Sea-level change during the Holocene in Sardinia and in the northeastern Adriatic (central Mediterranean Sea) from archaeological and geomorphological data

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Abstract

We provide new data on relative sea-level change from the late Holocene for two locations in the central Mediterranean: Sardinia and NE Adriatico. They are based on precise measures of submerged archaeological and tide notch markers that are good indicators of past sea-level elevation. Twelve submerged archaeological sites were studied: six, aged between 2.5 and 1.6 ka BP, located along the Sardinia coast, and a further six, dated ~2.0 ka BP, located along the NE Adriatic coast (Italy, Slovenia and Croatia). For Sardinia, we also use beach rock and core data that can be related to Holocene sea level. The elevations of selected significant archaeological markers were measured with respect to the present sea level, applying corrections for tide and atmospheric pressure values at the time of surveys. The interpretation of the functional heights related to sea level at the time of their construction provides data on the relative changes between land and sea; these data are compared with predictions derived from a new glacio–hydro-isostatic model associated with the Last Glacial cycle. Sardinia is tectonically relatively stable and we use the sea-level data from this island to calibrate our models for eustatic and glacio–hydro-isostatic change. The results are consistent with those from another tectonically stable site, the Versilia Plain of Italy. The northeast Adriatic (Italy, Slovenia and Croatia) is an area of subsidence and we use the calibrated model results to separate out the isostatic from the tectonic contributions. This indicates that the Adriatic coast from the Gulf of Trieste to the southern end of Istria has tectonically subsided by ~1.5 m since Roman times.
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1. Introduction

Sea-level change is the sum of eustatic, glacio–hydro-isostatic and tectonic factors. The first is global and time dependent, while the other two also vary according to location. The glacio–hydro-isostatic factor along the Italian coast was recently predicted and compared with field data, at sites not affected by significant tectonic processes (Lambeck et al., 2004a). The aim of this paper is to provide new data on the relative sea-level rise during the late Holocene along the coastlines of Sardinia and northeastern Adriatic (Slovenia, Croatia and Italy), where the recent relative sea-level rise has not yet been estimated. For

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Fig. 1. Map of central Mediterranean coast, location of the archaeological and geomorphological markers sites investigated in this paper.

this purpose, we have surveyed geoarchaeological and geomorphological markers (submerged for the most part) in tectonically stable Sardinia and in the northeastern Adriatic, the latter being an active region whose tectonic rates are still unknown. Archaeological and geomorphological findings together provide a powerful source of information from which the relative motions between the land and the sea can be constrained.

Archaeological evidence from small tidal range areas such as the Mediterranean Sea can provide significant information for the study of relative sea-level changes in historic times; this can be done through the use of old coastal structures whose successful functioning requires a precisely defined relationship to sea level at the time of construction. Along the Mediterranean shores, a large number of archaeological remains can be used to provide constraints on relative sea level. The first pioneering results using geophysical interpretations from archaeological indicators for sea-level change estimation were published by Flemming (1969), Schmiedt (1974), Caputo and Pieri (1976) and Pirazzoli (1976). Several more detailed local and regional studies concerning the Mediterranean

have been published in the past decade, providing new interpretation of the observed changes. Slipways, fish tanks, piers and harbour constructions generally built before ∼2 ka BP provide a valuable insight of the regional variation in sea level in the last 2000 yr (Columella; Lambeck et al., 2004a, b, and references therein). Quarries carved along the coastlines and located near fish tanks and harbours or villas of the same age can provide additional data, both on the past water level and on their own functional elevation above sea level, although the quarries are not very precise indicators (Flemming and Webb, 1986).

In this paper, we examine archaeological evidence from the Sardinian and northeastern Adriatic coasts (Italy), where the development of maritime constructions reached its greatest concentration during the Punic and Roman times and where many well-preserved remains are still present today. The best preserved sites were examined providing new information on their constructional levels that can be accurately related to mean sea level between ∼2500 and ∼1600 yr ago. Isostatic and tectonic contributions to this change are then estimated from observational

and model considerations to establish the eustatic change over this period.

We also present new data on late Holocene sea level and on the vertical rate of tectonic movements in Sardinia (Italy), Slovenia and Croatia (Fig. 1). These provide key elements for the understanding of the geodynamic evolution of the Mediterranean basin. Unpublished archaeological markers such as docks, piers, quarries, tombs, pavements, fish tanks (all presently submerged), and geomorphological markers such as core stratigraphy and beach rock (published previously only in national journals), as well as tidal notch data, are used as benchmarks recording the relative vertical motion between land and sea since their construction or formation.

The heights of the selected archaeological markers were measured and compared with the present sea level, applying corrections for tide, pressure and wind at the time of the surveys. The interpretation of their functional heights provided new evidence on relative sea-level changes. These data, together with their relative error estimation (elevation and age), are compared with predicted sea-level rise curves using a new prediction model for the Mediterrenenan coast; this model consists of a new equivalent sea-level (esl) function (the ice-volume esl change; Lambeck and Chappel, 2001) that assumes a small continuous melting of the Antarctic ice sheet until recent times. The accuracy of these predicted values is a function of the model parameter's uncertainties is defining the earth response function and the ice load history (esl). This new model is more accurate if compared to the previous one by Lambeck et al. (2004a), especially in northern Italy and Sardinia because of the inclusion of an Alpine deglaciation model (Lambeck and Purcell, 2005) and because of improved Scandinavian and North American ice sheet models (Lambeck et al., 2006).

The results provide new data on the rates of relative sea-level rise and on the vertical land movement rates in Sardinia and in the northeastern Adriatic coast during the late Holocene.

2. Geodynamic setting

The Alpine Mediterranean region marks the broad transition zone between the African and the Eurasian plates and its tectonics are a result of the evolution of the related collisional plate boundary system (Mantovani et al., 1996; Jolivet and Faccenna, 2000; Faccenna et al., 2001). The geodynamics of this region are driven by lithospheric blocks showing different structural and kinematic features including subduction, back-arc spreading, rifting, thrusting, normal and strike slip faulting (Montone et al., 1999; Meletti et al., 2000; Mantovani et al., 2001). The recent dynamics of the region are shown by the distribution of seismicity that outlines the plate boundaries and the quasi-aseismic domains such as the Adriatic and Tyrrhenian areas. These areas have been interpreted as rigid blocks or microplates or as undeformed sedimentary basins, limited by lithospheric-scale structures such as subduction fronts and large strike slip fault systems (Dewey et al., 1989; Reuther et al., 1993).

Recent GPS results of the current crustal deformation in the central Mediterranean show different behaviours for the Sardinia–Corsica block and the Adriatic regions. In the first area, the very low seismicity of the Sardinia–Corsica block and the lack of current crustal deformation of this continental fragment suggest that this area belongs to the rigid Eurasian plate and that the back-arc extension that characterized the past evolution of this area is no longer active (Kastens and Mascle, 1990). The continuous monitoring GPS stations, located in Cagliari (Sardinia) and Ajaccio (Corsica), witness the current stability of the region, showing horizontal velocities relative to Europe of 0.3 ± 0.6 mm/a, thus further suggesting that this area belongs to the stable Eurasian plate (Serpelloni et al., 2005).

In the second area, instrumental and tectonic data show a complex deformation pattern related to the kinematics of the Adriatic region, which has been interpreted as a block (Adriatic block) that is independent—or partially independent—from the African plate (Anderson and Jackson, 1987; Westaway, 1990; Ward, 1994; Calais et al., 2002; Oldow et al., 2002; Nocquet and Calais, 2003). Although this region displays an active deformation and its kinematics are still debated, interpretations of recent GPS observations suggest that this area is a unique crustal block rotating counter-clockwise (Serpelloni et al., 2005). This block moves independently from the African plate and displays a north–south shortening in the central and eastern southern Alps at 1–2 mm/a and a northeast–southwest shortening between 1.6 and 5 mm/a along the Dinarides and Albanides. A comparison between the motion predicted by the rigid rotation of Adria and the shortening observed across the area of the largest known earthquake that struck this region (the 1976 Friuli earthquake) suggests that the 2.0 ± 0.2 mm/a motion of Adria is absorbed in the southern Alps through thrusting and crustal thickening, with very little or no motion transferred to the north, and a northward-dipping creeping dislocation whose edge is located within a 50 km wide area beneath the southern Alps (D'Agostino et al., 2005). In the frame of the whole Mediterranean area, the geodynamic evolution of the Sardinia–Corsica block and of the Adriatic region is relevant for the estimation of the related recent sea-level changes driven by eustasy and isostasy that can be observed along their coastlines, as recently shown by Lambeck et al. (2004a, b) and discussed by Pirazzoli (2005).

The geological features of the two investigated regions are characterized by different lithologies: the Adriatic region displays a thick carbonate succession dating from Lower Trias to Lower Eocene, which continued during the Lower–Mid-Eocene with turbiditic flysch deposits (Herak, 1986; Cucchi et al., 1989; Velić et al., 2000). Northern Sardinia displays basaltic and granite rocks, developed during the Upper Pliocene and Lower

Pleistocene (Sias, 2002), while its southern part displays prevailing sedimentary units. Since the Upper Pleistocene, this region has experienced tectonic stability; the area is unaffected by seismicity (Valensise and Pantosti, 2001; Viti et al., 2001) and only local vertical movements occur along steep cliffs or as subsidence due to soil compacting along low coastlines (Orrù et al., 2004). In this study, only archaeological markers placed on the bedrock were selected, in order to avoid possible ground instabilities which may affect results.

3. Recent movements

3.1. Northeast Adriatic coast

Along the northern Adriatic coast, north of the slightly uplifted terraces of the Marche region (central Adriatic Italian coast, Fig. 1) (Ferranti et al., 2006), the MIS 5.5 shoreline is sharply down-warped, while it does not outcrop along the northeastern coast of the Adriatic Sea. The equivalent markers, which have been observed in boreholes between 85 and 117 m below sea level in the northern Emilia-Romagna region, provide evidence that a significant tectonic subsidence has occurred during the last 125 ka. Establishing the rate of subsidence, however, is not straightforward, since large uncertainties exist both in terms of the precise age and position of the palaeo-shorelines of the sampled deposits. Given these uncertainties, an approximate rate of subsidence of ∼1.0 mm/a can be estimated for this area. Two further sites located in the northern Adriatic (Veneto and Friuli) display lower subsidence values (−0.7 and −0.2 mm/a; Ferranti et al., 2006) with respect to those markers located in Emilia Romagna. These sites are located close to the Po Plain, and thus experience a crustal flexure due to the southern Alpine and Dinaric contraction.

Pirazzoli (1980) surveyed some sites in southern Istria and northern Croatia, which display a well-developed notch at 0.5/0.6 m below sea level, while Fouache et al. (2000) extended these investigations to northern Istria, finding archaeological and geomorphological markers around the same depths. These markers are related to the Roman Age remains. Lambeck et al. (2004a) summarized late Holocene data for the Emilia, Veneto and Friuli coastal plains (Fig. 1) using lagoonal markers sampled and dated in cores at different depths. The results show tectonic subsidence with lower values from west to east of 1.1, 0.45, 0.37 and 0.28 mm/a. Benac et al. (2004) made a detailed description of a marine notch between 0.5 and 1.0 m below sea level in the Gulf of Rijeka, possibly displaced downward by coseismic deformation that occurred during an earthquake in AD 361.

3.2. Sardinia

A large number of MIS 5.5 sites were recently reported for Sardinia by Ferranti et al. (2006), who recorded mainly tidal notches that are developed along limestone promontories. Sardinia is the region in the Tyrrhenian Sea where the elevation of these markers are lowest, being located at 6–8 m above current sea level in several sites. Sardinia was therefore chosen as the reference region for the estimation of the MIS 5.5 eustatic elevation (Lambeck et al., 2004a).

Despite its stable tectonic behaviour, minor local vertical motions of the order of 1 m can be identified due to the excellent lateral exposure of the tidal notches. For instance, at Capo Caccia (a calcareous promontory located on the NW side of the island) the marker altitude decreases from east to west from 5.5 to 3.5 m. The westward increase in subsidence suggests slow crustal motion, likely accommodated by faults related to the continental margin of the western Mediterranean. The central part of the eastern coast shows a remarkably well-developed tidal notch that can be traced along the coastline for more than 70 km, with a northward increase in elevation from 7.6 to 10.5 m (Carobene and Pasini, 1982; Antonioli and Ferranti, 1992), whereas, further north, the notch has an altitude of ∼5 m a.s.l. The small amplitude deformation of this notch can be related to the nearby Pliocene–Quaternary volcanic field, whose main activity ended at ∼140 ka, before MIS 5.5 (Bigi et al.,1992).

Data for the Holocene relative sea-level rise in Sardinia are mainly reported in Lambeck et al. (2004a) and consist of ^{14}C dated beach-rock markers from different elevations. The beach-rock observations from eastern and northern Sardinia yield age–depth results that are consistent with the geophysical model predictions. One archaeological observation at 7.5 ka from Capo Caccia is an upper limit and it is in agreement with the beach-rock observations from the north coast.

The comparison of the MIS 5.5 and of the Holocene data clearly shows that these two coastal areas from the two regions display different vertical movements during the last 125 ka: Sardinia has been stable, while the north Adriatic coast and the Istria region show active subsidence poorly defined.

4. Materials and methods

Twelve sites, 18 archaeological markers and several tidal notches were surveyed along the northeastern Adriatic Sea and Sardinia (Table 1). The analysis involved four steps.

First, we measured the elevation of the significant archaeological markers of submerged maritime structures with respect to the present mean sea level. Values reported in Table 1 are the average values of multiple measurements collected at the best preserved parts of the investigated structures. We corrected these measurements for tide and atmospheric pressure effects at the time of surveys, using the data and algorithms adopted by the Italian Istituto Idrografico della Marina for the Mediterranean Sea (Table 1).

