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Tectonic effects on Late Holocene sea level changes in the Gulf of Trieste (NE Adriatic Sea, Italy)

Stefano Furlani [a,b,*], Sara Biolchi [b,c], Franco Cucchi [b], Fabrizio Antonioli [d], Martina Busetti [e], Romana Melis [b]

[a] Dipartimento di Geografia "G. Morandini", Università degli Studi di Padova, via del Santo 26, 35123 Padova, Italy
[b] Dipartimento di Geoscienze, Università degli Studi di Trieste, via Weiss 2, 34127 Trieste, Italy
[c] Dipartimento di Scienze della Terra, Università degli Studi di Modena e Reggio Emilia, L.go Sant'Eufemia 19, 41121 Modena, Italy
[d] ENEA, ACS, via Anguillarese, Roma, Italy
[e] Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Borgo Grotta Gigante 42/c, 34010 Sgonico, Trieste, Italy

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A B S T R A C T

A multidisciplinary approach has been used to evaluate Late Holocene relative sea level change along the eastern coast of the Gulf of Trieste. Published data, together with new ^{14}C dating, have been compared with predicted curves in order to evaluate the tectonic behaviour of the studied area. Observations derived from precise geomorphological, archaeological and sedimentological measurements dated from 10 ka cal., sampled at elevations ranging between −25 and +0.10 m. Tectonic rates range from 1.01 mm/y (Gulf of Trieste) and −1.99 mm/y (Villaggio del Pescatore), but are probably higher in the northwestern sector, where the elevation of post-Roman geomorphological markers is lower. A detailed surveying of notches, beachrocks, submerged shore platforms and the geological setting of the coastal area highlight the variability of tectonic subsidence, indicated by geophysical data collected in the central part of the gulf. Analyzed data indicate active tectonism. The tectonic setting of the northernmost sector is affected by the presence of strike-slip faults which cause differential downdrop of the shoreline, as suggested by significant increases of notch depths, ranging between −1.0 m and −2.7 m.

1. Introduction

The northeastern Adriatic shores (Fig. 1) are acknowledged as being characterized by recent submersion. The underwater position of a number of intertidal morphologies or coastal anthropic structures (notches, platforms, Roman age remains, etc.), located around modern mean sea level in other Mediterranean areas, supports this idea (Dalongeville, 1980; Lambeck et al., 2004; Antonioli et al., 2007). Pirazzoli (1980) has surveyed the presence of a well-carved notch between −0.5 and −0.6 m in the Qvarner and suggested a co-seismic event to explain its downdrop. Recently, many authors have studied the submerged notch along the northern limestone Adriatic coasts, including Fouache et al. (2000) (Istria and Qvarner), Benac et al. (2004) (Qvarner area), and Antonioli et al. (2004, 2007) (Gulf of Trieste and Istrian area). They noted the complete absence of a present-day notch. Faivre et al. (this issue) suggested that the submerged notch could be post-Roman in age.

Archaeological data, recently collected by Antonioli et al. (2007), Auriemma and Karinja (2008) and Degrassi et al. (2008) described and measured many submerged Roman remains along the coast of the Gulf of Trieste (Fig. 2). They suggested that 2 ka BP sea level ranged between 0 m and −1.6 m m.s.l. and that tectonic rates range between 0 and −0.77 mm/y.

The main inland geological features of the study area have been described by Cucchi (1986) and Carulli and Cucchi (1991). Geomorphological features were discussed by D'Ambrosi (1948), Forti (1985), Brambati and Catani (1988) and Furlani (2003a, b). Recently, the GeoCGT Project (2008) Project (1:10.000 maps), promoted by the "Servizio Geologico of the Friuli Venezia Giulia Region" and the Interreg Project Italia-Slovenia "Alto Adriatico", allowed a detailed geological and geomorphological surveying of the coastal area. Collected data have been very useful to assess Late Holocene sea level changes and to estimate the vertical tectonic component. Sea level change is the sum of eustatic, glacio-hydro-isostatic and tectonic movements. While the first is global and time-dependent, the latter two vary with location, sediment load, compaction and anthropic factors. In particular, tectonic factors include all movements that are not eustatic and isostatic (Lambeck et al., 2004). The glacio-hydro-isostatic component of post-glacial

* Corresponding author. Dipartimento di Geoscienze, Università degli Studi di Trieste, via Weiss 2, 34127 Trieste, Italy. Tel.: +39 349 4975858.
E-mail addresses: sfurlani@units.it, sfurlani73@gmail.com (S. Furlani).

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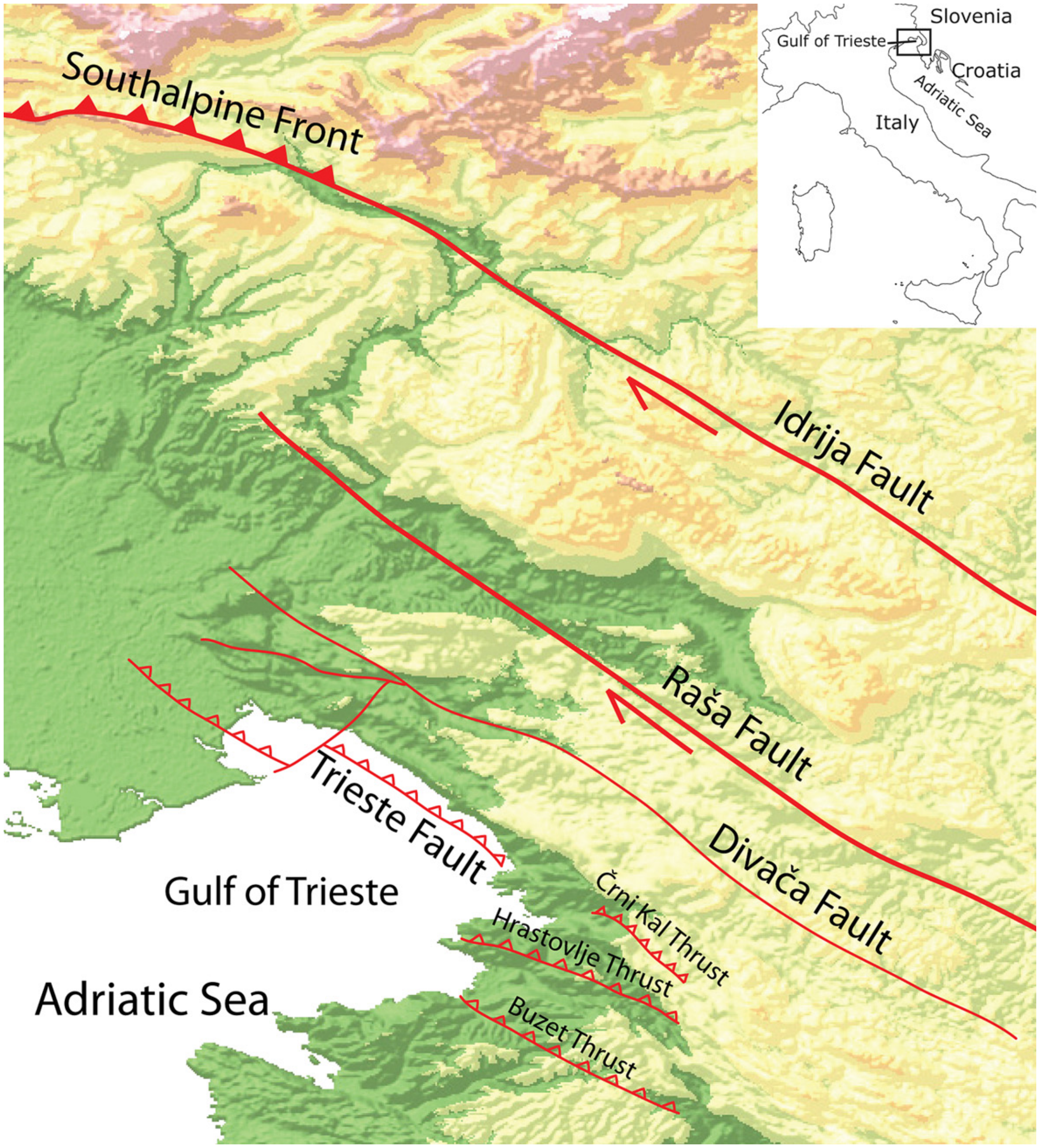

Fig. 1. Location map of the study area with major thrusts and faults. The base map is created by SRTM data.

sea level rise has been recently predicted and compared with field data at several coastal sites around the Italian coasts (Lambeck et al., 2004; Antonioli et al., 2007, 2009), and thus a framework for calculating vertical tectonic motions is available.

The results collected in this work refine the Antonioli et al. (2007) investigations of the relative sea level changes in the Gulf of Trieste (Fig. 2) and deepen the discussion on the tilting trend, highlighting local differences across the gulf. Moreover, starting from differences between sites that were significantly affected by tectonic movements or were supposed stable, a comprehensive picture of the Late Holocene sea level history of the surveyed areas is presented.

2. Geodynamical setting

The study area (Fig. 1) is located in the eastern part of the Gulf of Trieste (NE Italy), in the Classical Karst Area, where limestones belonging to the Adriatic Carbonate Platform (AdCP, Vlahovic et al., 2005) occur. It is located SE of the junction between the Southern Alps and Dinarides, in the western sector of the left-lateral strike-slip Idrija Fault. The zone is part of the External Dinarides.

