch (Furlani et al., 2011), which is post-Roman in age (Faivre et al., 2011). This sector has been interpreted as affected by a negative vertical tectonic rate (Furlani et al., 2011; Marocco & Melis, 2009). The central sector of the Gulf is also supposed to have been subject to downlifting during the late Holocene, while the town of Trieste is tectonically stable (Melis et al., 2012). In the southern part of the Gulf archaeological remains indicate tectonic subsidence (Antonioli et al., 2007).

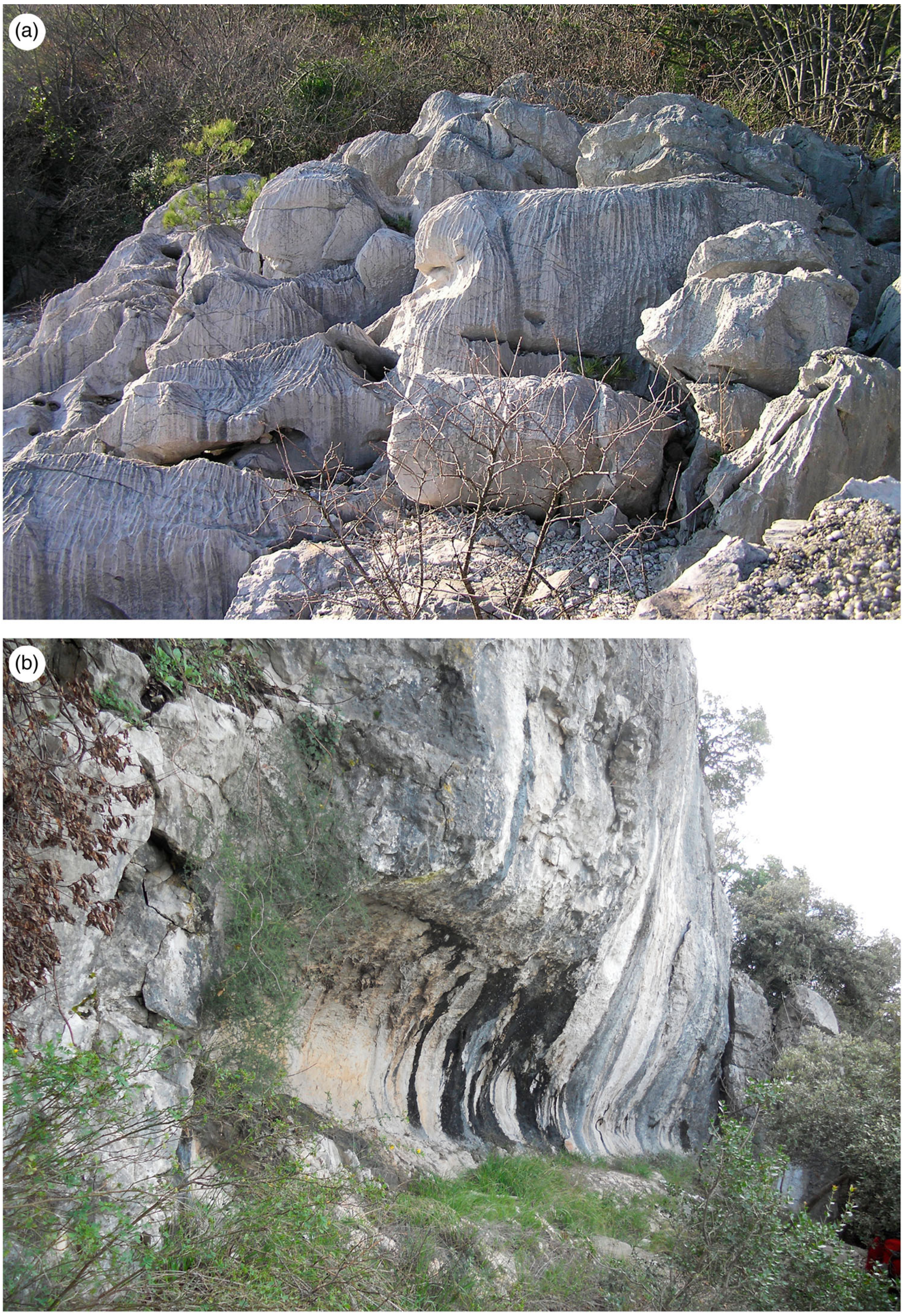

Figure 6. (a) Epigean karst features (rillenkarren, Duino cliffs, Trieste); (b) subaerial notch on a limestone cliff (Costa dei Barbari, Trieste, courtesy of Chiara Boccali).

3.5. Fluvial landforms and deposits

Three main rivers occur: the Rosandra, the Ospo and the Timavo. The last is a karst river and flows completely underground until exiting at the springs located at San Giovanni di Duino.

The deep karstification of the local limestones prevented the development of a permanent drainage pattern on the karst plateau. The seepage water is conveyed into the hypogean karst through joints, dolines and cave systems, contributing to feed the karst aquifer. Conversely, on the sandstone–marlstone slopes, small valleys have been incised, mainly oriented in the NE–SW direction. In the southeastern sector, the fluvial pattern follows a dendritic structure.

Alluvial deposits are mainly unsorted and coarse, with an open texture, sometimes with a silty-sandy matrix. The clasts are carbonate and arenaceous in composition.