The effect of atmospheric pressure on sea level is calculated to allow for the difference in pressure between

Table 1
Data and measurements

A Site name	B Coordinate	C Survey date (yyyy/mm/dd, h)	D Type and measured height (m)	E Archaeological age (yr BP)	F Tide (m)	G Pressure (hPa) correction (m)	H Corrected height (m)	I Functional height (m)	J S.l change (m)	K References
1. Stramare	45°36′07″, 13°47′24″	2005/07/16, h 13:40 GMT	Walking surface, −1.66	1900±100	+0.06	–	−1.60	0.0 a.m.s.l	−1.60±0.60	This paper
2. Punta Sottile	45°36′08″, 13°43′10″	2005/05/25, h 19:55 GMT	Pier, −1.65	1950±50	+0.25	–	−1.00	0.60 a.m.s.l	−1.60±0.60	Auriemma et al. (2007, in press)
3. Jernejeva draga San Bartolomeo	45°35′34″, 13°42′53″	2005/11/10, h 15:10 GMT	Vivaria dock, −0.70	1900±100	−0.10	–	−0.80	0.60 a.m.s.l	−1.40±0.60	This paper
4. Sv. Simon San Simone	45°31′57″, 13°38′41″	2004/10/26, h 10:30 GMT	Pier, −1.40	1950±50	+0.40	–	−1.00	0.60 a.m.s.l	−1.60±0.60	Degrassi (1957)
5a. Savudrija/ Salvore	45°29′59″, 13°30′13″	2005/10/17, h 13:00 GMT	Pavement, −1.18	1950±50	−0.32	–	−1.50	0.0 a.m.s.l	−1.50±0.60	This paper
5b. Savudrija/ Salvore	45°29′59″, 13°30′13″	2005/10/17, h 13:30 GMT	Pier, −0.10	1950±50	−0.40	–	−0.50	1.00 a.m.s.l	−1.50±0.60	Fouache et al. (2000) and this paper
6a. Brijuni	44°54′40″, 13°46′29″	2004/10/27, h 12:30 GMT	Pavement, −1.20	1950±50	0.00	–	−1.20	0.60 a.m.s.l	−1.80±0.60	Degrassi (1957) and Fouache et al. (2000)
6b. Brijuni	44°54′39″, 13°46′35″	2004/07/05, h 14:20 GMT	Dock/pier, −1.10	1950±50	+0.10	–	−1.00	0.60 a.m.s.l	−1.60±0.60	Degrassi (1957) and this paper
7a. Capo Testa	41°42′25″, 09°09′35″	2004/07/20, h 07:00 GMT	Quarry, −0.70	2000±100	+0.08	–	−0.62	0.30 above high tide (i.e. 0.23 a.m.s.l)	(>−0.85), −1.16±0.30	Careddu (1969), Usai and e Pirisino (1991) and Gallura
7b. Capo Testa	41°42′25″, 09°09′35″	2004/07/20, h 07:00 GMT	Pier, −0.60	2000±100	+0.10	–	−0.50	0.70 a.m.s.l	−1.21±0.23	Careddu (1969), Usai and e Pirisino (1991) and Gallura
8a. Tharros	39°52′01″, 08°26′24″	2004/07/21, h 11:00 GMT	Quarry, −0.50	2000±100	−0.06	–	−0.56	0.30 above high tide (i.e. 0.23 a.m.s.l)	(>−0.79), −1.11±0.30	Acquaro and Finzi (1999), Acquaro et al. (1999) and Schmiedt (1974)
8b. Tharros	39°52′01″, 08°26′24″	2004/07/21, h 11:00 GMT	Tombs, −0.70	2350±150	−0.06	–	−0.76	0.30 above high tide (i.e. 0.23 a.m.s.l)	(>−0.99), −1.29±0.30	Acquaro and Finzi (1999), Acquaro et al. (1999) and Schmiedt (1965)
9. Capo Malfatano	38°53′30″, 08°48′11″	1999/07/20, h 12:00 GMT	Breakwater dock, −1.50	2200±200	−0.06	–	−1.56	>0.70 a.m.s.l	−2.26±0.23	Mastino et al. (2005) and Orrù and Lofty (2003)
10a. Nora molo Schmiedt	38°59′05″, 09°00′45″	2005/12/19, h 13:00 GMT	Pier, −1.00	1900±300	+0.14	1026, −0.12	−0.98	0.60 a.m.s.l	−1.58±0.23	Orrù and Lofty (2003), Schmiedt (1974) and Solinas and Sanna (2006)
10b. Nora Basilica	38°59′05″, 09°00′45″	2005/12/19, h 13:00 GMT	Pavement, −0.60	1650±50	+0.14	1026, −0.12	−0.58	0.60 a.m.s.l	−1.18±0.23	Bejor (2000)
11. Perd'e Sali	39°01′19″, 09°01′31″	2005/12/19, h 11:00 GMT	Quarry, −0.75	2000±300	+0.14	1026, −0.12	−0.73	0.30 above high tide (i.e. 0.23 a.m.s.l)	(>−0.96), −1.26±0.30	This paper
12. Santa Gilla	39°15′48″, 09°01′55″	1991	In situ amphorae, −1.70 (70)	2450±40	−0.01	–	−1.71	above high tide (i.e. 0.23 a.m.s.l)	−1.94±0.23	Solinas (1997) and Solinas and Orrù (2006)

Site numbers in column A are also reported in Fig. 1; B: WGS84 coordinates of the surveyed site; C: year, month, day and hour of measurement; D: field measurements (before correction); E: inferred ages based on archaelogical data; F: tidal correction applied for tide amplitude at the moment of surveys. Tide values at each location are computed with respect to the mean sea Level of Genova, using data from the local reference tide gauge data of Trieste and Cagliari, which are the nearest permanent stations to the archaeological sites. Tide time delay at each site has been included in the computation; G: atmospheric pressure and correction values at the time of surveys. Pressure data from www.wunderground.com; H: site elevation as derived from data of columns D, F and G; I: functional height of the used marker, with respect to the functional mean sea level. For quarries and tombs we assume a minimum elevation at 0.30 m above high tide to be always dry, plus an uncertainty of ±0.30 m for their functional heights; J: estimated relative sea level change. Error within the tide amplitudes (± 0.23 m for the Tyrrhenian Sea and ±0.60 m for the Adriatic Sea). *Remarks:* The functional height of the quarries, as well as of the tombs of Tharros, can be estimated taking into account the following considerations: (i) they were carved outside the water, at a minimum elevation just above the high tides. For this reason we applied 0.23 m of correction determined by the value of the average tide excursion in the central Mediterranean; (ii) we can consider a minimum functional error at ±0.30 m on their elevation. This is reasonable and in agreement with the observations collected at other coastal archaeological sites (Lambeck et al., 2004b). For more information about the tide gauge of Trieste see also http://www.univ.trieste.it/~dst/OM/OM_mar.html.

Table 2
North Sardinia beach rock data (used in Lambeck et al., 2004a) calibrated with Calib 5 (Stuiver et al. 2005)

Sites	Altitude (m)	^{14}C Age (yr BP)	Age (cal yr BP)
Figari	0	180	Modern
Figari 2	−3	2620 ± 100	2281 ± 86
Cala Lunga	−0.3	1300 ± 70	841 ± 72
Isola Dei Gabbiani	−1	2200 ± 55	1793 ± 72
Barca Brusciata	−2	2507 ± 68	2191 ± 92
Palumbaggia	−3 to −4	2360 ± 60	1981 ± 81
San Bainzo	−4	2625 ± 100	2299 ± 141
Monti Russu	−6 to −8	4850 ± 110	5139 ± 150

the time of observation and the mean annual pressure for the site. These corrections are based on the inverted barometer assumption using the closest available meteorological data (www.metoffice.com) (Table 2).

We estimate errors for the elevations and ages of the archaeological markers and evaluate their functional heights on the basis of accurate archaeological interpretations provided by maritime archaeologists. Age errors are estimated from the architectural features; elevation errors derive from the measurements, corrections and estimates of the functional heights (for example, the lower limiting values for the quarries).

Lastly, we examine the predicted and observed sea levels, by comparing the current elevations of the markers (i.e. the relative sea-level change at each location) with the sea-level elevation predicted by the new geophysical model for each location. We hypothesize tectonic stability at the sites where the elevations of the markers are in agreement with the predicted sea-level curve. Conversely, we hypothesize that the area has experienced tectonic subsidence when the elevations of the markers are below that of the predicted sea-level curve.

Field elevation measurements were performed with optical and mechanical methods (Salmoiraghi Ertel automatic level or invar rod). All the measurements of the archaeological features's depths were made in times of low wave action and they were related to the sea-level position for that particular moment. Since the investigated archaeological structures were originally used year round, we assume that the defining levels correspond to the annual mean conditions at the time of construction. The measurements are therefore reduced to mean sea level applying tidal corrections at the surveyed sites, using the data of the nearby tide gauges (Trieste and Cagliari) and the tidal data base of the Istituto Idrografico della Marina (2006). The latter was computed through tide gauge data over a time span of ~20 yr and referred to the mean sea level at Genova. Elevation measurements are therefore referred to the zero reference levelling benchmark belonging to the levelling network of the Italian Istituto Geografico Militare (Genova mean sea level) and located nearby the tide gauges.

In the case of Nora and Perd'e Sali (sites 10 and 11, Figs. 1 and 2), tide gauge data were not available from the nearby gauge at Cagliari and we used the predicted tide estimation, corrected for local pressure values.

Estimating and correcting for tide amplitudes is a crucial element for the northern Adriatic Sea; the measurement of the markers' elevation must be properly corrected for tides, as they here show the largest values in the whole Mediterranean basin (up to ~1.8 m and mainly produced by meteorological variability in a closed basin, as opposed to the normal values of max ~0.45 m, from the tidal data base of the Italian Istituto Idrografico della Marina). For these reasons, local tide amplitudes were also estimated through a portable tide gauge temporarily installed nearby the archaeological sites during surveys and cross-checked by the tidal data base of the Italian Istituto Idrografico della Marina. The latter also uses data from the nearby permanent tide gauge located in Trieste (established in 1890).

We defined the "functional heights" of the archaeological benchmarks, in order to estimate the sea-level change in each location, and to compare the observed results in different locations. This parameter is defined as the elevation of specific architectural parts of an archaeological structure with respect to an estimated mean sea level at the time of their construction. It depends on the type of structure, on its use and on the local tide amplitudes. Functional heights also define the minimum elevation of the structure above the local highest tides.

To improve our interpretations, we also measured the functional heights at some modern harbour structures (piers and docks) located along the coasts of Sardinia and in the Gulf of Trieste, comparing them with those measured at the archaeological sites located in the nearby areas. This showed that the pavements at the top of the piers were in the range 0.5/1.0 m above sea level. Because the tide amplitude is generally within ±0.23 m in the Mediterranean, and up to ±0.9 m in the Gulf of Trieste during particular meteorological events (Istituto Idrografico della Marina, tidal data base), the top surfaces of some small piers or docks can be nearly submerged during maximum tides. On the other hand, the seafloor in some harbours and docks can become dry during the lowest tides.

It is notable that the architectural features and functional heights of modern piers and docks are in agreement with those of the Roman Age. This information can also be deduced from previous publications (Schmiedt, 1965; Flemming, 1969; Flemming and Webb, 1986; Hesnard, 2004), from historical documents (Hesnard, 2004, Vitruvius), from the remnants of the Roman Age shipwrecks (which provided data on the size of the ships or boats and their draughts, as reported, for example, in Charlin et al., 1978; Steffy, 1990; Pomey, 2003; Medas, 2003) and through rigorous estimation of the functional heights of the piers, by using and interpreting different type of markers on the same location (Lambeck et al., 2004b). As far as we know, navigation during Roman times was mainly seasonal (due to the frequent storms during autumn and winter times,
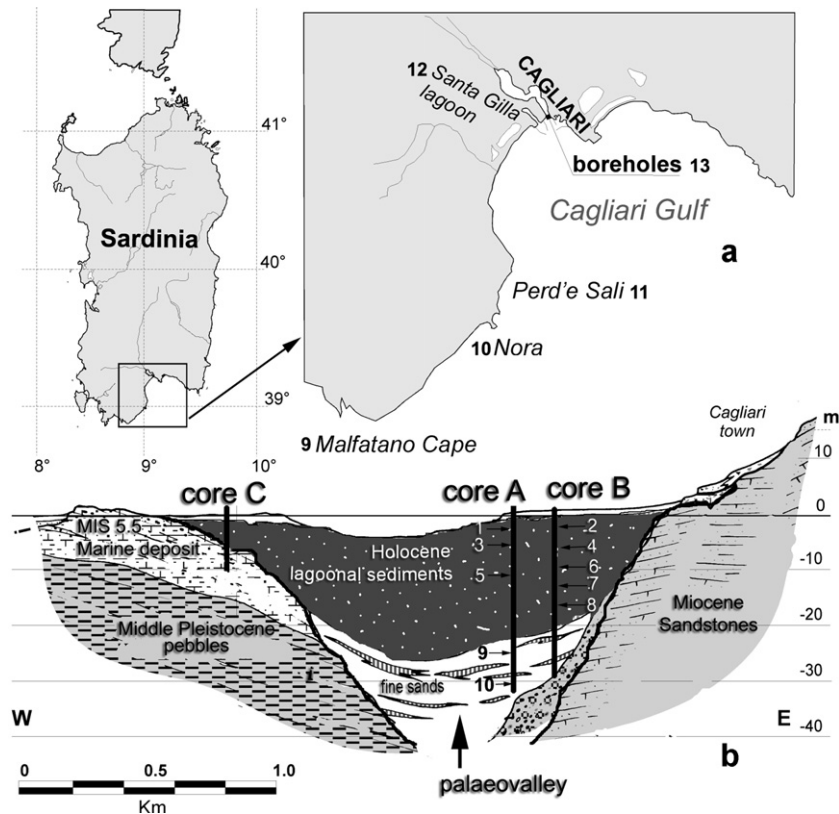
Fig. 2. (a) The southern Sardinia coast: locations are reported in the map; (b) details of the three boreholes (A, B, C) stratigraphy across the Holocene marine deposit are reported. Numbers of cores A and B are the AMS ^{14}C ages reported in Table 2.

sailing was not safe) and the Roman ships that used these coastal structures had draughts of ∼0.5 m (Matijašić, 2001a), which fit the features of the observed archaeological markers. The use of these structures, their age and conservation, the accuracy of the survey and the estimation of the functional heights were all used in considering the observational uncertainties at each site.

5. Data

5.1. NE Adriatic coast: geomorphological markers

The northeastern Adriatic coast has experienced a rising Holocene relative sea level that was largely complete by about 7 ka calibrated (cal) BP, after which sea level rose only slowly up to the current elevation. With the exception of storm or tsunami deposits found nearby Pula (Antonioli, 2005) at an elevation of about +0.7 m along the northeastern Adriatic coast, no marine notches or fossils have been found at elevations higher than current mean sea level.

Tidal marine notches are considered to be good indicators of coastal tectonic movement. Pirazzoli (1980) observed submerged marine notches in Croatia at approximately −0.6 m and Fouache et al. (2000) studied and measured some submerged notches along the Istrian coast also at an altitude of about −0.6 m. These notches have been attributed to the Roman Age. Benac et al. (2004) measured the submerged notch on the Gulf of Rijeka at

between −0.5 and −0.6 m, and in Bakar Bay at between −1.03 and −1.15 m (Fig. 3), both measured with respect to the local biological mean sea level (here typically 0.6 m below biological mean s.l). These authors ascribe the notches to rapid coseismic subsidence following an earthquake in AD 361.

In view of these observations and with the aim of providing new measurements on the whole NE Adriatic area, we surveyed the northern limestone coast of Istria and the Gulf of Trieste (Italy). South of this area, further data were collected in the Kornati Islands of southern Croatia as well as in Montenegro (Fig. 3).