Following the development of the extensive Mesozoic Adriatic Carbonate Platform, the main geodynamic event, the Dinaric orogeny, occurring mainly from Late Jurassic to Late Eocene and Early Oligocene, produced a chain-foredeep system (Venturini and Tunis, 1991; Placer, 2008). The compressional tectonics caused the development of NW–SE oriented and SW vergent thrusts, and of the relative foredeep, with flexuring of the Mesozoic carbonate and filling by the Eocene terrigenous turbidite sequences of the Flysch were produced by the erosion of the rising chain. Paleocene-Early Eocene carbonates were deposited locally. Late compressional phases also involved the Flysch sequence in the thrusts. Later, the Alpine orogeny developed during the Late Oligocene–Pliocene

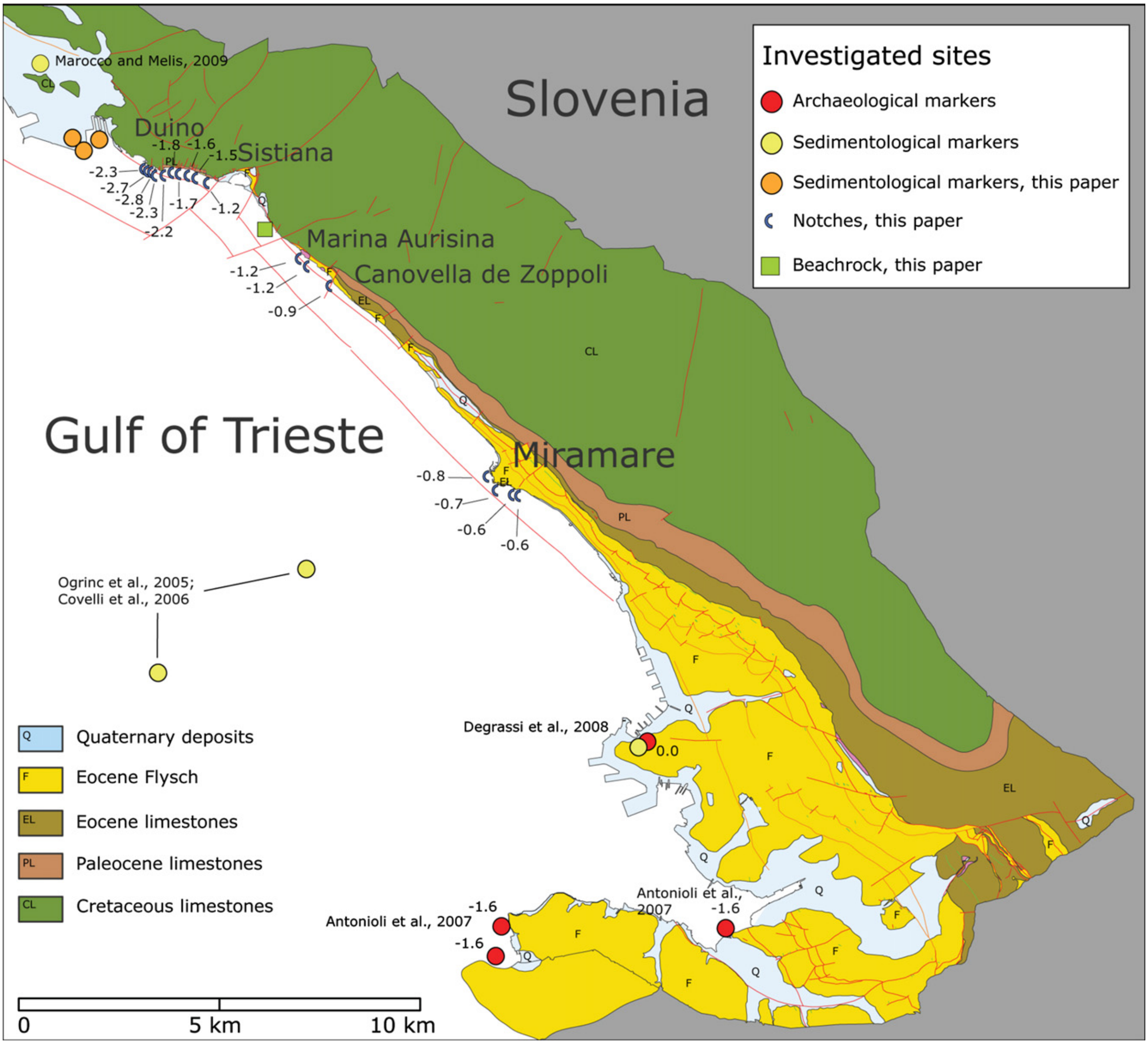

Fig. 2. Map of the eastern part of the Gulf of Trieste showing the location of the sites investigated in this paper. The geological map is redrawn and improved from the "*Carta di Sintesi geologica GeoCGT, Foglio 109 – Grado* (scientist responsible, F. Cucchi; coordinator, R. Marocco), *Foglio 110–110 and 131* (scientist responsible and coordinator F. Cucchi).

(Doglioni and Bosellini, 1987; Castellarin et al., 1992) and produced a foredeep in the Veneto and Friuli Plain.

Presently, the main feature in the Gulf of Trieste area is the Dinaric frontal ramp, a NW-SE thrust system located at the Karst coastal front (Fig. 1). This feature, named the Trieste Fault by Del Ben et al. (1991), has been regarded as an accommodation zone from the Karst coastal front and the 2–3 km offshore belt with a vertical displacement of about 1400 m (Busetti et al., 2008). The limestones on the coast, at the hanging wall of the ramp, are 1200 m deep offshore, at the eastern and deepest side of the foredeep flexured carbonate. Placer (2008) hypothesized that the Trieste Fault continues in Slovenia as the Črni Kal thrust fault.

A thrust system crossing the Gulf of Trieste with Dinaric orientation has been recently found from a multichannel seismic survey (Busetti et al., 2008, 2010). The system represents the most external Dinaric thrusts, and it is possible to connect it with the inland Hrastovlje Thrust in Istria. It is characterized by intense deformation, in particular within the Eocene Flysch sequences, and it is affected by tectonic activity lasting to the Plio-Quaternary. The structure deepens toward the northwest, probably due to the offset of NE-SW faults: the Monte Spaccato Fault parallel to the northern Istria coast (Cavallin et al., 1978; Carobene and Carulli, 1981), and a possible fault zone located in the middle of the gulf, separating the northern part from the southern part (Busetti et al., 2008, 2010).

Modelling of gravity data of the Gulf of Trieste and Karst area interpreted the minimum in the northern corner of the gulf as due to the deepening toward northwest of the limestones and to the increase of flysch thickness (Coren et al., 2006). Pendulum data indicate a secular trend of tilting toward the northwest of the Karst area (Braitenberg et al., 2005).

The seismicity of the area is considered to be low, in particular in the foredeep zone with few and low magnitude events (about or less than 3.0 M) (Slejko et al., 1987). Del Ben et al. (1991) considered the Trieste Fault to have been generated in the Middle Alpine orogenic activity (Paleogene), slighty reactivated in the Neo Alpine phase (Messinian-Pliocene), but modestly active or inactive in

Table 1
Location and measurements of submerged tidal notches in the Gulf of Trieste.