3.6. Karst landforms and deposits

The karst plateau is characterised by epigean and hypogean landforms. Several small-scale landforms, such as *kamenitza*, solution pools and *karren* occur at the edge of plunging cliffs between Sistiana and Duino (Figure 6(a)). Large-scale features, such as dolines, up to a 100 m across and often filled with *terra rossa* up to 10 m deep, occur on the karst plateau (RAFVG, 2008a). Dolines mainly formed through dissolution, but some of them are due to the collapse of cave roofs. Groups of aligned dolines are common and are located in correspondence with dominant tectonic structures. Cave entrances are represented with the same symbol, following the database of the Regional land register for caves.

Subaerial notches occur in correspondence with vertical or subvertical cliffs and are mainly related to karst processes due to selective corrosion of limestone beds (Figure 6(b)).

3.7. Gravity landforms and deposits

Cliffs and screes are affected by several slope-failures, which are mapped as areas affected by landslides. Rock falls and block slide phenomena occur on limestones. Rotational slides occur on flysch and are often related to human activities (RAFVG, 2008a, 2008b).

Scree deposits are made up of angular, carbonate and arenaceous pebbles and gravels. Clasts are heterometric in size and locally metric blocks, which can exceed 1 m in length, have been deposited by gravitational processesr.

Along the limestone-flysch contact and locally on the cliffs at Duino (Figure 7(a)) and *Costa dei Barbari* (Figure 7(b)), a cemented or partially cemented scree deposit, often with paleosoils, outcrops. The carbonate clasts are angular and heterogeneous in size. 14C dating on a continental Gastropod (Figure 7(c)) provided a late Pleistocene age (35,791 ± 300 years BP).

Eluvial and colluvial deposits outcropping on the surrounding hills are composed of heterometric, angular-subrounded clasts in a clayed-silty matrix. Their

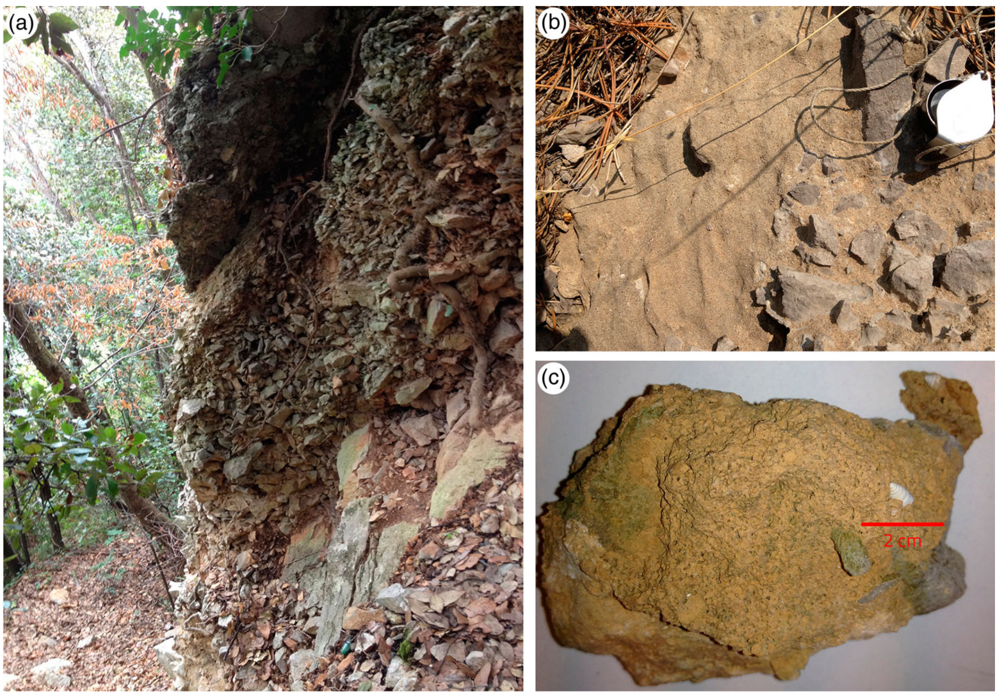

Figure 7. (a) Scree deposit outcrop (Costa dei Barbari, Trieste); (b) zoom on the matrix of the scree deposit (Duino Cliffs, Trieste); (c) the dated Gastropod (Costa dei Barbari, Trieste).

thickness can vary from decimetres to metres on the slopes and to several metres at the foot of the cliff (Cucchi & Piano, 2013).

3.8. *Archaeological and anthropogenic landforms and deposits*

The shoreline is mainly occupied by human-made coastal structures, such as docks and harbours. Few of the sites here described are completely natural. During the Roman period, cliffs and shore platforms were the main geomorphotypes along the coastline of the city of Trieste. During the seventeenth century, reclamation work started, first with landfill, then with new off-shore embankments, which now constitute the entire waterfront of the city. In any case most of the reclaimed areas were once used as saltpans (Melis et al., 2012). These areas are mapped as 'landfills'. We also mapped quarries and dumps using RAFVG (2008a) data, because along the coast there are significant remains related to quarry activity, such as slipways used to load barges with the extracted rocks.

4. Conclusions

This paper and related maps provide a review of the morphoneotectonic characteristics of the Gulf of Trieste during the late Holocene by means of published and new geological, geomorphological, sedimentological, geophysical and archaeological data. The map gathers, for the first time, all these data which so far were included in distinct international papers or local report maps.

The main map, provided at a 1:30,000 scale is an original and detailed geomorphological representation of the coast facing the Gulf of Trieste. The coastline has been classified as a function of its topographical, lithological and geomorphological features, while the seabed has been classified in terms of its lithological characteristics. The main map is accompanied by a morphoneotectonic sketch, which describes the neotectonic behaviour of the gulf during the late Holocene.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Software

The map was produced using Esri ArcGIS, with Adobe IllustratorCS6 used for preparing the layout.

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