At the Gulf of Trieste (Italy), we observe at Miramare a distinct notch at an elevation of −0.6 to −0.8 m (tide corrected). Only ∼6 km west from Miramare, the elevation of the notch decreases to −0.9 m. In a northwest direction between Sistiana and Duino (Italy), the altitude of the notch continues to decrease from −1.3 to −2.5 m (Fig. 3). In accordance with the local tide amplitudes (the highest in the whole Mediterranean Sea) the width and amplitude of the notch are larger than 1 m (Fig. 4). Unfortunately, biological organisms have not been preserved, preventing dating of the notch. A submerged tidal notch partially described by Pirazzoli, (1980), Fouache et al. (2000) and Benac et al. (2004) runs along the coastlines of Istria and Croatia at an average elevation of −0.6 m. South of the Gulf of Rjeka, towards Montenegro, a present day tidal notch was not observed. Instead, a submerged notch was
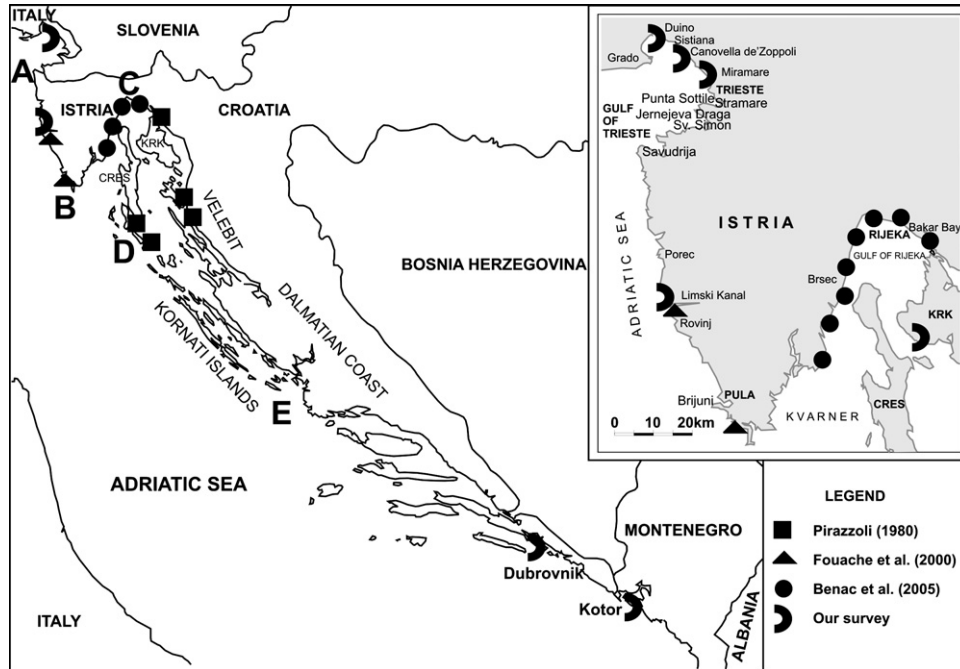
Fig. 3. Map of the NE Adriatic coast showing the locations quoted. The legend contains the locations where the submerged tidal notches were measured by the authors.
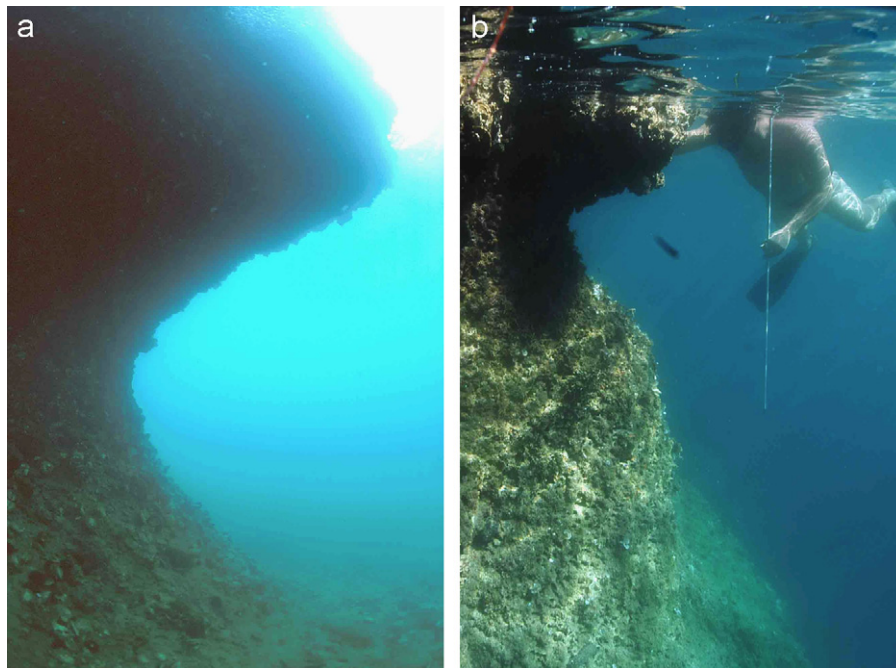

Fig. 4. (a) The submerged tidal notch at −2.2 m, Duino (Trieste, Italy). The notch amplitude is larger than about 1 m in accordance with the local high-energy exposition; (b) the submerged tidal notch is found at −0.8 m at Rovinj (Croatia).

observed at about −0.5 m. Fig. 3 illustrates the overall spatial distribution of this notch. Our observations show that the present day notch is absent along the limestone coasts of the northeastern Adriatic, between Duino (Italy) and Kotor (Montenegro), while a submerged notch occurs at about −0.6 m below the present day sea level.

5.2. NE Adriatic coast: archaeological markers

In addition to the tidal notch data, sea-level constraints were also obtained from seven coastal Roman Age archaeological sites (see Figs. 1 and 2 and Table 1) that were well related with sea level.

5.2.1. Stramare (Muggia, Trieste)

At Stramare, near the Ospo Stream mouth, the terrace behind the narrow beach is characterized by many traces of Protohistoric and Roman habitation, found despite the damage caused by the modern industrial district (Cannarella, 1962, 1965, 1966, 1968; Peracca, 1968; Maselli Scotti, 1977, 1979; Piani, 1981; Paronuzzi, 1988; Župančič, 1989–1990). The lower terrace extends below the current sea level. In ancient times, the terrace was a land extension protecting the left side of the Ospo Stream mouth. Probably, the pars rustica or the pars dominica of a maritime "villa" once faced this open area. On the west side, this terrace was contained by a wall that was very similar to the emerged ones. The upper side of this wall is currently 1.6 m above the present day sea level (Table 1). The wall was built with thick stone slabs laid facing the ground with its foundation 0.5–0.6 m below its actual upper surface. At the time of its construction, the wall's foundation level, now at 1.66 m below the sea level (−1.60 corrected for tide, pressure and wind), would have been emerged at least for part of the day. On the northern and eastern sides, the terrace slopes down to −3.0 m: this elevation difference most likely marks the old seashore, and it is sheltered by large stone blocks, some close together, some scattered. Shards of amphorae and common ware of

Roman Imperial Age occur in this submerged terrace but it is difficult to establish the building's chronological range and its exact use (Fig. 5, site 1, Table 1).

5.2.2. The pier at Punta Sottile SW (Muggia, Trieste)

The Punta Sottile pier was discovered in the 1980s (Carta Archeologica del Friuli-Venezia Giulia; Gobet, 1983, 1986; Župančič, 1989–1990; Museo Muggia, 1997). The structure lies 40–50 m off the coastline. The first portion of the pier is made up of blocks belonging to the shore platform that in this area is very regular such that the break lines could be wrongly interpreted as an artificial structure, and, partially, it is composed of cut blocks arranged and flanked in the areas where there is no shore platform (Fig. 5, site 2).

The pier is 12 m long from its foot and 2.5–2.6 m wide. It was built with the so-called "a cassone" technique, typical of the landing structures of the eastern Adriatic Sea. Its façade is made of opus quadratum, with large 3 m long parallelepiped sandstone blocks containing a nucleus made of rubble and joined (in places) by transverse blocks. There are two overlapping layers of blocks: the first one is placed on a foundation that follows the marly shore platform. The foundation is made of a small heap of stones, pebbles, ceramic shards; the last of which allowed a secure dating of the time of pier construction, i.e. to the middle
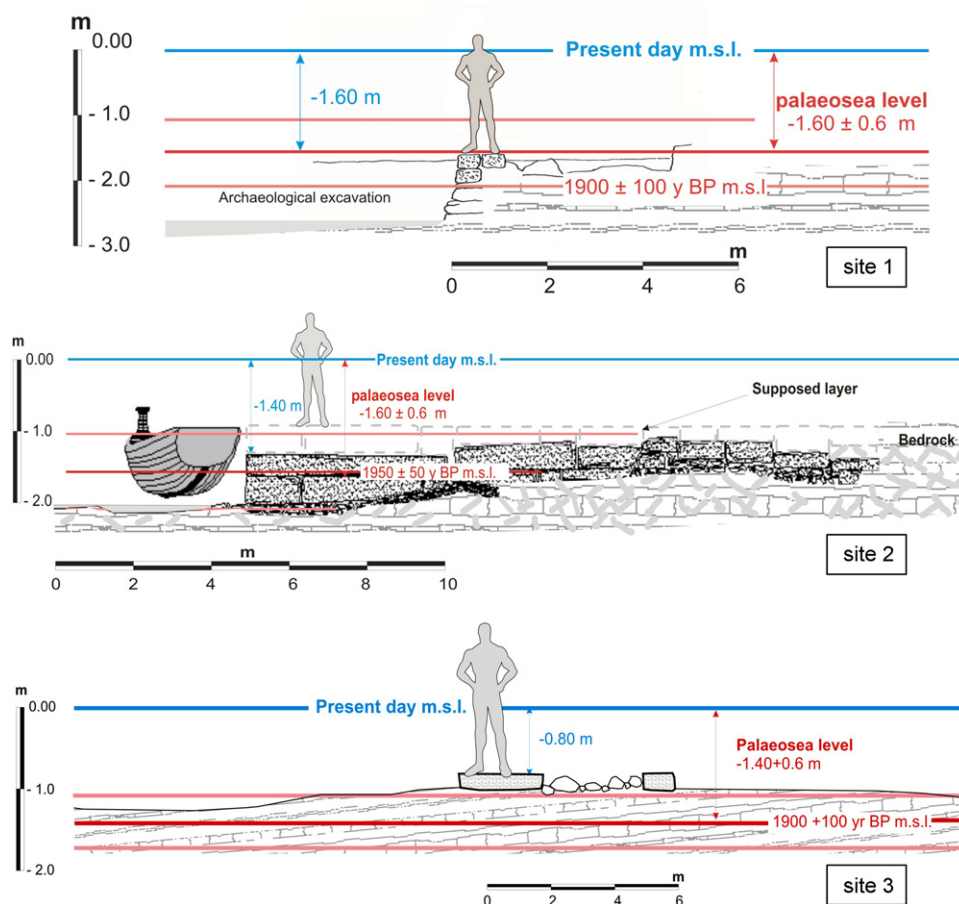

Fig. 5. Representative cross-sections of the archaeological sites located in NE Adriatic coast and their relationships with the current and past sea level. Site 1: Stramare, site 2: Punta Sottile, site 3: San Bartolomeo, site 4: San Simone, site 5: Salvore, site 6: Brijuni.
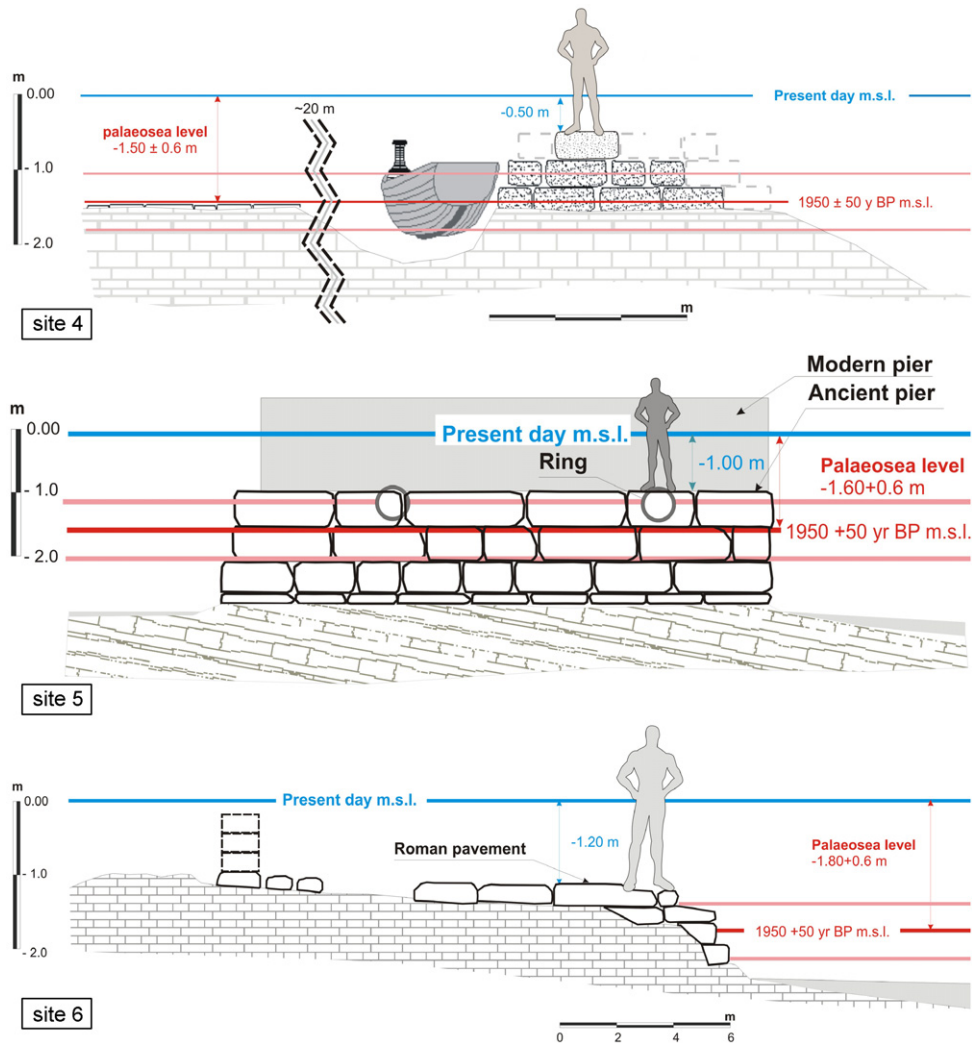
Fig. 5. (*Continued*)

decades of the first century AD. The sea bottom is 1.1 and 2.2 m deep at the pier foot and at its head, respectively, slowly sloping westwards, whereas the actual upper pier surface lies on a sub-horizontal plane at a depth of between 1.15 and 1.4 m below mean sea level. We hypothesize the former existence of a third layer which would have resulted in a near horizontal surface of the pier that joined the shore platform behind it (Fig. 5, site 2). The hypothesis of the existence of a third row of blocks is supported by the excavated outcrops placed at the beginning of the pier: their surface lie at the same elevation of the pier's top, when we include a missing row of blocks (0.4 m thick). So far, the pier surface and the outcropping unit become both placed at the same elevation of 1.0–1.10 m below the current mean sea level.

This leads us to the assumption that the original pier depth was about 1 m, while the walking surface was possibly between at 1.1 and 1.0 m. If we therefore add the initial depth of -1.65 m (corrected to -1.00 m) to the functional height, the data corresponds to a former relative

sea level rise of -1.60 ± 0.60 m below mean sea level (Fig. 5, site 2, and Fig. 9A).

5.2.3. Jernejeva Draga/S. Bartolomeo (Ankaran, Slovenia)

A large fishery was discovered and excavated (this paper) in the S. Bartolomeo Bay, situated close to the Italian–Slovenian border (Župančič, 1989, 1989–1990; Karinja, 2002). The structure is composed of two large docks and most probably a pier. Its total length is 135 m, with a width of 50 m, while the west side is 80 m long. The docks are today contained in an embankment made of disconnected stones, but in Roman times the embankment probably had façades, at least on the inner side. Its eastern side is the main sea-level indicator: it is an embankment for the eastern dock, serving as a pier and a quay at the same time. Its shape is arched, but its foot is straight, 30 m long and 2.6 m wide. The pier has two (external) façades built close to the adjacent stone blocks and the rubble of heap of stones. The actual pier surface seems to have lost one or two rows of blocks since its construction, as inferred from

the nearby remnants. Two of these blocks are fallen along the north side of the pier. On the basis of their shape and size, and if placed one over the other, these blocks allow a reliable reconstruction of the former elevation of the ancient walking surface, which was at −0.7 m (corrected −0.80 m). When this value is added to the functional height (0.60 m), a relative sea-level rise can be estimated since the construction of this structure of 1.40 m (Fig. 5, site 3, Table 1). The suggested age of the S. Bartolomeo fishery is the beginning of the Imperial Age (1900 yr BP) because of its analogy with other similar structures and of the amphora shards found between the stones of the embankment (Fig. 5, site 3).

5.2.4. Sv. Simon/San Simone (Izola, Slovenia)

The splendid structures of the S. Simone Bay "villa" and its harbour (the largest one on the Istrian coast and measuring over 8000 m²) have been well known since the 16th century AD. Unfortunately, these structures were filled with concrete in recent decades (Degrassi, 1923, 1957; Šribar, 1958–1959, 1967; Stokin, 1986; Boltin Tome and Kovačič, 1988; Labud, 1989; Boltin Tome, 1991; Karinja, 1997, 2002; Matijašić, 2001b).

The building includes a quay, a pier, a breakwater and other working areas. The pier starts from the southwest quay corner and is today only visible in the foundations of the modern wharf. The pier is 55 m long and 2.5 m wide and, in different stretches, it shows three layers of large (∼2 m long) yet differently sized stone blocks. The lower layer is larger, in accordance with the Vitruvian construction rules and, on its upper layer, large mooring rings were probably placed, as recalled by the 19th and early 20th century observers. Today, the pier surface lies at a corrected height of −1.0 m and if the functional height was at least ∼0.6 m, relative sea level has risen by ∼1.60 m since its construction. The archaeological findings from the excavations at the "villa" allow us to date the most important habitation phase as being the first and second centuries AD (Fig. 5, site 5).