A	B	B		C	D	E	F	G	H	I	L	M
No	Site	Lat.	Long.	Coastal slope (°)	Limestone bedding (°)	Lithology	Geological age	Notch morphology	Measured elevation	Time of surveying	Tide correction	Corrected depth
1	Duino (Harbour)	45.77013	13.59311	90°	–	Limestones	Cretaceous	Symmetric	−2.00	13/08/09 12.30	−0.3	−2.30
2	Duino (Old Castle)	45.76996	13.60018	90°	–	Limestones	Cretaceous	Symmetric	−2.40	13/08/09 12.45	−0.3	−2.70
3	Duino (Old Castle)	45.76981	13.60028	90°	–	Limestones	Cretaceous	Symmetric	−2.50	13/08/09 12.45	−0.3	−2.80
4	Duino (Old Castle)	45.76987	13.60048	90°	–	Limestones	Cretaceous	Symmetric	−2.35	13/08/09 12.45	−0.3	−2.65
5	Duino (Dante Rock)	45.76953	13.60096	70°	–	Limestones	Cretaceous	Symmetric	−2.20	13/08/09 16.45	−0.1	−2.30
6	Duino (Dante Rock)	45.76956	13.60126	80°	–	Limestones	Cretaceous	Symmetric	−2.30	13/08/09 16.45	−0.1	−2.40
7	Duino (New Castle)	45.76938	13.60211	80°	–	Limestones	Cretaceous	Symmetric	−2.10	13/08/09 16.45	−0.1	−2.20
8	Duino (New Castle)	45.76942	13.60244	90°	–	Limestones	Cretaceous	Symmetric	−2.10	13/08/09 13.30	−0.3	−2.40
9	Duino (New Castle)	45.76956	13.60279	90°	–	Limestones	Cretaceous	Symmetric	−2.10	13/08/09 13.30	−0.3	−2.40
10	Duino	45.76983	13.60393	60°	60°	Limestones	Paleocene	Roof notch	−1.45	21/08/2009 16.15	−0.35	−1.80
11	Duino	45.76993	13.6046	60°	60°	Limestones	Paleocene	Roof notch	−1.35	21/08/2009 16.15	−0.35	−1.70
12	Duino	45.76985	13.60512	60°	60°	Limestones	Paleocene	Roof notch	−1.15	21/08/2009 16.15	−0.35	−1.50
13	Duino	45.76974	13.60582	60°	60°	Limestones	Eocene	Roof notch	−1.30	21/08/2009 16.00	−0.4	−1.70
14	Duino	45.76963	13.60625	60°	60°	Limestones	Eocene	Roof notch	−1.30	21/08/2009 16.00	−0.4	−1.70
15	Sistiana	45.76964	13.60704	70°	70°	Limestones	Paleocene	Roof notch	−1.25	21/08/2009 15.45	−0.35	−1.60
16	Sistiana	45.7697	13.60767	70°	70°	Limestones	Paleocene	Roof notch	−1.15	21/08/2009 15.45	−0.35	−1.50
17	Sistiana	45.76955	13.60844	70°	70°	Limestones	Paleocene	Roof notch	−1.25	21/08/2009 15.30	−0.35	−1.60
18	Sistiana	45.76937	13.60883	60°	60°	Limestones	Eocene	Roof notch	−1.25	21/08/2009 15.30	−0.35	−1.60
19	Sistiana	45.76924	13.6094	60°	60°	Limestones	Eocene	Roof notch	−1.20	21/08/2009 15.15	−0.30	−1.50
20	Sistiana	45.76922	13.60974	90°	90°	Limestones	Eocene	Roof notch	−1.30	21/08/2009 15.15	−0.30	−1.60
21	Sistiana	45.76911	13.61722	90°	90°	Limestones	Eocene	Roof notch	−1.50	21/08/2009 13.10	+0.10	−1.40
22	Sistiana	45.7687	13.61775	90°	90°	Limestones	Eocene	Roof notch	−1.50	21/08/2009 13.00	+20.0	−1.30
23	Sistiana	45.7686	13.61792	90°	90°	Limestones	Eocene	Roof notch	−1.50	21/08/2009 12.30	+0.25	−1.25
24	Sistiana	45.7685	13.61847	90°	90°	Limestones	Eocene	Roof notch	−1.50	21/08/2009 12.15	+0.25	−1.25
25	Sistiana	45.76847	13.61869	90°	90°	Limestones	Eocene	Roof notch	−1.40	21/08/2009 12.00	+0.3	−1.10
26	Sistiana	45.76846	13.61889	80°	80°	Limestones	Eocene	Roof notch	−1.40	21/08/2009 12.00	+0.3	−1.10
27	Sistiana	45.76846	13.6192	90°	90°	Limestones	Paleocene	Roof notch	−1.40	21/08/2009 11.20	+0.4	−1.00
28	Sistiana	45.76834	13.61937	110°	110°	Limestones	Eocene	Roof notch	−1.50	21/08/2009 10.30	+0.5	−1.00
29	Sistiana	45.76825	13.62029	110°	110°	Limestones	Eocene	Roof notch	−1.50	21/08/2009 10.20	+0.5	−1.00
30	Marina Aurisina	45.7527	13.6501	Block	–	Limestones	Cretaceous	Symmetric	−1.00	15/01/2010 12:45	0.20	−1.20
31	Marina di Aurisina	45.7524	13.6504	Block	–	Limestones	Cretaceous	Roof notch	−1.00	15/01/2010 13:00	0.2	−1.20
32	Canovella de Zoppoli	45.7465	13.6598	Block	–	Limestones	Eocene	Roof notch	−0.60	15/01/2010 14:45	0.50	−1.10
33	Miramare	45.7046	13.7109	Olistolithes	–	Limestones	Eocene	Roof notch	−1.00	01/07/2009 14.15	0.2	−0.80
34	Miramare	45.7017	13.7142	Olistolithes	–	Limestones	Eocene	Roof notch	−0.90	01/07/2009 14.15	0.2	−0.70
35	Miramare	45.7016	13.7152	Olistolithes	–	Limestones	Eocene	Roof notch	−0.95	01/07/2009 14.30	0.25	−0.70

(*continued on next page*)

Table 1 (*continued*)

A	B	B		C	D	E	F	G	H	I	L	M
No	Site	Lat.	Long.	Coastal slope (°)	Limestone bedding (°)	Lithology	Geological age	Notch morphology	Measured elevation	Time of surveying	Tide correction	Corrected depth
36	Miramare	45.7011	13.7188	Olistolithes	–	Limestones	Eocene	Roof notch	−0.85	01/07/2009 14.30	0.25	−0.60

A, site number and location; B, WGS84 coordinates of the surveyed sites; C, slope degree (°); D, limestone bedding (°); E, lithology outcropping at the surveyed site; F, geological age of the outcrop; G, notch morphology. Asymmetric notches characterized by flat roof or symmetric notches, characterized by bent roof; H, field measured depth (before correction); I, year, month, day and hour of measurement; L, tidal correction applied for tide amplitude at the moment of surveying; M, corrected depth. Tide values are calculated with respect to the mean sea level of Genova, using data from the local reference tide gauge data of Trieste, that is the nearest permanent station to the surveyed area. For more information about the tide gauge of Trieste see also the following site: http://www.univ.trieste.it/_dst/OM/OM_mar.html.

historical times. On the other hand, eastward of the study area in Slovenia, moderate seismicity occurs, related to the active Raša and Idrija Faults (Michelini et al., 1998).

The carbonate platform is represented by the provisional and informal "Trieste Karst Limestones Formation" spanning from lower Aptian to Ypresian (Cucchi et al., 1987; GeoCGT Project, 2008). The top of the carbonate sequence is composed by limestone marls couplets, termed the "Transitional beds", and it is characterized by nodular structures and rounded pebbles, interpreted as diagenetic nodules further reworked by resedimentation processes, probably triggered by tectonic movements (Burelli et al., 2008a, b). It is followed by a turbiditic succession (Flysch of Trieste) dated as Lutetian (Bensi et al., 2007; GeoCGT Project, 2008), which is exposed in the city of Trieste, at the base of the coastal slope, in the inner Gulf of Trieste and is involved in minor NW–SE thrusts (GeoCGT Project, 2008; Bensi et al., 2009).

3. Material and methods

The elevation of 11 dated sea level markers (archaeological remains and sedimentological samples) and 35 submerged notches have been measured using the method suggested by Antonioli et al. (2007). Field surveying consists in: (1) measurement of the depth of the marker with respect to the local sea level at the time of surveying. Values reported in Tables 1 and 2 represent the mean value of multiple measures; (2) correction of surveyed measures with respect to the nearest tide gauge data collected at the time of surveying. Data are reported in Tables 1 and 2; (3) comparison of predicted (Lambeck et al., this issue) and observed sea level elevation of the markers, which corresponds to the relative sea level change at each location. The tectonic stability of an area corresponds to data in agreement with the predicted sea level curve, while downlift or uplift is supposed when the elevations of the markers differ from the predicted sea level curve. Error bars for the elevation and age values of the sea level markers have been provided in order to consider the inaccuracy of measurements. Moreover, the errors connected to the use of Late Holocene lagoon fossils as sea level markers are considered, because the elevation of samples could be due mainly to sedimentation rates (sediment load and compaction) rather than tectonic subsidence.

Elevation measurements were collected via optical (Salmoiraghi Ertel automatic level) or mechanical instruments (invar rod). The

Table 2
Sea level markers dated along the coast of the Gulf of Trieste.

A	B	C	D	E	F	G	H	I	L
No	Site name	Kind of marker or stratigrapy	Centesimal coordinates	Lab. and core number	Age (14C uncal. BP)	Age Cal BP 1σ archaeological	Corrected measured height (m a.s.l.) and reference	Predicted height Lambeck et al. (this volume) (m m.s.l.)	Vertical tectonic rates (mm/yr)
1	Jernejeva Draga –	Vivaria dock	45.59278 13.7224	/	/	1900 ± 100	−1.40 ± 0.6 Antonioli et al. (2007)	−0.4	−0.52
2	Punta Sottile	Pier	45.60222 13.71944	/	/	1950 ± 50	−1.60 ± 0.6 Auriemma et al. (2007)	−0.45	−0.59
3	Stramare	Walking surface.	45.60194 13.79	/	/	1900 ± 100	−1.60±0.6 Antonioli et al. (2007)	−0.4	−0.63
4	Trieste town	Lagoonal fossils	45.64861 13.7675	Poz-15855	2020 ± 30	1576.5 ± 47.5	+0.10 ± 0.5 Degrassi et al. (2008)	−0.3	0.25
5	Trieste town	Lagoonal fossils	45.64861 13.7675	Poz-15854	2065 ± 30	1639 ± 48	0.00 ± 0.5 Degrassi et al. (2008)	−0.31	0.19
6	Trieste Gulf	Lagoonal fossils	45.67 13.67972	Core GT1	9140 ± 40	9928.5 ± 104	−25 ± 0.5 Ogrinc et al. (2005), Covelli et al. (2006)	−35	1.01
7	Trieste Gulf	Lagoonal fossils	45.6075 13.55278	Core GT3	8810 ± 40	9479.5 ± 32.5	−26 ± 0.5 Ogrinc et al. (2005), Covelli et al. (2006)	−28	0.21
8	Monfalcone Harbour	Peat	45.7939 13.5651	LTL2083A	5431 ± 55	6245 ± 75	−9.28 Marocco and Melis (2009)	−3.36	−0.94
9	Villaggio del Pescatore	Wood	45.7795 13.5833	DSH869	1985 ± 25	1922 ± 26	−2.00 This paper	−0.44	−0.81
10	Villaggio del Pescatore	Lagoonal shell	45.7792 13.575	DSH815	1238 ± 35	774 ± 23	−0.70 This paper	−0.1	−0.77
11	Villaggio del Pescatore	Lagoonal shell	45.7805 13.574	Anto2	838 ± 35	473 ± 26	−1.00 This paper	−0.06	−1.99
12	Villaggio del Pescatore	Lagoonal shell	45.7805 13.574	Anto4	1298 ± 51	845 ± 45	−0.70 This paper	−0.11	−0.70

A, site number; B, location of the site; C, kind of marker and stratigraphy; D, WGS84 coordinates of the surveyed sites; E, laboratory number; F, ^{14}C age (uncal. BP); G, age (cal. BP) or archaeological date; H, corrected height and reference; I, predicted sea level (Lambeck et al., this issue); L, calculated vertical tectonic rates.

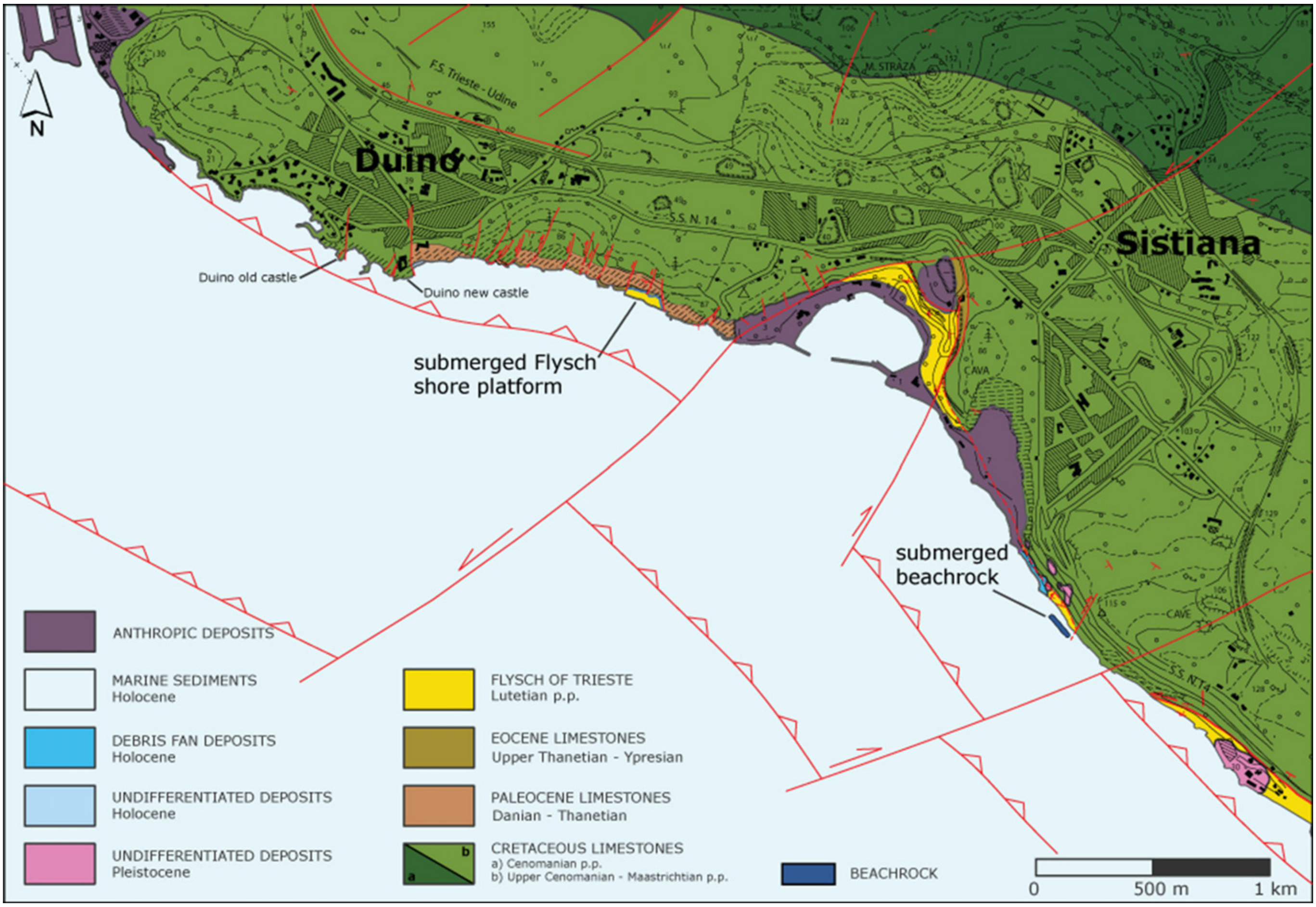

Fig. 3. Geological map of the NW part of the Gulf of Trieste and location of the submerged shore platform and beachrock. The geological map is redrawn and improved from the "*Carta di Sintesi geologica GeoCGT, Foglio 109 – Grado* (scientist responsible, F. Cucchi; coordinator, R. Marocco).

surveying was performed during periods of low wave energy in order to minimize the errors. Measurements have been reduced to the mean sea level applying tidal corrections at the surveyed sites, using the data of the Trieste tide gauge. Tidal amplitude is particularly significant in the northern Adriatic Sea, as it can be up to ∼2 m. Elevation measurements are given (Stravisi and Purga, 2005) with respect to the Italian reference plane network of the Istituto Geografico Militare, Genova Mean Sea Level 1942 (Gamboni, 1965).

The collection of submarine data (topographical surveying, sampling and pictures) was carried out by diving geologists in collaboration with the "Nucleo Carabinieri Subacquei di Trieste". Limestone samples were collected using a geological hammer. Measurements were collected using a ruler, while the depth of the shore platform and the beachrock were measured via an electronic scuba depth-meter and corrected with the Trieste tide gauge data. Sandstone and marlstone beddings were collected using an underwater compass and a purpose-made underwater clinometer. The rock identification has been carried out through thin sections in the Department of Geosciences in Trieste, while nannoplankton dating (on marls and silty marls) was carried out by Prof. Jernej Pavšič of the University of Ljubljana, following Pavšič and Peckmann (1996).

4. Results

Geological and geomorphological surveying, together with detailed measurements on the submerged notch (Table 1), shore platforms and beachrock has been carried out along the coasts of Trieste. Chronological data have been obtained using precise measurements of 3 coastal Roman archaeological sites dated 1.95 ka (Antonioli et al., 2007) and 8 ^{14}C dates of lagoon fossils and organic carbon from lagoon cores and marine deposits in urban archaeological sites (Ogorelec et al., 1997; Covelli et al., 2006; Degrassi et al., 2008; Marocco and Melis, 2009). Dated markers are summarized in Table 2.

4.1. Geology and geomorphology

Geological underwater surveying has been carried out along the northwestern sector of the gulf (Fig. 3). The westernmost investigated sector is intersected by limestone plunging cliffs, cut in Cretaceous, Paleocene and Eocene limestones. Vertical beds, dipping south and parallel or sub-parallel to the shoreline, occur along the coast.

The Duino area is characterized by Cretaceous limestones dipping west, but vertical faults, joints and fractures fragment the cliff. In the Duino Castle promontory and surrounding area, the stratification becomes chaotic due to a left-lateral strike-slip fault, which causes a downdrop of the left sector and results in the contact between Cretaceous and Paleocene limestones. Eastward, toward Sistiana Harbour, Paleocene and Eocene limestones alternatively crop out, as a number of strike-slip faults intersect the shoreline. These faults, N–S or NNE–SSW oriented, are not evident inland.

The top of the Eocene unit is exposed only in a narrow sector of the cliff. At the base of this unit, a submerged flysch platform occurs. Geomorphological features of the flysch platform are described in Section 4.3.

Southwards from Sistiana, Eocene marly-sandstone outcrops and small gravel-pebble beaches are developed at the cliff-foot. Large Eocene or Cretaceous limestone blocks, collapsed from the cliff, and cemented continental breccia occur at the beachrock site. At Marina Aurisina, Cretaceous limestone blocks are 0.1–5 m, and similar Eocene limestone blocks occur at Canovella de' Zoppoli. Flysch cliffs are protected by coastal walls to Miramare, where Eocene olistoliths occur.

4.2. Submerged notch

Notch depths collected in 35 sites are reported in Table 2. The present research extended previous surveys of notches in the Gulf of Trieste (Antonioli et al., 2004, 2007) and added some new sites.

The deepest notches have been surveyed in the northern sector of the Gulf of Trieste, between Duino and Sistiana, where the elevation ranges between −2.80 m and −1.0 m. Near Duino, the notch is carved on Cretaceous limestones, whereas from the Duino castle to Sistiana it is carved on Paleocene/Eocene limestones. In Duino, notch shape is symmetric (Fig. 4a), while toward Sistiana it becomes a roof notch, similar to the ones described by Benac et al. (2004, 2008) in the Qvarner area. In the Sistiana-Duino sector, the coastal slope is vertical or toppled, as limestone bedding. South of Sistiana, the depth of the notch decreases, and it is cut on limestone blocks: −1.20 cm at Marina Aurisina (Fig. 4b, c), −0.9 m at Canovella de' Zoppoli and −0.80/−0.60 on the Eocene olistoliths in the Miramare National Reserve. At Marina Aurisina, notch shapes are both symmetric and roofed. The width and amplitude of the surveyed notches are larger than 1 m, in accordance with the local tide amplitudes, although with some variations due to local environmental conditions.