5.2.5. Savudrija/Salvore (Umag, Hrvatska)

The bay is sheltered by two large piers stretching out from opposite seashores. Excavations allowed us to conclude that the piers were built with large local stone blocks to protect the quay, which was 70 m long. Two inscriptions—one of which dates to the first half of first century AD—were retrieved from the harbour area. These inscriptions suggest the presence of many buildings, both residential and commercial (Degrassi, 1957; Kovačić, 1988, 1996; Jurišić, 1998a; Matijašić, 2001a). We collected measurements from two different areas: the first is an underwater terrace, in front of a well-preserved building standing on the beach (the so-called cistern); the terrace is contained by large blocks lying on the shore platform at a corrected height of −1.50 m. Neither the function nor the date of this terrace is known. We assume that it was a shipyard or other functional working area connected with

the buildings behind it and emerging above sea level only sometimes during the day. The second measurement is from the southern pier which was built "a sacco", i.e. with walls of large overlapped blocks in several layers (up to three conserved in the inner side) and stone rubble within it; this pier is higher than the others and it is located at a corrected height of −0.50 m below the present day sea level. For this indicator, we estimated a functional height of at least 1 m above sea level, because it was probably a breakwater built to protect the inner basin of the harbour. Thus, a functional height of 1 m can be estimated as a minimum value (Fig. 5, site 4).

5.2.6. Brijuni/Brioni (Hrvatska)

On Brijuni Island in Verige Bay (Val Catena) lies the archaeological area of a Roman "villa" with its harbour. The latter was active up to the late-Roman period and its breakwaters, quays and piers are all presently below sea level. Recent archaeological excavations mapped the shapes of the underwater structures and specified the period of use (Degrassi, 1957; Vrsalovič, 1979; Jurišić, 1998b; Schrunck and Begović, 2000; Matijašić, 2001a, b). We performed measurements of a pavement surface (previously interpreted as a pavement of a fish tank, as reported in Matijašić, 2001b) that we relate to a wide terrace of a "villa" which was built using large stone blocks. Its shape is rectangular and it is 12.5 m long and 5 m wide. In the middle of its eastern side, a set of steps following the natural slope of the seafloor reach the lower layer. Nowadays, the pavement surface is at −1.20 m (tide, wind and pressure corrected) and indicates a relative sea-level change of 1.80 m since its construction. Because of the depth (which is the same as the quay behind the piers) or because of the architectural typology and building technique, we cannot exclude that this may have been a thermal bath (no longer active) built along the coastline, with steps at its entrance. Additional measurements were made at one of the two piers that close the Bay of Verige. This pier's upper surface is currently located at −1 m (Fig. 5, site 6) and, for this site, a sea-level change of 1.60 m can be estimated.

5.3. Sardinia: geomorphological markers

5.3.1. Beach rock

Sea-level change data around the Sardinian coast were estimated through the use of radiocarbon-dated submerged beach rock (Demuro and Orrù, 1998). Current beach-rock cementation processes in Sardinia occur within the tidal zone (i.e. about ± 50 cm). In particular, in coastal areas of limited tide amplitude such as the Mediterranean region, beach-rock outcrops typically show thicknesses under 1 m (El Sayed, 1988). In this context, the deep beach-rock deposits surveyed in the Sardinian continental shelf represent an anomaly, as they lie at about 45–50 m below sea level up to the present coastline and display average thickness at 4–5 m (Ulzega et al., 1984). These features can

Table 3
Details of the Cagliari core data calibrated with Calib 5 (Stuiver et al., 2005)

A	Lab. number	Fossil species	Depth (m) (a.s.l)	[14]C Age (BP)	Calendar age 2σ (cal BP)
1	GX-30104-AMS	*Gasteropoda turriculata*	−3.20	520 + 50	216 + 100
2	GX-30099-AMS	*Gasteropoda turriculata*	−4.30	550 + 50	232 + 100
3	GX-30103-AMS	*Gasteropoda turriculata*	−5.70	2070 + 60	1951 + 120
4	GX-30098-AMS	*Cerithium vulgatum*	−7.80	4090 + 70	4129 + 130
5	GX-30097-AMS	*Hinia reticulata mamillata*	−14.90	6620 + 80	7030 + 150
6	GX-30101-AMS	*Cerithium vulgatum*	−16.80	6660 + 80	7132 + 130
7	GX-30096-AMS	*Cerithium vulgatum*	−19.20	6930 + 80	7420 + 150
8	GX-29076-AMS	*Cerithium vulgatum*	−22.50	6569 + 30	7084 + 50
9	GX-30100-AMS	*Hinia reticulata mamillata*	−25.20	7270 + 30	7770 + 140
10	GX-29077-AMS	*Hinia reticulata mamillata*	−30.56	9050 + 30	9730 + 120
11	GX-25487-AMS	*Tellina* sp.	−45.00	9950 + 80	10,835 + 170

AMS ^{14}C ages are from Geochron Labs (Cambridge, MA, USA). Site numbers in column A are also reported in Fig. 2.

be explained through the syn-sedimentary cementation processes associated with the Holocene transgression. These beach rocks consist of a series of overlain shorelines (Demuro and Orrù, 1998). The beach-rock facies have height uncertainties of between −5 and +1 m (Lambeck et al., 2004a). The near-shoreline beach rocks that occur in shallow sea water on the NE Sardinian coast are usually >1 m thick (Demuro and Orrù, 1998) (Table 2).

Several beach-rock formations occur near current sea level on the southern coast of Sardinia. Some of these, such as at Nora Bay in the Palmas Gulf, include small fragments of Roman terracotta remains. This suggests that these deposits formed as beach ridges originally deposited above mean sea level and were then submerged by rising relative sea level to be finally cemented in an intertidal environment (Kelletat, 2006).

5.3.2. Cagliari core

Three boreholes (A, B, C of Fig. 2) were drilled (Orrù et al., 2004) on the borders of the Santa Gilla Lagoon in the coastal plain of Cagliari (site 13 of Figs. 1 and 2). This area is a palaeovalley filled with marine deposits during the Holocene transgression. It therefore represents a good location for the sampling of the sedimentary series deposited during the Holocene sea-level rise. Outcrops of lagoonal marine deposits occur up to 3 m above m.s.l and contain fossils of *Cladocora coespicosa* that were U\Th dated to a MIS 5.5 age (Ulzega and Hearty, 1986). In other surrounding areas fossil marine deposits containing *Strombus bubonius* were also found in the fossil beach at about 3 m above present sea level, giving the age of MIS 5.5 and confirming the stability of the area (Hearty and Ulzega, 1986). Ten samples of gastropods were gathered from the borehole palaeo-lagoonal deposits and ^{14}C AMS dated providing the dating shown in Table 3 and Fig. 2.

5.3.3. Tidal notches

On the carbonate promontories located along the coast of Sardinia is a well-developed present day tidal notch (Orosei Gulf, Capo Caccia). In the Orosei Gulf, the present

Fig. 6. A well-developed tidal notch at Orosei Gulf, Sardinia, Italy.

day tidal notch is particularly wide (up to 1.8 m, Fig. 6) when compared to the one located at Capo Caccia or in other Sardinian carbonate cliffs (Antonioli et al., 2006). This is likely due to chemical dissolution aided by the action of mixed layers of salt and plain water, the latter coming from submarine springs, as described by Cigna et al. (2003). The significance of these observations are: (i) the larger width of the notches at Capo Caccia (Sardinia) is not due to the lack of vertical land isostatic movements as reported in Pirazzoli (2005), but instead due to the continuous action of the chemical dissolution of submarine springs (Cigna et al., 2003; Antonioli et al., 2006); (ii) in Sardinia, the signal of the isostatic vertical land movements is well recorded by the continuous vertical distribution of the submerged notches, as described in Antonioli et al. (2006).

5.4. Sardinia: archaeological markers

In Sardinia, archaeological sites were examined in St. Gilla, Nora and Capo Malfatano (southern Sardinia)

as well as in Capo Testa and Tharros (northern and western Sardinia, respectively). These sites provide useful archaeological indicators for reconstructing relative sea-level changes in the last three millennia (Fig. 1, Table 1).

5.4.1. Capo Testa

In Capo Testa we studied a large quarry excavated in granite and a preserved small pier nearby (Schmiedt, 1965). Both structures are of the Roman Age (Acquaro and Finzi, 1999; Acquaro et al., 1999).

The pier: In a protected bay stands a small pier about 15 m long and 3–8 m wide. Its top is at a mean elevation of −0.50 m below s.l (Table 1, Fig. 7, site 7). The pier served the nearby quarry and was probably used to move the excavated blocks of rock onto ships. A nearby breakwater, built from remnants of columns, is located between 1.0 and 3.0 m below mean sea level south of the pier. If the top of the pier had a functional height of ⩾0.70 m above mean sea level in order to provide adequate protection, a sea-level change of ∼1.21±0.23 m is estimated. This functional height was estimated from observations in other harbours and piers and cross-checked with other archaeological sites, as, for example, reported in Schmiedt (1965), Flemming and Webb (1986), Steffy (1990), Pomey (2003) and Lambeck et al. (2004b). The present elevation of the breakwater, which is a less accurate indicator, further supports this observation.

The quarry: The lower cuttings of the nearby quarry are submerged at −0.62 m below the present sea level (Table 1); this marker indicates a relative sea-level change of >0.85 m. However, based on the assumption that the quarries were carved (i) above water level (i.e. at a minimum elevation above the maximum tide level, which here is 0.45 m) because of the quarrying methods used to split the rock, and (ii) most likely at a minimal functional elevation of at least +0.30±0.30 m above maximum high tide so as to facilitate loading onto the steps. The latter value was also assumed on the basis of the relative elevation differences observed at Ventotene where a quarry, a harbour and a fish tank coexist, all dating to the Roman Age. Data from this site provide a very precise estimation of the relative elevation of the different markers with respect to the sea level at the time of their construction (Lambeck et al., 2004b). We thus obtain a lower limiting value of sea-level change for the Capo Testa quarry at 1.16±0.30 m at 2000±100 yr BP (Table 1, Fig. 7, site 7).

5.4.2. Tharros

At Tharros, the archaeological indicators are a Roman Age quarry (∼2.1–1.9 ka BP) and some tombs of Punic Age (∼2.5–2.2 ka BP) (Schmiedt 1965; Acquaro and Finzi, 1999), all excavated along an abrasion platform and now mostly submerged (Careddu, 1969; Usai and Pirisino, 1991). For this site there are no other significant preserved archaeological indicators, such as piers or fish tanks.

The quarry: The lowest cuttings of the quarry are at 0.50 m below mean sea level (−0.56 m corrected for tides

and pressure). From these, a relative sea-level change of at least >0.79 m can be estimated (−0.56 m is the present elevation of the lowest cutting and 0.23 m is the height of the maximum tide excursion, so as to place the quarry just above sea level during maximum tides). As in the case of the Capo Testa quarry, we assume a minimum functional elevation at +0.30±0.30 m above the maximum high tide. This value is based on the assumption that the quarry was carved (i) above water level (i.e. at a minimum elevation above the maximum tide level, which here is 0.45 m) because of the quarrying methods used to split the rock, and (ii) most likely at a minimal functional elevation of at least +0.30±0.30 m above maximum high tide so as to facilitate loading onto the steps. The latter value was also assumed on the basis of the relative elevation differences observed at Ventotene where a quarry, a harbour and a fish tank coexist, all dating to the Roman Age (Lambeck et al., 2004b). Thus, we obtain a lower limiting value of sea-level change at 1.11±0.30 m, which is in concordance with the observations from Capo Testa (Table 1, Fig. 7, site 8).

Tombs: The tombs, excavated above the abrasion platform, have tops at about 0.20 m below current mean sea level and elevation is >1 m above the nearby groundfloor. The latter is covered with a thick layer of sand and resembles a partially submerged breakwater. The present bottoms of the tombs are 0.76 m below mean sea level. Allowing for the present tide amplitude is in the region (0.45 m), the tombs indicate a relative sea-level change of at least >1 m. If we assume a minimum functional elevation of at least 0.30±0.30 m above the maximum high tides (values inferred from the cuttings of the nearby quarry, and compared with those from Capo Testa), we obtain an upper limiting value for this site, of 1.29±0.30 m (Table 1, Fig. 7, site 8), to keep the tomb dry.

5.4.3. Malfatano

Near Capo Malfatano (northwest of Nora and of the Phoenician emporium of Bithia, an important Punic settlement that later became a Roman civitas) lies a deep bay that is today partly filled with fluvial–deltaic silts and colluvial deposits. This site was previously identified with the Ptolemaic Portus Herculis (La Marmora, 1921; Barreca, 1965) and, more recently, with Bithia Portus (Mastino et al., 2005). Shards of Phoenician Age (2.7–2.6 ka BP) pottery, as well as the presence of fragments of Roman (∼2 ka BP), late-Roman (∼1.6 ka BP) and Medieval amphorae and a Phoenician–Punic (∼2.4 ka BP) bronze coin, were found during investigations (still in progress).

The entrance of the original bay was partially protected by two breakwaters and by two jetties that reduced the energy of the incoming waves and protected the inner bay. The latter are composed of blocks of differently sized metamorphic rock (up to 0.50 × 0.70 × 2 m). The top of the west jetty is 1.50 m (corrected) below mean sea level, while the whole structure is about 4 m high. The jetties are partially damaged and the top layer of blocks has slipped

downwards. Considering a maximum tide amplitude of 0.45 m, we estimate a functional height of 0.70 m above sea level at the time of their construction and a palaeo-sea level of -2.26 ± 0.23 m. Dating of the jetties—which are unique in Sardinia and on which no stratigraphic investigation has been performed—can reasonably be limited to the Punic and Roman environment (2.2 ± 0.2 ka BP), on the basis of the findings (Table 1, Fig. 7, site 9, and Fig. 10B).
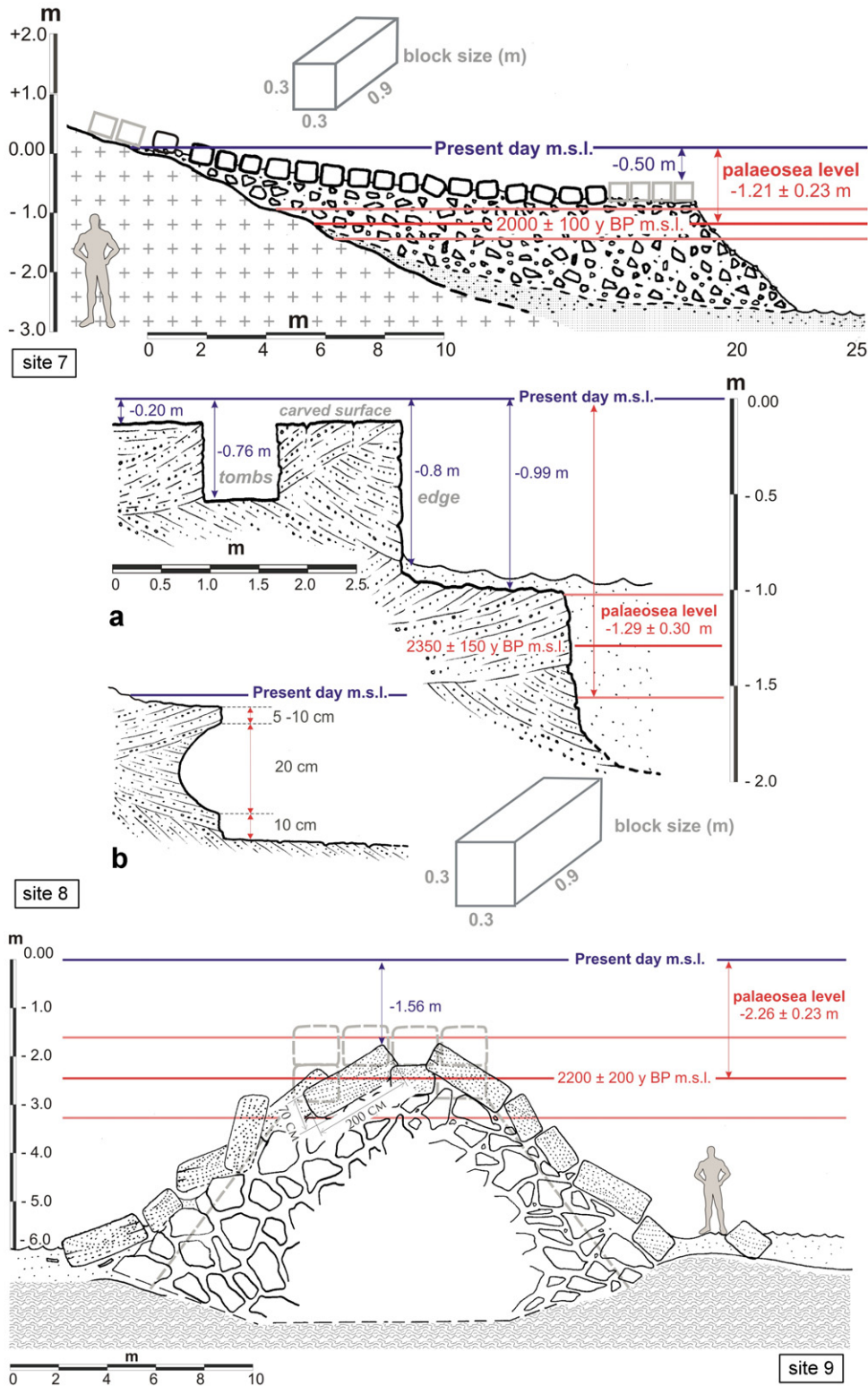