4.3. Submerged flysch platform

Results of the surveying carried out on the submarine flysch platform between Sistiana and Duino are presented. The platform outcrops along a narrow sector of the plunging cliffs, in correspondence to the last units of the Eocene limestones. The analysis of nannoplankton associations in the silty marls terms suggested that samples belong to the NP16 biozone, upper Lutetian in age (Furlani et al., 2009a, b, 2010).

The outcrop is composed by centimetric and decimetric sandstones with millimetric or centimetric interbedded marlstones (Fig. 5a, b). Their bedding is similar to limestone beds (290/90).

The platform is located in a small embayment, about 200 m westward from Sistiana Harbour. It is 170 m long and 45 m wide. Its depth ranges between −1.5 m and −5.0 m. At the cliff-foot, collapsed limestone blocks, metres in size, locally hide the underlying flysch outcrop. At the seaward edge, a 50 m long sandstone bed results in a wall-like morphology. It is 0.8 m higher than the platform and it ends laterally in a mushroom-like rock (Fig. 5c). The tectonic structures, including joints, fractures and faults that involve the limestone cliffs persist in the underwater sandstone beds.

4.4. Submerged beachrock

Submerged beachrock has been discovered in the northwestern part of the Gulf of Trieste, at Costa dei Barbari (Fig. 2). The structure is 120 m long and 22 m wide. Its depth ranges between −5.1 m and

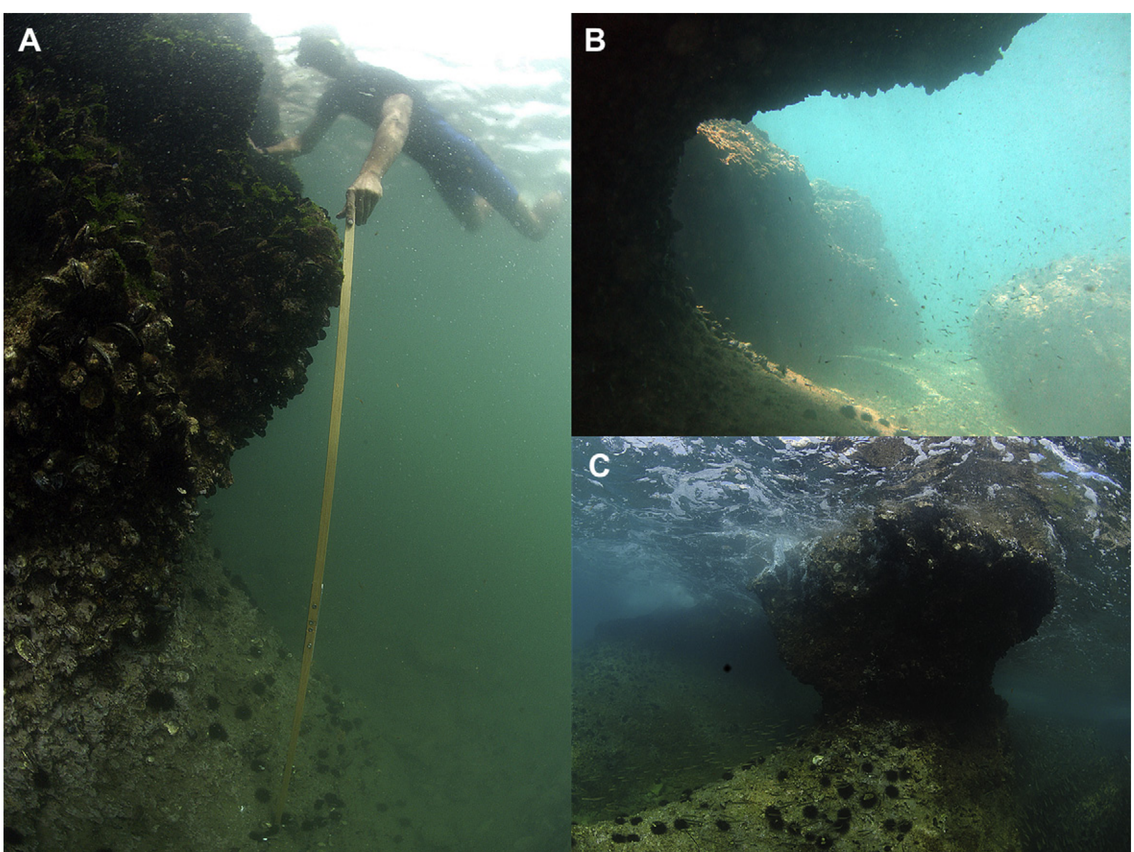

Fig. 4. Submerged tidal notches in the Gulf of Trieste. (a) Sistiana-Duino; (b) Ginestre; (c) Ginestre. Notch amplitude is approximately the same of the local tide amplitude.

−3.5 m. It develops at a distance of 25 m parallel to the shoreline. Between the shoreline and the beachrock, sub-rounded limestone and sandstone blocks cover the sea bottom and partially hide the underlying flysch outcrop. Offshore, the sea bottom is covered by sandy marine sediments.

The surface of the beachrock gently dips seaward ($<10°$) and form brown tabular beds 0.05–1.5 m thick. The structure is undercut by wave action: at its base, a decimetric niche (Fig. 6a, c) or, quoting Pirazzoli (1986) "abrasion notch", joins the beachrock to the sea bottom. Moreover, it is broken into flagstone and the structure is interested by breaches and channels (Fig. 6b) erosionally enlarged over time.

From a sedimentological point of view, the feature can be considered a beach breccia because it consists of sand and gravel cemented with calcite. Sandy fragments are mainly silicates (Fig. 7), composed of quartz grains (Fig. 7b, d), feldspar grains and heavy minerals; the clasts are generally well sorted and subangular. Larger clasts are always fragments of calcareous rocks (Fig. 7c), containing small foraminifera (Fig. 7a). The calcareous cement varies from friable to well-cemented depending on the zone, but it is not homogeneous through the structure: there are more and less cemented areas.

Very rare fossils or bioclasts (Fig. 7a), mainly foraminifera and mollusc remains, have been found in samples, but no archaeological fragments or pottery have been found. Few reworked beachrock fragment of various sizes are commonly found, mainly as intraclasts within the observed ledges.

4.5. Archaeological and sedimentological markers

In Muggia and the surrounding area, three Roman age archaeological structures have been studied by Antonioli et al. (2007). The error has been lowered because of further analysis. In particular, in S. Bartolomeo (Slovenia) (Table 2, site 1), an ancient walking surface on the eastern side of a large fishpond at −0.8 m indicates a sea level rise of 1.40 ± 0.30 m. At Punta Sottile (Table 2, site 2), the structure suggests a relative sea level rise of 1.60 ± 0.30 m since Roman times, while at Stramare (Table 2, site 3), an anthropogenic terrace suggests the same Roman level (Antonioli et al., 2007, 2009).

In Trieste (Degrassi et al., 2008), during an archaeological excavation, three ^{14}C dates have been determined on two samples (Table 1, sites 4 and 5) of *Bittium reticulatum* at 0.0 m a.s.l. (1639 ± 48 BP) and a *Cerastoderma glaucum* at +0.10 ± 0.1 m (1576.5 ± 0.1 BP). In the central part of the gulf, a sample of mottled peat at −25 m (9140 ± 40 BP – core GT1, site 6) and a *Cerastoderma glaucum* at −26 m (8810 ± 40 BP – core GT3, site 7) have been dated (Covelli et al., 2006).

At Monfalcone harbour, 1 sample of lagoon peat (Table 2, site 8) collected at −9.26 m was dated 6245 ± 75 BP (Marocco and Melis, 2009). Nearby, at Villaggio del Pescatore, ^{14}C dating has been made on 1 sample of wood (Table 2, site 8) at −2.0 m (1985 ± 25 BP), and 3 samples of lagoon shells, collected at −0.7 m (fragment of *Cerastoderma*), −1.0 m (bivalve) and −0.7 m (fragment of *Cerastoderma*) and dated, respectively 1238 ± 35, 838 ± 35 and 1298 ± 51 BP (Table 1, sites 9–11).