Fig. 7. Representative cross-sections of the archaeological sites located in Sardinia and their relationships with the current and past sea level. Site 7: Capo Testa, site 8: Tharros, site 9: Capo Malfatano, site 10: Nora, site 11: Perde Salis, site 12: Santa Gilla.
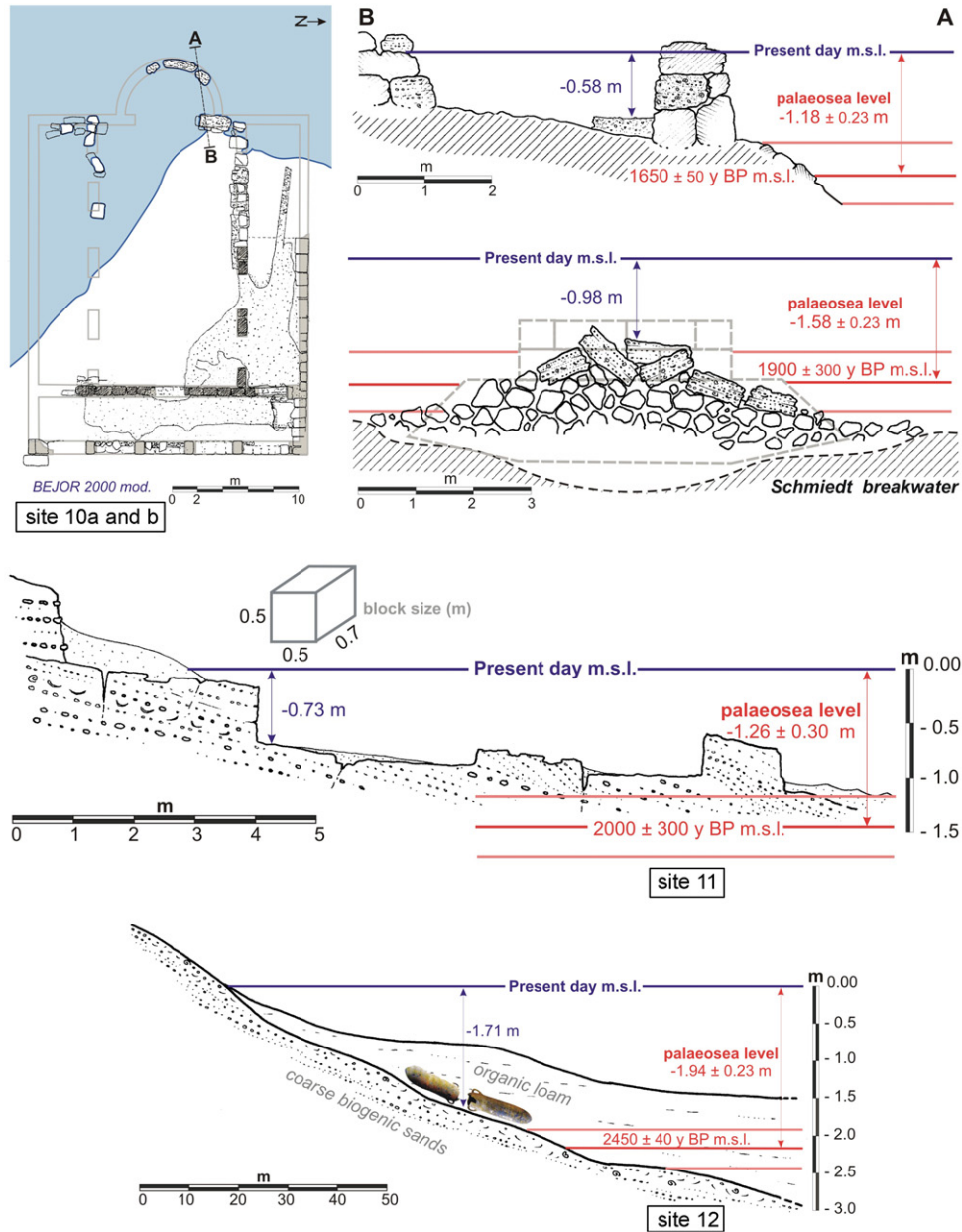
Fig. 7. (*Continued*)

5.4.4. Nora and Perd'e Sali

The ancient settlement of Nora is located close to the promontory of Capo di Pula (Bartoloni, 1979). Recent excavations show a long period of urban settlement with evidence from Phoenician Age (2.7–2.6 ka BP) to the Punic period (2.5–2.4 ka BP) (Bondì, 2000) and up to the late-Roman and Byzantine epochs (1.35 ka BP) (Colavitti and Tronchetti, 2000). Marine archaeological and geomorphological investigations (Solinas and Sanna, 2006) between Punta 'e su coloru and the beach of Águmu have identified a coastal lagoon bordered by a "fossil sandbar" (Ulzega and Hearty, 1986) of MIS 5.5 age and which forms the peninsula of Is Fradis Minoris. The latter has been excavated on both slopes (Finocchi, 2000). Here, an underwater archaeological structure occurs at a depth of 0.100 m (−0.98 m tide and pressure corrected, Fig. 7, site 10). This structure is known as the Schmiedt jetty (Schmiedt, 1965) and is composed of Tyrrhenian sandstone blocks. It has been interpreted as connected to the so-called house of the tetrastyle atrium, although they are separated from each other by about 80 m. The structure runs parallel to the coast and was built in front of the baths at the sea and the Christian basilica. The latter, constructed on buildings abandoned around 1.65 ± 5 ka BP, has an extension of 33 m in length and a width of 22 m (Bejor, 2000). Its architectural features show three naves ending with an apse

that is now at −0.58 m (corrected). Still visible and partially outcropping are the remains of the foundations. The ca 0.10 m thick beaten shard pavement still lies over a well-formed embankment (Fig. 7, site 10, and Fig. 10E).

In contrast to the other two inlets, in which Phoenician and Punic amphorae occur (Cassien, 1981, 1982, 1984; Chessa, 1988), in the western one only Roman (prevalently imperial) or modern materials have been brought to light. These remains do not appear in association with shipwrecks but are deposits from berthing and traffic activity. On the available evidence we cautiously limit the dating of the Schmiedt jetty, as well as that of the exploitation of the Is Fradis Minoris peninsula to a period not before the Roman epoch (1.9 ± 0.2 ka BP). The same cultural and chronological attribution can be also estimated for the quarry located in the site known as Perd'e Sali, not far from the inhabited area of Nora and along a coast where the remains of Roman villas were found. The open quarry, largely submerged at −0.73 m (corrected), still clearly shows the cuttings left by carvers and the parallelepiped blocks of different sizes, all multiples of the Roman foot (0.30 m) (Table 1, Fig. 7, site 11). At molo Schmiedt we apply a minimum functional height at 60 cm above mean sea level, obtaining a relative sea-level change of −1.58 ± 0.23 m since its formation. For the basilica, our estimations are > −1.18 ± 0.23 m using the same functional height of 0.60 m (the lower pavement of the basilica must be safely above the maximum high tide). Finally, for the Perd'e Sali quarry, we estimate a value > −0.96 m but applying the same assumption used for Capo Testa and Tharros. We obtain a −1.26 ± 0.30 m relative sea-level change for this marker assuming a minimum functional elevation of +0.30 ± 0.30 m above the maximum high tide (Fig. 7, site 11, and Fig. 10F).

5.4.5. Santa Gilla Lagoon

The eastern banks of the Santa Gilla Lagoon, once hosting the site of the Punic settlement of Karali (Nieddu, 1988; Stiglitz, 2002), are today hidden by the suburbs of the town of Cagliari. Many objects of Phoenician and Punic Age—such as terracotta statues and amphorae—have been found in the settlement's warehouses (Spano, 1869; Vivanet, 1892, 1893).

During recent underwater explorations near the Cala Moguru inlet we found trading amphorae, of Punic manufacture, that are comparable to types Bartoloni D4, D6 (T-1.4.4.1.) and Bartoloni D7 (Bartoloni, 1988; Ramon Torres, 1995), dated between the fifth and fourth centuries BC (2.5–2.4 ka BP). All the artefacts were found on a layer of shells under 1 m of mud (an average 1.71 m below corrected mean sea level) which preserved the contents of the unbroken items (Solinas, 1997). We took a Bartoloni D4/T-1.4.4.1 amphora, found on 1991/08/08 in canal F (the area closest to the NE bank) as an indicative sample, being remained in its original position as evidenced by stratigraphy.

A rise in relative sea-level variation of −1.94 ± 0.23 m can be estimated for this site. The dating evidence

(2.45 ± 0.4 BP; Solinas and Orrù, 2006) allows us to hypothesize the environmental features of the site: a beach emerging from the gently sloping lagoon bottom (elevation 0 ± 1 m), suitable for the approach and beaching of small sized crafts with shallow draught (Fig. 7, site 12).

6. The isostatic model

The theory used here for describing the glacio–hydro-isostatic process has been previously discussed (Lambeck et al., 2003) and its applications to the Mediterranean region have been most recently discussed in Lambeck et al. (2004a, b) and Lambeck and Purcell (2005). The input parameters into these models are the ice models from the time of the Last Interglacial to the present and the earth rheology parameters. These are established by calibrating the model against sea-level data from tectonically stable regions and from regions that are sensitive to particular subsets of the sought parameters: data from Scandinavia to constrain the northern European and Eurasian ice models (Lambeck et al., 1998, 2006), a re-evaluation of the North American data for improved Laurentide ice models (Lambeck et al., unpublished) and data from far-field sites to improve the ice-volume esl function (Lambeck et al., 2002). Iterative procedures are used in which far-field data are used to establish the global changes in ice volume and mantle rheology and near-field data are used to constrain the local ice sheets and mantle rheology. The procedure is then iterated again, using the near-field derived ice models to improve the isostatic corrections for the far-field analysis. The Mediterranean data, being from the inter-mediate field, have been previously included in this analysis mainly to establish constraints on regional mantle parameters and the eustatic sea-level function (Lambeck et al., 2002) and on rates of tectonic vertical movements (Lambeck, 1995; Antonioli et al., 2006).

In this paper we have used the most recent iteration results for the ice models (Lambeck et al., 2006) which include improved ice models for the three major ice sheets of Europe, North America, Antarctica and Greenland back to the penultimate Interglacial, as well as mountain glaciation models including the Alps (Lambeck and Purcell, 2005). This last addition impacts primarily on the sea-level predictions for northern Italy and Slovenia. The time-integrated ice volumes are consistent with the ice-volume esl function previously established (Lambeck, 2002; Lambeck et al., 2002). The Italian data discussed in Lambeck et al. (2004a) have not been used in arriving at the new model parameters.

The adopted earth-model parameters are those that have provided a consistent description of the sea-level data for the Mediterranean region. The Mediterranean data alone have so far not yet yielded solutions in which a complete separation of earth-model parameters has been possible, nor in which these parameters can be separated fully from eustatic or ice-model unknowns. However, the combination used here provides a set of very effective interpolation

parameters that describe well the observational data and that allow for an effective separation of tectonic and isostatic–eustatic contributions to sea level. Also, the eustatic parameters determined from the Mediterranean region are consistent with those obtained from other regions of the world (Lambeck, 2002). The solutions indicate that three-layer rheological models largely suffice for the region: an effective elastic lithosphere with thickness ~65 km, an upper mantle from the base of this lithosphere to the 670 km seismic discontinuity with an effective viscosity of 3×10^{20} Pa s and a lower mantle with an

average effective viscosity of $\sim 10^{22}$ Pa s (earth model m-3) (see also Lambeck et al., 2004a).

Fig. 8A illustrates the comparison of predicted and observed data for the ENEA core from the Versilia Plain (Antonioli et al., 1999) for both the earlier and the present ice-model information and for earth model m-3. The new parameters, despite the Italian data not having been used, yield better agreement with the observations than before: the terrestrial indicators lie on or above the prediction, the marine indicators lie mostly below the expected results and the transitional data points are also close to predicted
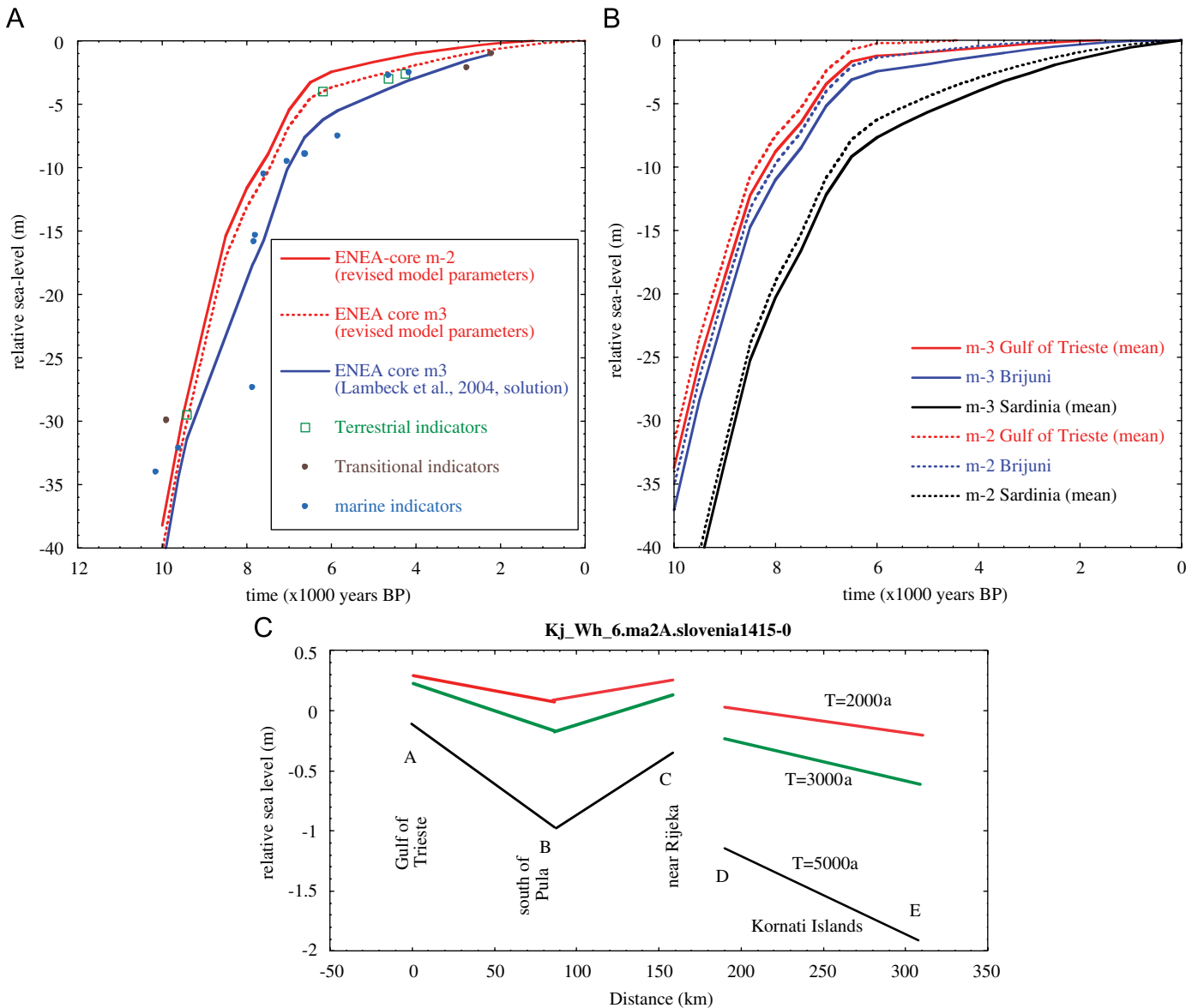
Fig. 8. (A) Model predictions and observations for the ENEA core site on the Versilia Plain, Italy. The two red curves are based on the revised model parameters used in this paper and the blue function is for the Lambeck et al. (2004a) parameters. The solid lines are for the earth model m-3 and the dashed line is for model m-2. The observational data are from Lambeck et al. (2004a). The terrestrial indicators should lie above the predicted mean sea levels, the marine indicators should lie below the predicted values and the transitional data points should lie between these two limiting values. Error bars are not shown. (B) Model predictions for the mean Sardinia location, for the mean Gulf of Trieste location and for Brijuni (Croatia). The solid lines are for the model m-3 and the dashed lines are for m-2. (C) Model predictions for sea level at three epochs before present along the Adriatic coast from Savudrija at the southern end of the Gulf of Trieste, to the southern end of Istria (south of Pula) and on to Rijeka, and also along the Kornati Islands from Losinj to Zirje; see also Fig. 3 for location.