5. Discussion

Late Holocene sea level change is not expected to follow the eustatic function but will vary geographically across the Mediterranean due to isostasy. Moreover, any tectonic responses will modulate this spatial variability. Thanks to the new observations carried out for the present research, as dated (shells, roman piers, etc.) and non-dated markers (beachrock, shore platforms and notches) together with data published on previous works, the

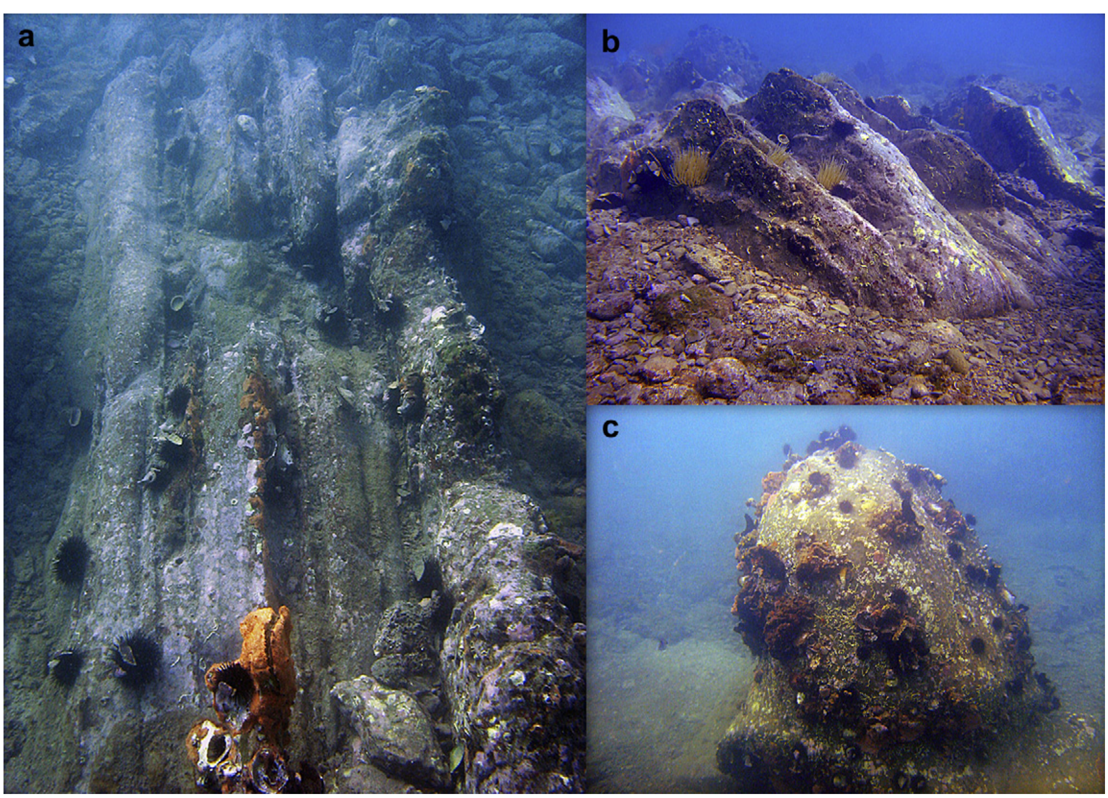

Fig. 5. Flysch beds on the submerged shore platform: (a, b) underwater sandstones and marlstone; (c) mushroom-like sandstone blocks.

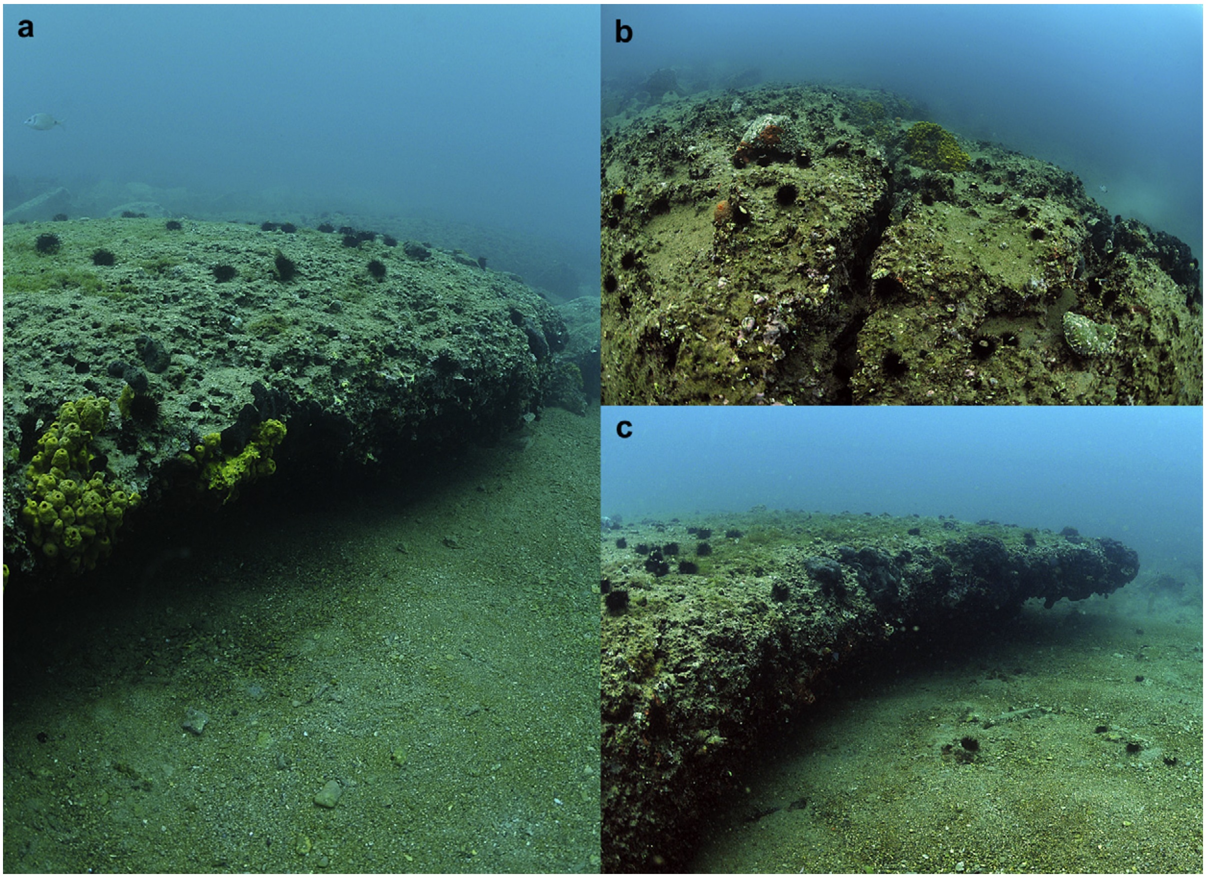

Fig. 6. The submerged beachrock. (a) Overall view of the submarine outcrop; (b) subhorizontal surfaces with fractures and kettles; (c) niches at the base of the beachrock.

tectonic setting and its consequences on the relative sea level change in the Gulf of Trieste were studied. Space variations (Fig. 8) and time-space variations (Fig. 9) have been analyzed, indicating the differences between the southern and the northern area and the evolution since pre-Roman times. Unfortunately, the studied markers are spread over the area and never overlap, preventing their direct comparison, so the local sea level history emerges from logical considerations on the distribution of the studied indicators.

Submerged flysch platforms have been recognized, at increasing depths, up to −10 m m.s.l. in the southern part of the gulf (Furlani, 2003b) and Roman docks and piers were built above. In Trieste, quays, docks and other coastal structures have been found at present sea level, while they are mostly in underwater positions in the surroundings of Muggia. In the northwestern sector, between Trieste and Duino, no preserved Roman structures have been measured (Auriemma and Karinja, 2008), but a submerged notch is carved on limestone outcropping along the shoreline and other geomorphological markers, beachrock and the shore platform, occur.

The formation of the beachrock and its cementation was driven by the presence of abundant freshwater occurring in the area from coastal and submarine karst springs (Accerboni and Mosetti, 1967). Even if relations with sea level must be considered carefully (Kelletat, 2006), its development decreased due to sea level rise. During Roman times, its accretion was probably already stopped.

The genesis of the flysch platform derives from cliff retreat enhanced by sandstone weathering at the level of former platform horizons, which have subsequently been eroded. The presence of limestone cliffs at the back, much more resistant than flysch, brakes cliff recession. It represents a relict shore platform, as it is broadly below the lowest tide. Its depth suggests that it developed broadly during the Late Holocene (Fig. 8) and its widening resulted from cliff recession. In the Gulf of Trieste, recent cliff retreat has been estimated at 10–20 mm/y on flysch lithologies (Furlani, 2007) and 0.14 mm/y on limestone (Cucchi et al., 2006; Furlani et al., 2009a, 2010).

Previous works recognized the occurrence of NW tilting along different geological time scales: pendulum data (Braitenberg et al., 2005), geomorphological markers (Antonioli et al., 2004, 2007), archeological markers (Degrassi et al., 2008) are evidence of recent tilting, while geophysical data (Busetti et al., 2008, 2010) structural data (Carulli et al., 1980) and gravity modeling (Coren et al., 2006), indicate that the tilting is regional and long lasting. Moreover, the topography and the decrease of the carbonate platform surface heights toward NW (from 200–300 m to 0 m m.s.l.) confirm the occurrence of the NW tilting.