function. Of the earth-model parameters, the parameter most sensitive to the predictions is the upper mantle viscosity and this is also illustrated in Fig. 8A for model m-2 for which the effective upper mantle viscosity is 2×10^{20} Pa s and the other parameters are unchanged. These comparisons indicate some of the trade-offs between parameters that occur. Model m-3 with the new ice model leads to very similar results as model m-2 with the old ice parameters. However, the old ice model is less consistent with the sea-level data from North America than the new model and we adopt the former here.

The predictions for the Sardinia locations are all very similar with differences not exceeding 0.2 m during the past 7000 yr. Thus, for these locations it is permissible to project all data points onto a single sea-level curve. The Sardinia predictions are characteristic of the sea-level rise in most parts of the Mediterranean: an initially rapid rise as eustasy dominates isostasy, but after ∼6500 yr, a much slower rate of increase as isostasy dominates eustasy right up to the present time. The rates of rise are dependent on the rheology as is illustrated for the comparison of the two model results m-2 and m-3 with a difference of ∼1.5 m at 7000 yr BP.

For the sites within the Gulf of Trieste (Slovenia) the predictions are also very similar for the individual sites and the observations can be combined into a single sea-level function within the gulf. At these sites the hydro-isostatic signal is greater than it is in Sardinia because of the coastal geometry and the alpine glaciation signal (cf. Lambeck and Purcell, 2005) and as a consequence the predicted sea levels for recent millennia lie significantly closer to present sea level than do the Sardinia levels at comparable times (Fig. 8B) and for the model m-3 sea levels are predicted to approach the present level at about 6000 yr ago. Differences in predictions for the two earth models are about the same as for Sardinia.

Beyond the Gulf of Trieste, geographic variability in sea level becomes more significant and observations from Brijuni lie up to 2 m lower than the first group because of the coastal geometry and alpine glaciation effects. This is further illustrated in Figs. 8C, D in which the predicted shoreline elevations and gradients are shown for three coastal sections: along the western and inner coasts of Istria and along the Kornati Islands (see Fig. 3 for locations). The predicted gradients for the two earth models m-2 and m-3 are similar over these distances and the major rheological dependence is shown through the elevations. Between the southern side of the Gulf of Trieste to the southern end of Istria, a shoreline that formed at 2000 yr BP would slope from north to south at about 0.3 m/100 km and one along the Kornica Islands would be predicted to slope at ∼0.2 m/100 km.

7. Discussion

As discussed above the sea-level response to the Last Glacial cycle is not expected to follow a eustatic function but will vary geographically across the Mediterranean and this is seen also between the two localities examined in this paper (Fig. 8B). Any tectonic responses will accentuate this spatial variability. Thus, whether the observational evidence for sea-level change is used for establishing a reference surface for estimating quantitative rates of vertical motion, for estimating eustatic change, or for evaluating the glacio–hydro-isostatic parameters, consideration must be given to all contributions.

We have used here the Last Interglacial shoreline (MIS 5.5, defined by fossil data, tidal notches, terraces, etc.) as an indicator of tectonic stability (Ferranti et al., 2006). From this, as well as from an absence of active seismogenic structures (Valensise and Pantosti, 2001), a general absence of instrumental (Chiarabba et al., 2005) and historical (Guidoboni et al., 1994) seismicity (Wells and Coppersmith, 1994) and not significant horizontal deformation detected from space geodetic measurements (Serpelloni et al., 2005), we deduce that Sardinia has remained relatively stable on the time scale of recent glacial cycles. Thus, sea-level data from Sardinia should primarily reflect eustatic and glacial–isostatic processes, where the latter includes all the effects associated with global ice sheet evolution during the Last Glacial cycle. Thus, these data has been used to calibrate the isostatic model previously developed for the Mediterranean Sea and the results are consistent with conclusions drawn from other tectonically stable areas in Italy.

In contrast to Sardinia, the NE Adriatic coast is a subsiding environment although for the Istria and southern Croatia coast the elevation of the MIS 5.5 shoreline is still unknown and long-term vertical tectonic rates have not yet been established. But this is an area with both historically and instrumentally recorded seismicity (Guidoboni et al., 1994; Chiarabba et al., 2005) and one of horizontal deformation as measured by space geodetic methods (D'Agostino et al., 2005; Serpelloni et al., 2005). The two regions chosen here are therefore likely to have different sea-level variations and we will use the Sardinia data to verify or calibrate the eustatic and isostatic models and then use the Adriatic data to estimate rates of vertical movement.

Figs. 9A, B compare the observed and predicted sea levels for Sardinia where the predictions are for the "mean" site and for the two earth models m-2 and m-3. The archaeological data from all sites is in excellent agreement with the model m-3 which is also the preferred model for the Versilia Plain (north of Livorno) data (Fig. 8A). This latter agreement is particularly useful because the isostatic signals are different at the two locations due to different coastal geometries (thus different hydro-isostatic signals) and due to different distances from the former ice sheets (thus different glacio-isostatic contributions) (see Lambeck and Purcell, 2005, Figures 1 and 2). Therefore, the assumption of tectonic stability for at least the past 3000 yr appears to be valid and the isostatic–eustatic model describes well the relative sea-level change in Sardinia from
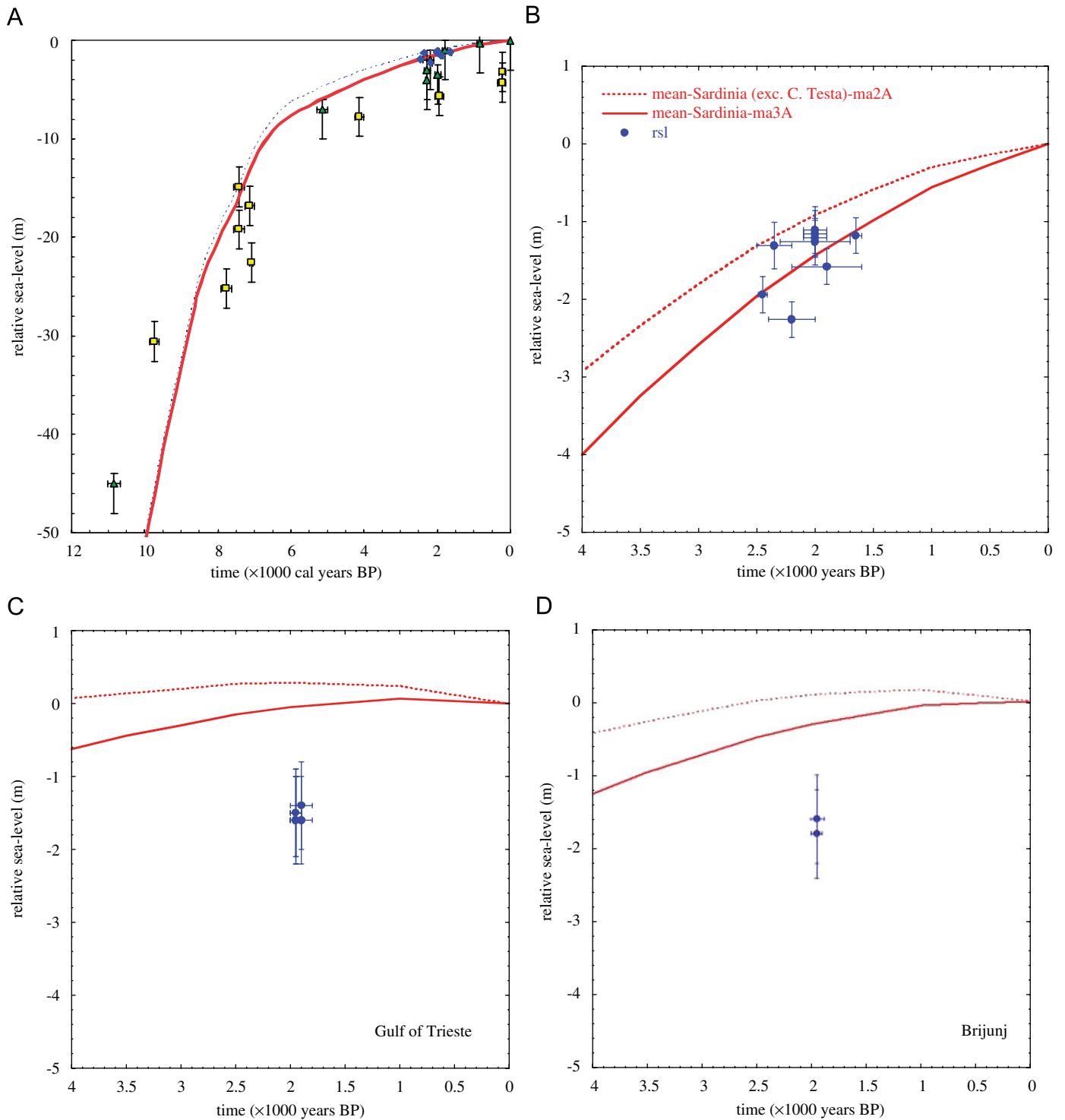
Fig. 9. (A) Comparison of predicted model results with observational evidence for Sardinia. Because the spatial variability for the data sites is small in this case all data have been projected onto a single sea-level curve corresponding to the mean location. Square: core, triangles: beach rock, dot: archaeological remains. Dashed curve corresponds to model m-2 and solid curve to model m-3. (B) Same as Fig. 8A but on expanded scale. (C) Same as (A) but for the Gulf of Trieste sites where the prediction is for the mean location. (D) Same as (C) but for the Brijuni location.

the interval 2500–1600 yr BP to the present as well as the differences in sea level observed between Sardinia and the Versilia Plain site. The model predictions are also consistent with the beach-rock observations although at

the time of the archaeological data they lie 2–3 m lower (but within our assumed range, see above), suggesting that they formed a few metres below mean sea level. The Cagliari core data lie, with one exception, below the

predicted values, which is consistent with these data being from lagoonal deposits, and therefore affected by compaction. For the late Holocene the core estimates lie below both the archaeological data points and the beach-rock estimates, confirming that the core samples yield mainly lower limits to past sea level. Together, the Sardinia and Versilia data sets, both from areas of relative tectonic stability, are well represented by the glacio–hydro-isostatic models presented here.

Recently, Pirazzoli (2005) suggested that the Lambeck et al. (2004a) model predictions overestimated the glacio-isostatic contribution sea-level change in Sardinia and that unpublished model predictions by W.R. Peltier overestimate the hydro-isostatic contribution, although he gives no reasons, or a break-down of the model predictions into its components, to justify these specific attributions to one component or another since both models would predict the combined effect. He concludes that the field evidence indicates that "submergence has been almost negligible during the last two millennia, apart from the sea-level rise of 10–15 cm reported by tide gauges during the last century (Pirazzoli, 1996). He also states that "on the Sardinia coasts, generally recognized as tectonically stable, data on recent sea-level changes are scarce and sometimes contradictory" but he does not discuss the evidence from either the beach rock (Demuro and Orrù, 1998) or the core data from the Cagliari coastal plain (Orrù et al., 2004). The new archaeological data from Sardinia are consistent with the beach rock and core data in that they indicate a rise in sea level of about 1.5 m in the past 2000 yr as predicted by the eustatic–isostatic model of Lambeck et al. (2004a) as well as the present model and show that it is unwise to draw conclusions based on "scarce" and "contradictory" data.

Figs. 9C, D illustrate the comparisons of observations and predictions for the evidence from the Gulf of Trieste (Fig. 9C) and from Brijuni (Fig. 9D). At both locations the predictions lie above the observed values, irrespective of whether earth-model m-2 or m-3 is used and this is consistent with a regional subsidence. The Gulf of Trieste data points are self-consistent suggesting that the entire southern side of the gulf has subsided by the same amount, between 1.4 and 1.6 m over 2000 yr, depending on the choice of earth model. Likewise, the two data points from Brijuni are self-consistent and point to a comparable subsidence, of 1.4–1.7 m during the past 2000 yr. The average sea-level estimates for the two localities are −1.53±0.08 and −1.70±0.10 for the Gulf of Trieste and Brijuni, respectively, and the difference, while statistically not significant, is consistent with the predicted gradient along the coast of Istria.

As previously noted, tectonic subsidence along the NE Adriatic coast can be anticipated from the absence of deposits or morphological expressions of the MIS 5.5 level above present sea level. The late Holocene data points alone do not permit a distinction to be made between coseismic displacement and uniform subsidence.

The model predictions indicate that, in the absence of tectonics, sea level has been close to its present level, and possibly marginally higher, for a prolonged period (Figs. 8C, D) and the absence of the present tidal notch as noted in areas of falling relative sea level (relative uplift) (Kershaw and Antonioli, 2004) here indicates that the recent relative change has been one of rising sea level. This lends support to the model m-3. West of the Gulf of Trieste from Venice, Tagliamento and Grado Plains, earlier estimates indicate that here the subsidence rates have been greater at between 0.7 and 0.3 mm/a (Lambeck et al., 2004a).