The present study confirms the progressive deepening of the notch toward the NW. Fig. 10 illustrates the comparison of observations and predictions for the evidence studied in the Gulf of Trieste from archaeological and sedimentological markers. In the northern and the southern part of the gulf the markers lie below, while in the city of Trieste marine deposits lie slightly above the predicted curve (Lambeck et al., this issue). Archaeological and sedimentological data, when compared with the predicted sea level curve (Degrassi et al., 2008), suggest a relative stability, or perhaps slight uplift, in the urban area of Trieste, in accordance with recent tide gauge data (Antonioli et al., 2009). Moreover, the dataset suggests that the southern side of the gulf has subsided, at least since Roman time (about −0.6 mm/y), while the northern side has subsided during the Holocene, probably faster than the southern

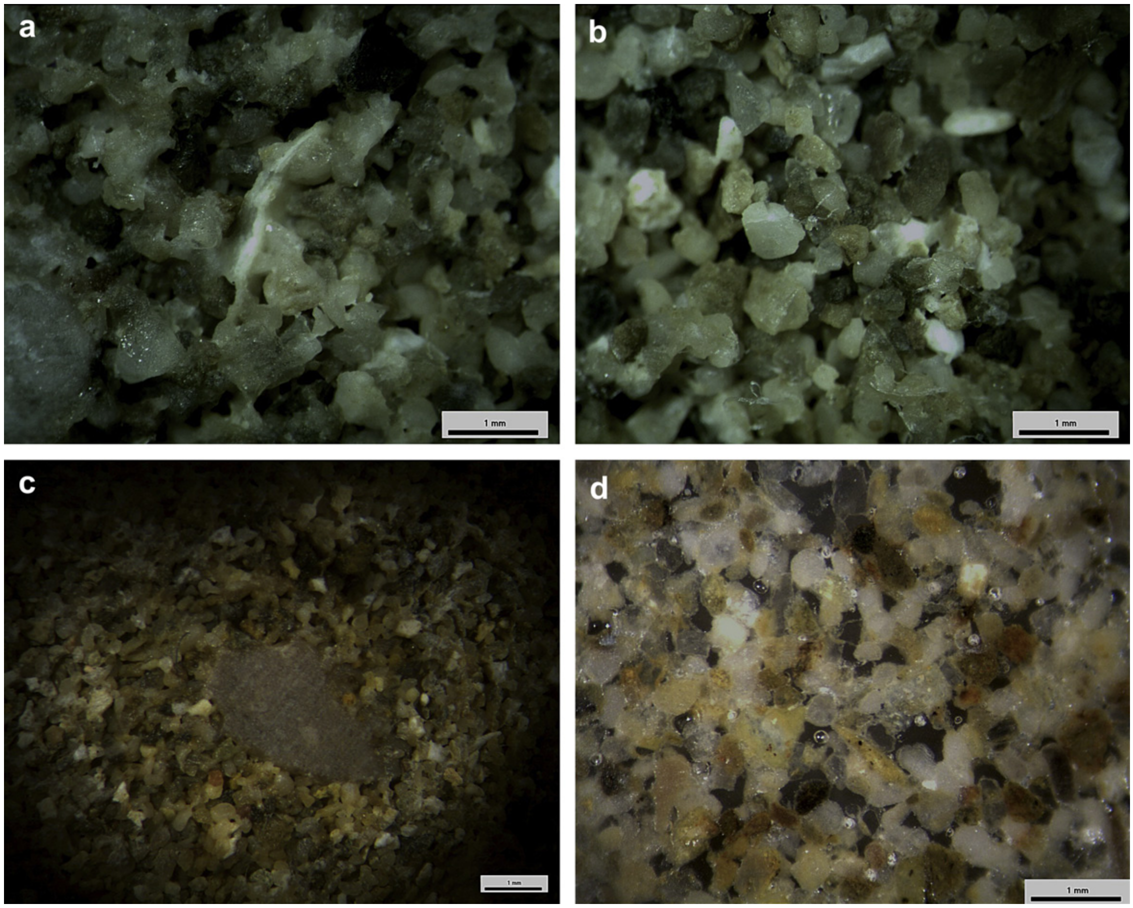

Fig. 7. Section of samples collected on the beachrock. (a) Poorly cemented sand containing a bivalve fragment; (b) poorly cemented abiotic sand; (c) poorly cemented sand with a subangular limestone clast; (d) thin section of well-cemented sand. (a), (b) and (d) Photos have the same magnification – see the bar in the photo (d).

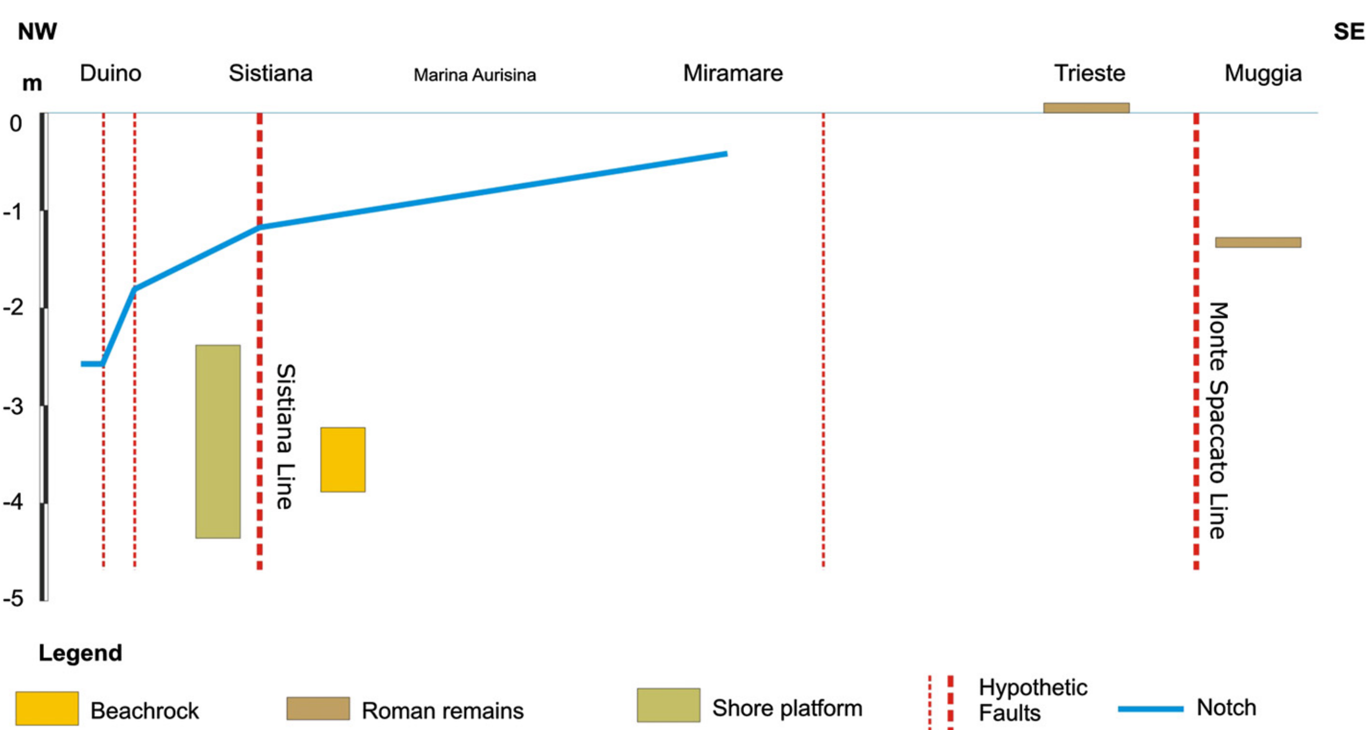

Fig. 8. NW–SE trend of evolution of the coast of the Gulf of Trieste.

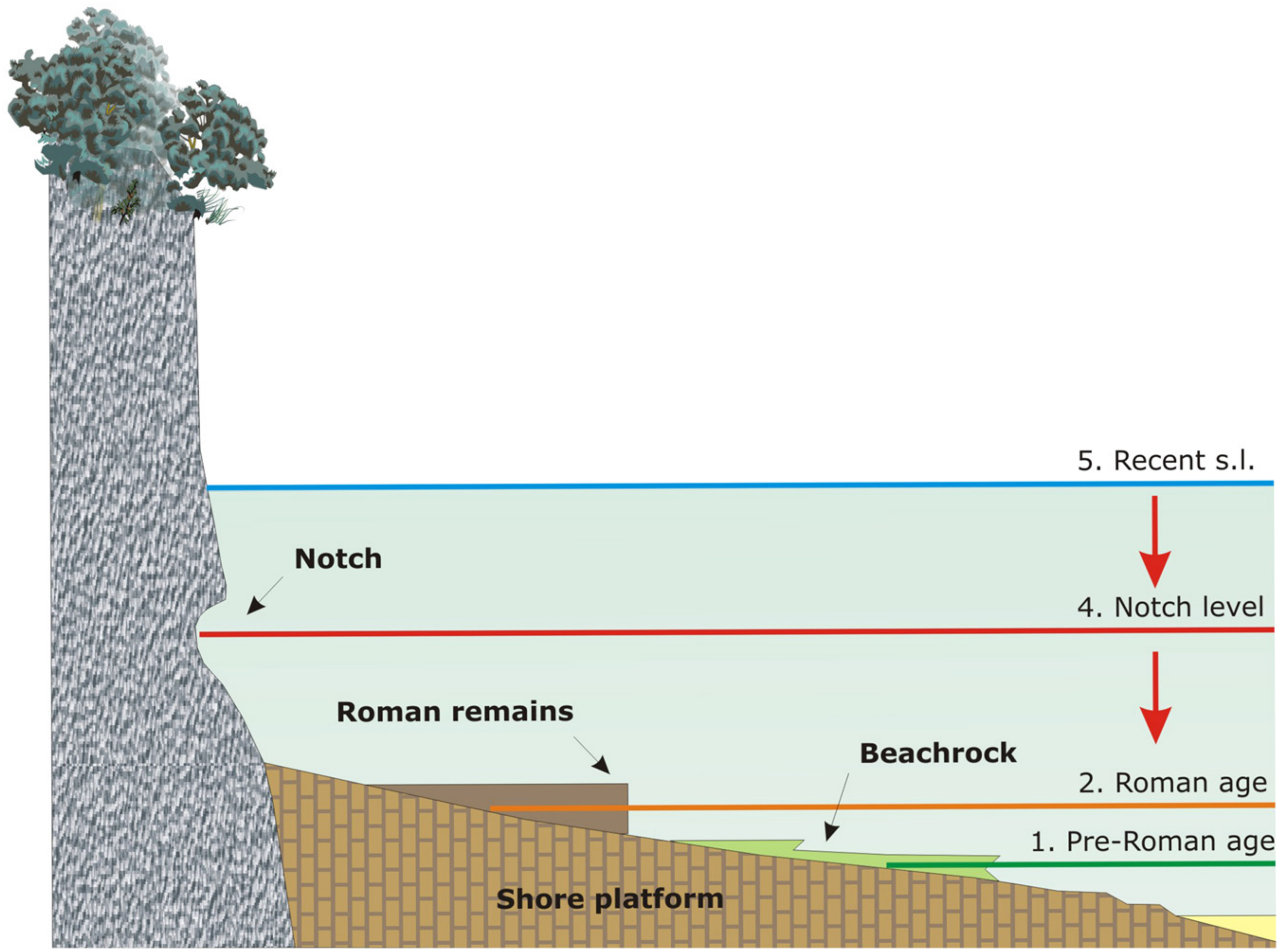

Fig. 9. Sketch of the coast of Trieste, not to scale, and its relationship with the current and past sea level. The studied sea level indicators have been represented on a single cross-section.

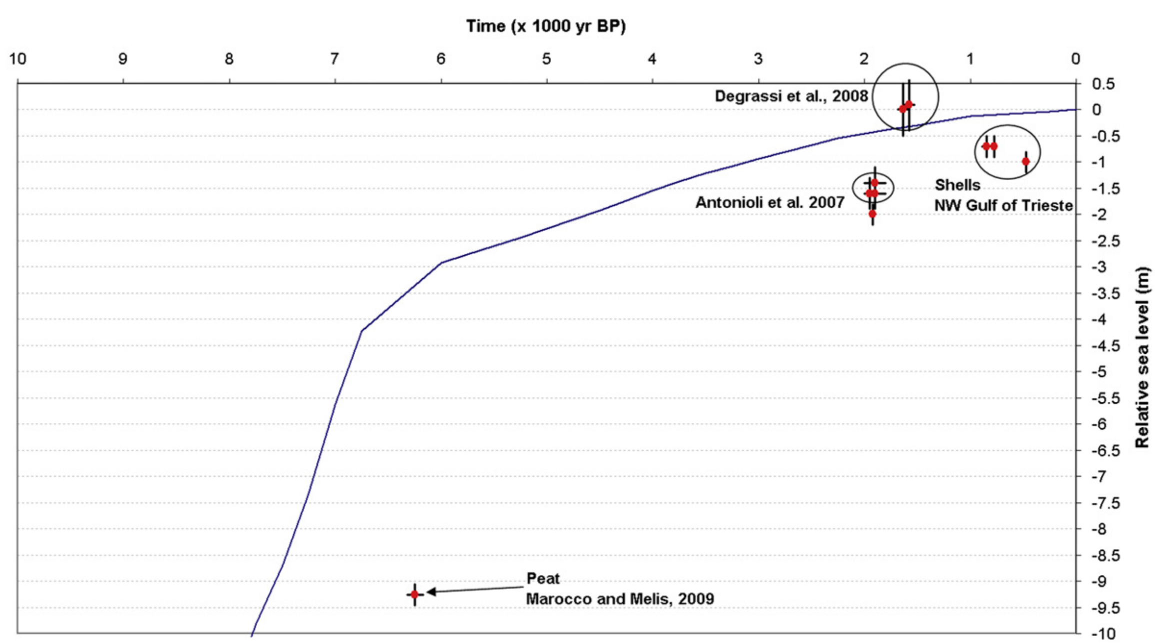

Fig. 10. Model predictions and observations for coastal sea level markers in the Gulf of Trieste, Italy, based on Lambeck et al. (this issue) model.

side (up to −1.99 mm/y, even if (probably) this value is mainly due to high sedimentation rates), following the aforementioned tilting. It was active at least up to the Late Holocene and maybe in historical times, as the notch could have down-dropped during post-Roman time, as suggested by Faivre et al. (this issue).

The regional tilting is not regular (Fig. 8). This regional behaviour is modulate by discrete tilting as the result of differential movement between distinct blocks separated by anti-Dinaric NE–SW faults, as for instance the Sistiana Fault in the northern part and the Monte Spaccato Line in the southern part, and a fault crossing the gulf, the latter suggested by Busetti et al. (2010) (Fig. 11).

The northwestern part of the gulf follows a different tectonic pattern. The coast between Sistiana and Duino is E–W oriented,

Fig. 11. The map, modified after Busetti et al. (2010) represents the Gulf of Trieste with the Dinaric thrusts and the NE–SW faults. Inset map with ipocenter of earthquakes, occurred from 1977 to 2007 (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale – Dipartimento Centro di Ricerche Sismologiche, CRS - http://www.crs.inogs.it). Panzano Line from Carulli et al. (1980) and Nicolich et al. (2004), Trieste Fault from Carulli et al. (1980), Sistiana Fault from Carulli et al. (1980) and Nicolich et al. (2004), Monte Spaccato Fault from Cavallin et al. (1978) and Carobene and Carulli (1981), Buzet, Gračišče, Hrastovlje and Črni Kal Thrusts from Placer (2008).

and the Karst Thrust is supposed to be buried and to involve the flysch (GeoCGT Project, 2008). The NW shoreline is fragmented by a number of tear-faults, N–S oriented because of the proximity to the main thrust. They are attributable to the break of the rigid front of the thrust. They have been interpreted as tear-faults of the main thrust. The surveyed faults and fractures have been recognized both in the carbonate sequence and inside some caves in the Classical Karst (Zini, 2002).

The detailed surveying of the submerged notch in the area highlights that, in correspondence to some N–S oriented faults, significant vertical displacements have occurred (Fig. 8). Considering the lack of documented earthquakes with adequate magnitude in the area, the tectonic downdrop is caused by creeping along pre-existent discontinuities, in a regional context of NW downdrop. Regarding the age of these displacements, considering that the notch is probably post-Roman, the creeping acted and maybe is still acting since post-Roman times. On the other hand, the lack of a present-day notch and notch occurrence at the same depth on a regional scale, suggests that it is submerged because of a tectonic downdrop, a co-seismic event, as suggested by a number of authors (Pirazzoli, 1980; Benac et al., 2004, 2008; Antonioli et al., 2007) or because of an increasing of denudation rates, perhaps related to a more aggressive environment during constant downdrop of the area (Furlani et al., this issue).

Stage 1 *Pre-Roman age*. Shore platforms widen in response to the Holocene sea level rise. They are well-developed on flysch lithologies. Considering the elevation of the beachrock vs the elevation of the notch, its formation probably occurred before the Roman age.

Stage 2 *Roman age*. The rising of the sea level submerged the pre-existing geomorphological markers, and new anthropic structures (docks, piers, quays, etc) were built along the coast.

Stage 3 The Trieste area remained stable while the northernmost part of the gulf down-dropped, following the trend of the tilting. The vertical movements could be co-seismic.

Stage 4 *Post-Roman age*. A tidal notch was carved along the limestone outcrops along the coast, perhaps at rates higher than recent ones (Furlani et al., this issue). The variability of its shape, from symmetric to roof notch, seems to be mainly due to local morphological setting or different wave exposition rather than differences in tectonics or sea level rise. In some locations (e.g. Marina di Aurisina), both shapes have been surveyed with short distances (few metres).

Stage 5 The downdrop of the area stopped the carving of the notch and "froze" its development, due to a co-seismic event or to a decrease in limestone erosion rates, as suggested by Furlani et al. (this issue).

Stage 6 The sector between Sistiana and Duino was intersected by vertical displacements after the co-seismic event (phase 5), explained as creeping along pre-existent discontinuities (N–S and NE–SW oriented faults that fragment the coast sector), perhaps accelerated by seismic events.

Further detailed subaerial and underwater measurements, including geophysical surveying, and new dates on the submerged beachrock are required.

6. Conclusions

Detailed analysis of sea level markers allowed to estimate relative sea level changes and vertical displacements of the coast of the Gulf of Trieste based on archaeological, sedimentological, geomorphological and geophysical data. The southern side is characterized by downdrop since Roman times. The city of Trieste was almost stable during the same period, and the northern side is characterized by downdrop that follows a SE–NW tilting. The tilting is not regular but is affected by relative movements between blocks, separated by anti-Dinaric NE–SW faults. Moreover, the northwestern sector is intersected by vertical displacements, highlighted by the topographical trend of the submerged notch. The studied indicators (beachrocks, shore platforms, notches, archaeological remains – all submerged – and marine and lagoon sediments) and geophysical data collected in the central part of the gulf allowed reconstruction of the relative sea level change, resulting in the submersion of the coastal area of the Gulf of Trieste.

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