The submerged notch widely reported from the Gulf of Trieste as far south as Montenegro (Pirazzoli, 1980; Benac et al., 2004) occurs at a depth of about 0.6 m in both the eastern portion Gulf of Trieste and along the Istria coast, reaching 0.85 m at Brijuni. For both earth models, there is a prolonged period when sea level is predicted to have been close or slightly above the present sea level (Figs. 9C, D) and in which notches could have been carved into the limestone coast only to be subsequently displaced by coseismic events of sufficient amplitude to displace the notch below the tidal range. Thus, the notch itself is postulated to be the result of the eustatic–isostatic balance in sea level while its current position is an indication of coseimic activity having occurred after notch development and after the formation of the deeper sea-level markers at 2000 yr BP. If model m-2 is appropriate then the notch formation would have started as early as 4000 yr ago in the Gulf of Trieste and the absence of a notch below the 2000 yr marker lends support to the model m-3 in which sea level did not reach its present level until later (Figs. 9C, D). The absence of any trace of a modern notch suggests that the coseismic event was relatively recent and that sea level has continued to rise into recent time unless notch formation is influenced by surface water conditions (salinity, temperature, pH) in which case it would mean that these conditions have changed over the past 2000 yr. It has been postulated that a major displacement occurred as a fourth–sixth century paroxysmic seismic event (Pirazzoli, 1996; Stiros, 2001; Benac et al., 2004) but this hypothesis cannot be validated by the present data as the historical catalogues (Boschi et al., 1995) do not extend into this region.

Recent measurements of limestone erosion–dissolution rates in the intertidal zone have shown that along the northern Adriatic coast they are approximately 0.2 mm/a compared with 0.02 mm/a at measurement sites in the Trieste Classical Karst (Inner Karst) (Furlani and Cucchi, 2006).

The new data from the Adriatic and Sardinian regions provide further evidence for the complexity of sea-level change across the central Mediterranean region and they contribute to the understanding of this change by making it possible to separate out the two principal processes: the isostatic–eustatic changes associated with the deglaciation of the last great ice sheets and tectonic changes associated

with the African–Eurasian collision. For Sardinia it is primarily due to the first process while for the Adriatic tectonics have been the major contributor over the past 2000 yr. In particular, the Adriatic coasts of Croatia and Italy have subsided by ~1.5–1.6 m since Roman times at an average rate of ~0.75 mm/a. (Fig. 10).
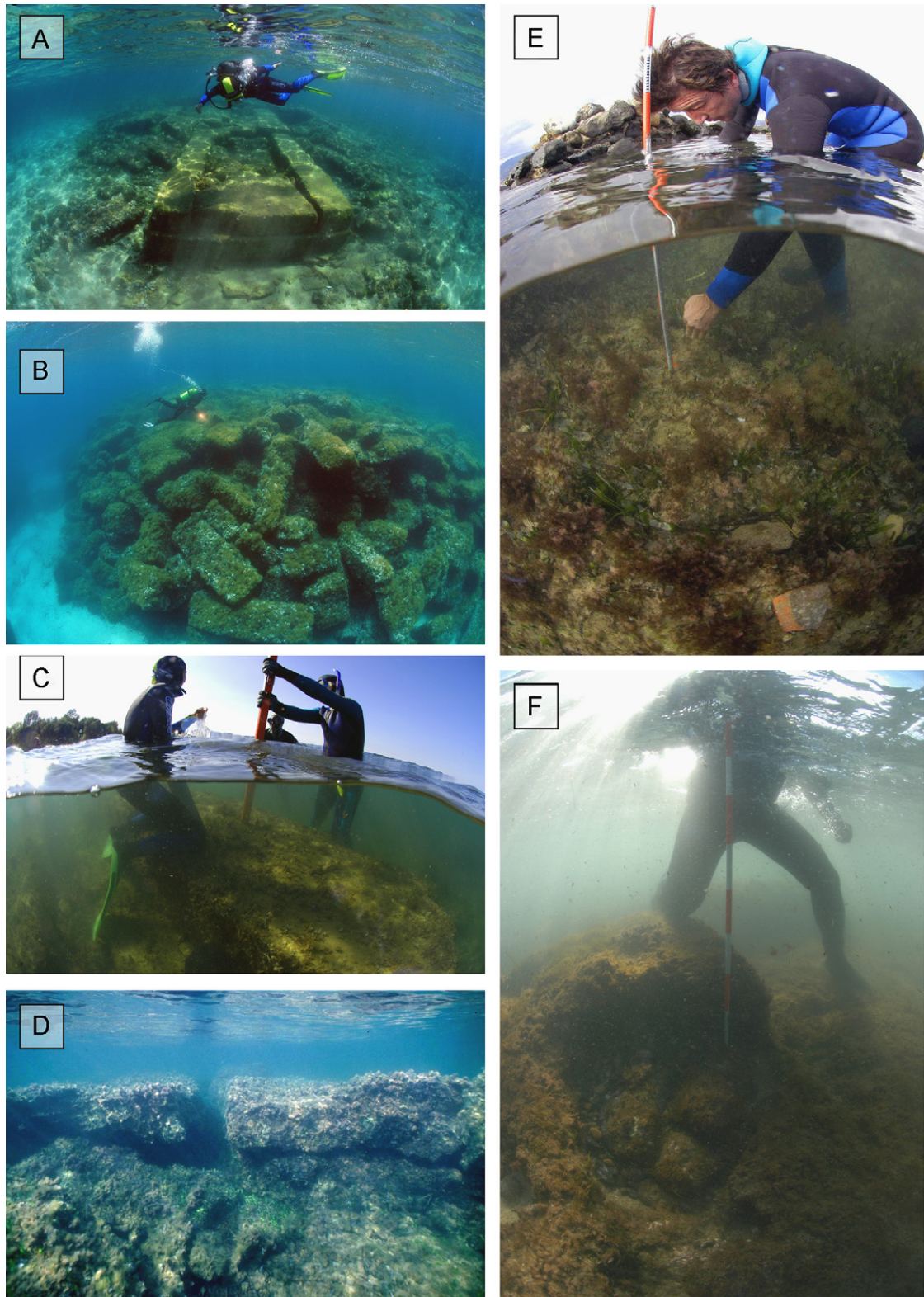

Fig. 10. Photographs of the sites described in this paper. (A) The Punta Sottile pier, site 2 of Table 1. (B) The Capo Malfatano breakwater dock, site 9 of Table 1. (C) Measuring the Salvore pier, site 5b of Table 1. (D) The pier "molo Schmiedt" at Nora, site 10a of Table 1. (E) Measuring the Nora Basilica pavement, site 10b of Table 1. (F) Measuring the Perd'e Sali quarry, site 11 of Table 1.

8. Conclusion

Our data provide new estimate of the relative sea-level change and vertical land movements in two crucial tectonic areas of the Mediterranean basin, based on archaeological, geomorphological data as well as geophysical data and model. In the tectonically stable Sardinia our observations are consistent with the isostatic model (Lambeck, et al., 2006), while in the northern Adriatic coast, the misfit between the data and the used model can be attributed to active tectonics intervening during the last ~2000 yr. Results show that during the past ~2400 yr, a relative sea-level change has occurred at up to -1.98 ± 0.23 m in Sardinia and up to -2.08 ± 0.60 m since 1900 ± 100 yr BP in northern Adriatic. In Sardinia, the observed changes are largely isostatic/eustatic and occurred without any tectonic contribution, while in the Adriatic region, changes include a vertical tectonic signal at a rate of ~0.75 mm/a occurring in the last two millennia, which produced a significant downward displacement of the coastline of ~1.5–1.6 m.

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Recent coastal tectonic movements along the NE Adriatic coast and comparison between long (geological) and short term (instrumental) relative sea level data

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A. Amorosi Bologna University
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Tectonic movements
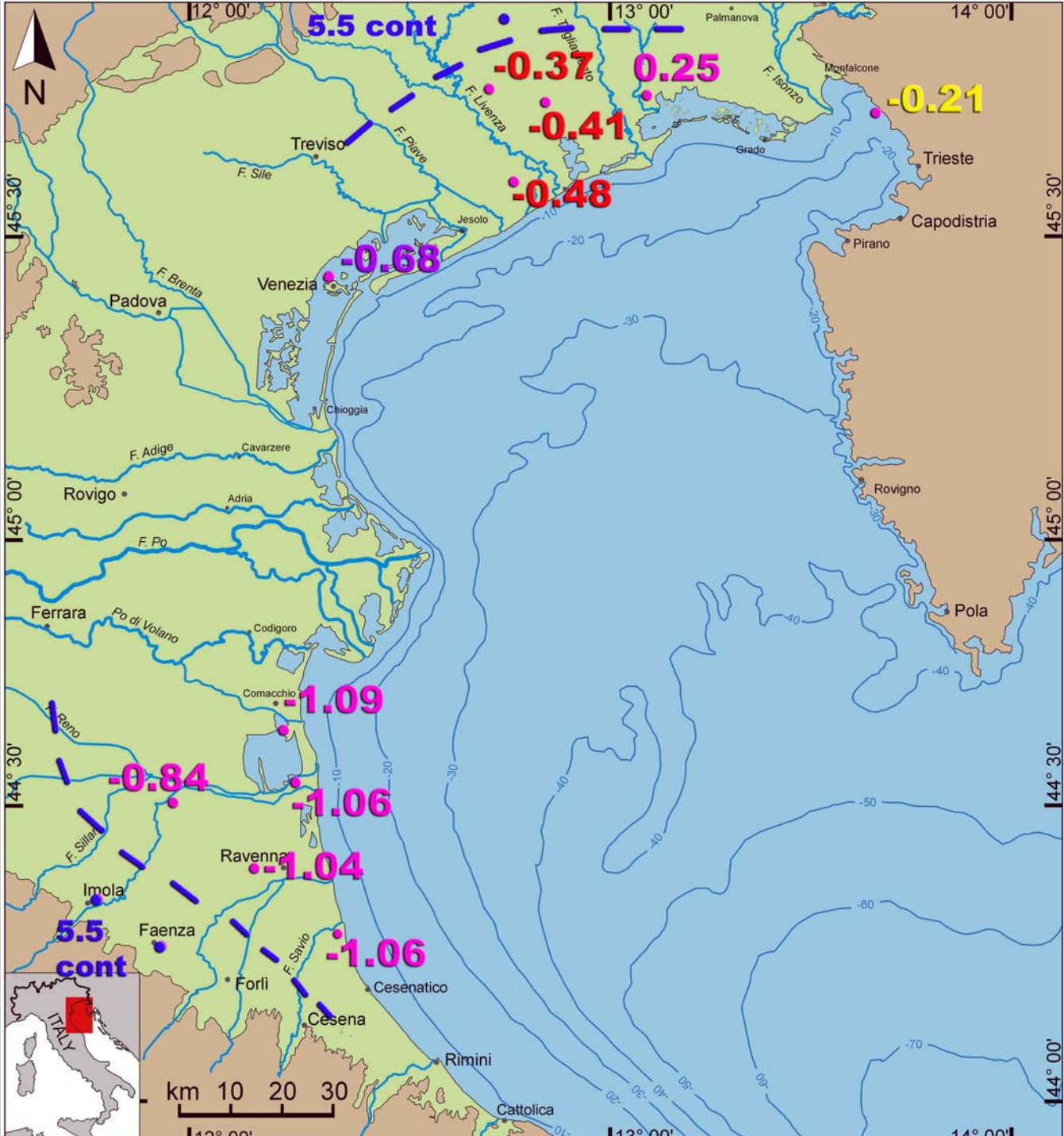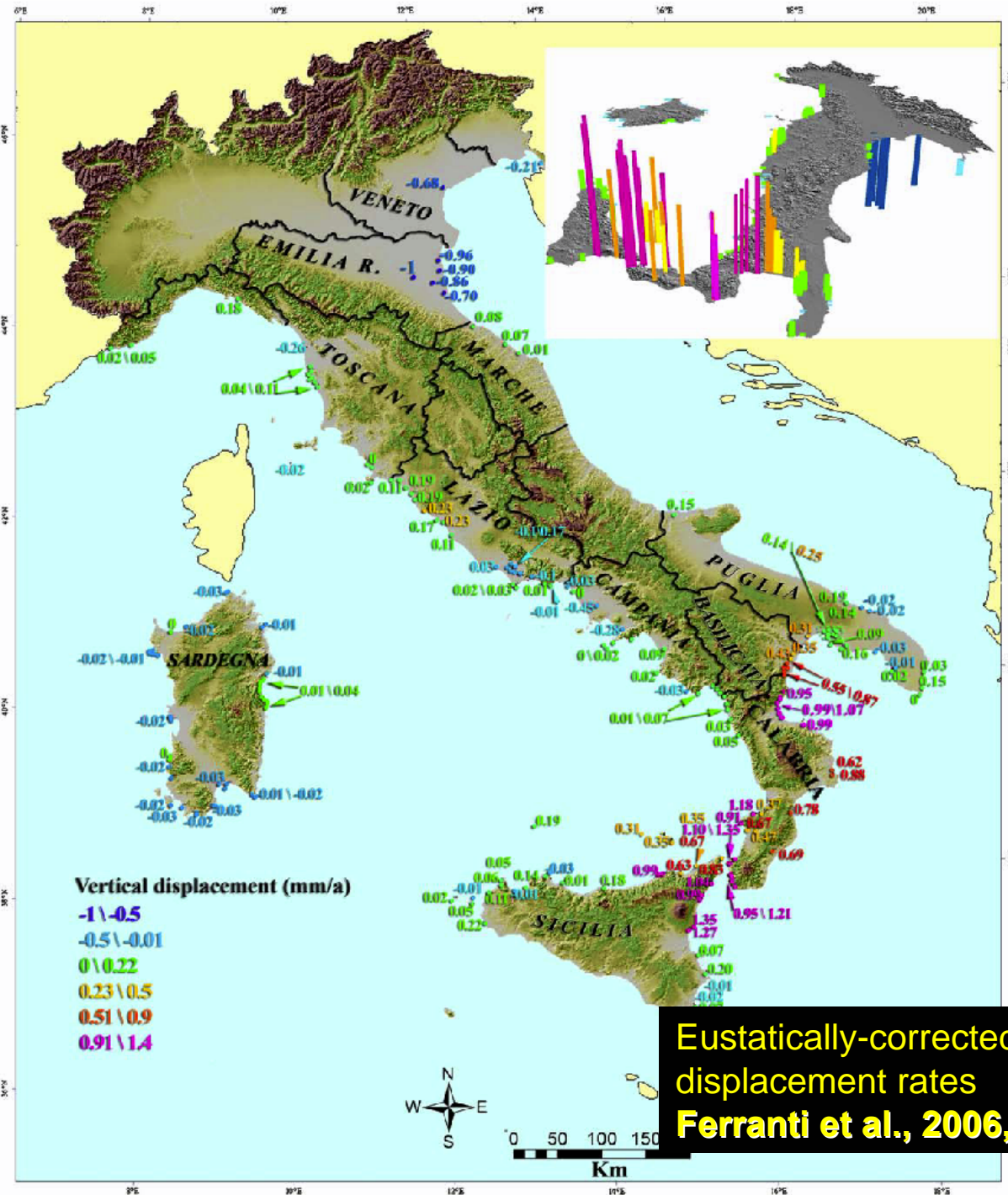
No tidal notch

down-dropped Late Holocene tidal notches, Trieste

MIS 5.5
Last interglacial 125 ka

Vertical displacement (mm/a)
-1 \ -0.5
-0.5 \ -0.01
0 \ 0.22
0.23 \ 0.5
0.51 \ 0.9
0.91 \ 1.4

Eustatically-corrected tectonic displacement rates
Ferranti et al., 2006, Quat Int

HOLOCENE

Antonioli et al 2007 QSR
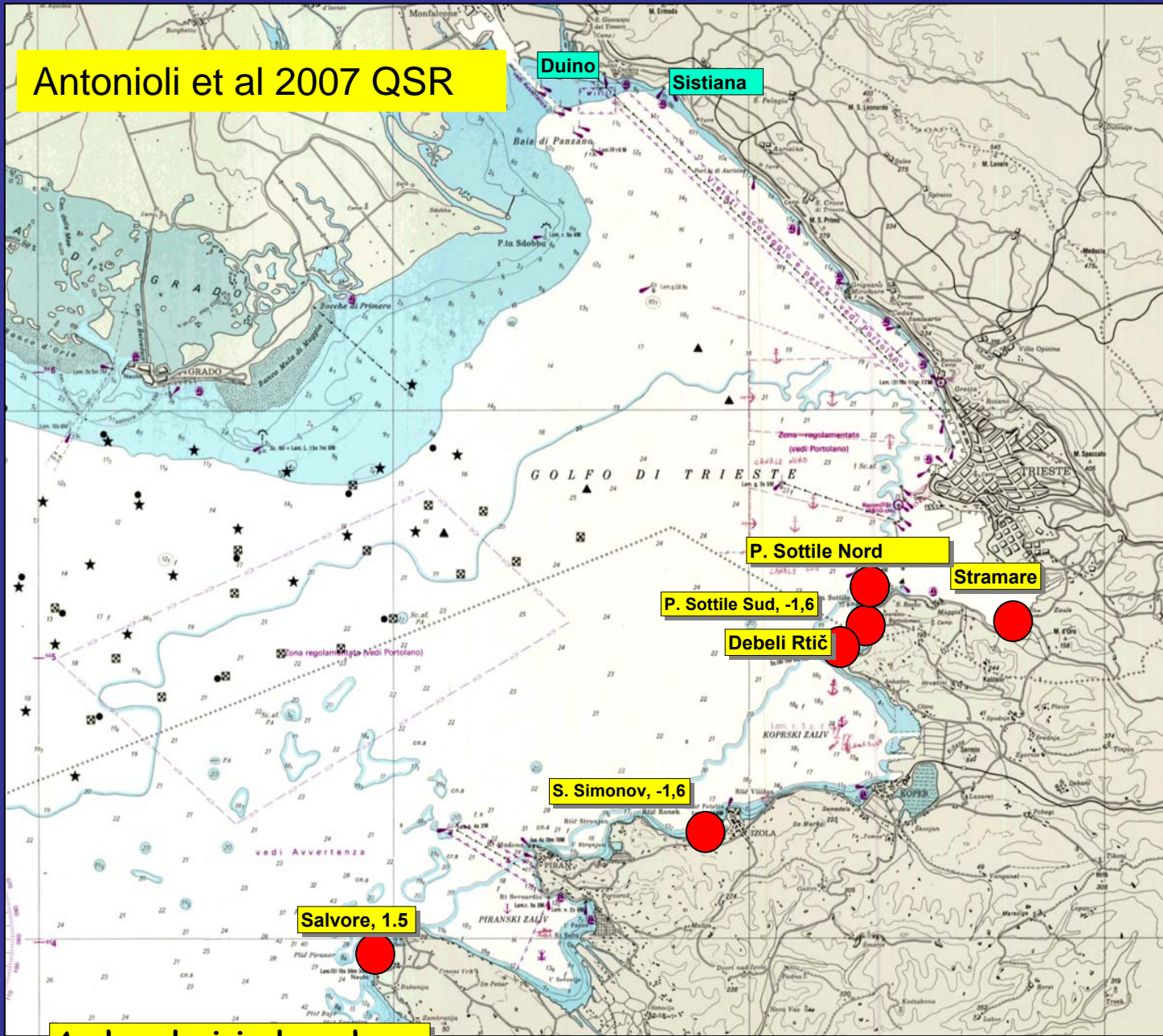
Duino

Sistiana

P. Sottile Nord

Stramare

P. Sottile Sud, -1,6

Debeli Rtič

S. Simonov, -1,6

Salvore, 1.5

Archaeologicical markers

m	
0.00	Present day m.s.l.
	-1.40 m palaeosea level
	-1.60 ± 0.6 m
- 1.0	
	1950 ± 50 y BP m.s.l.
- 2.0	

m

0   2   4   6   8   10
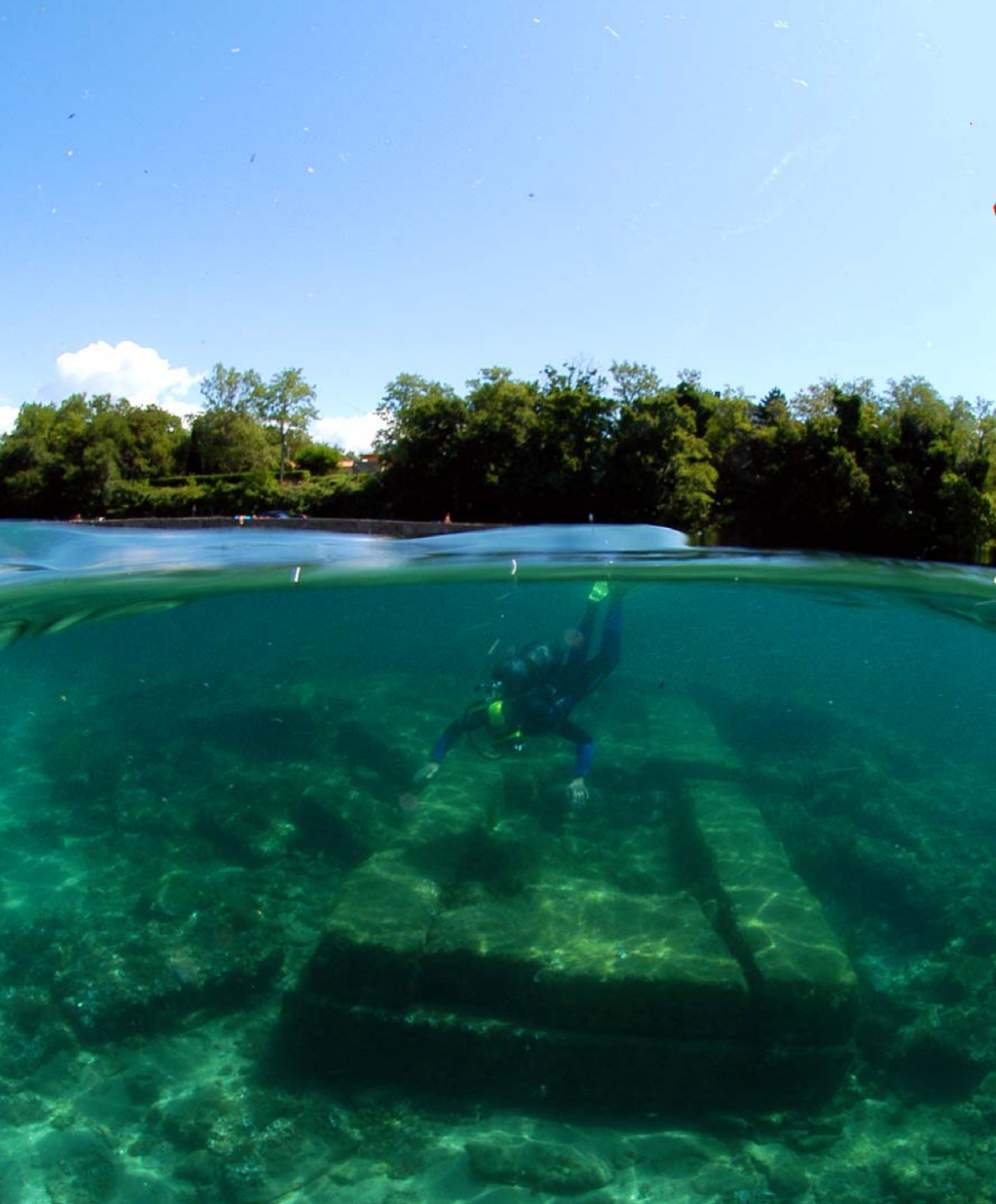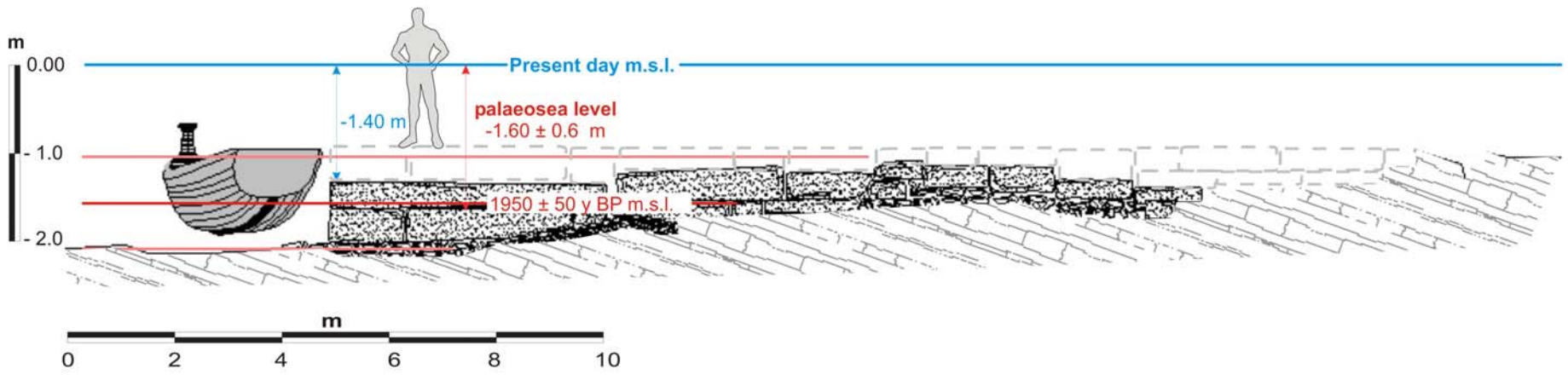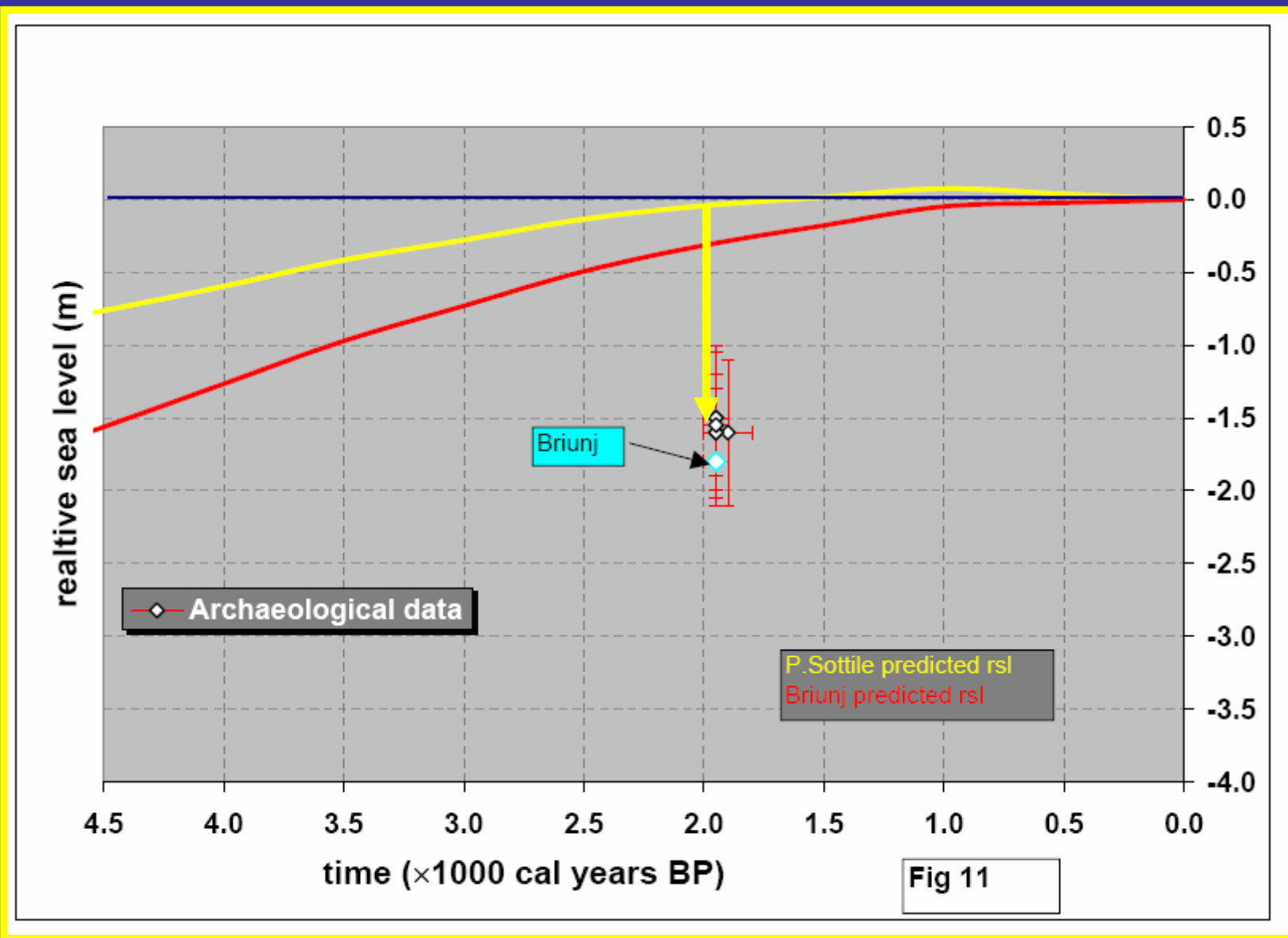
Antonioli et al 2007 QSR

Core used for CARG by Bondesan, Fontana et al.,
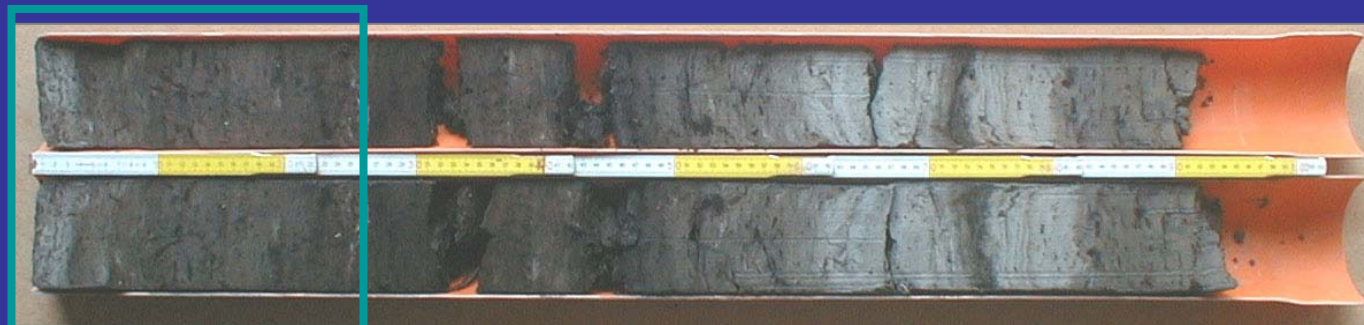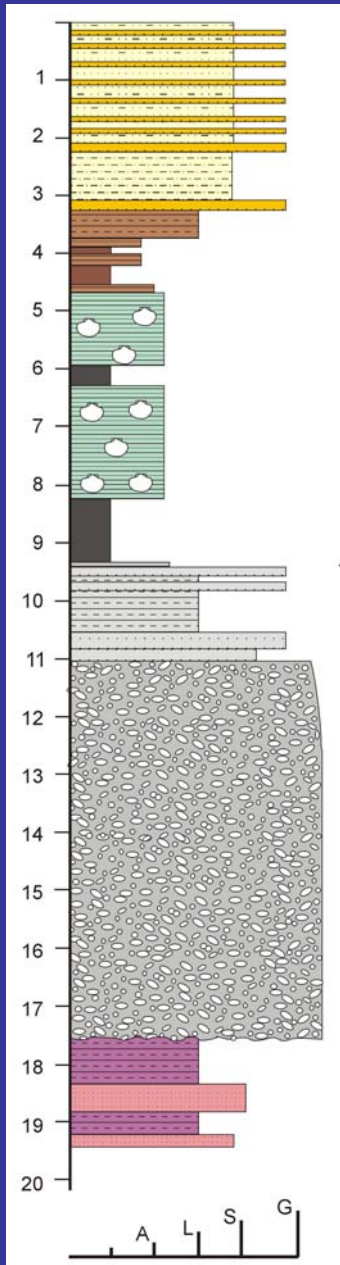
ANALISI
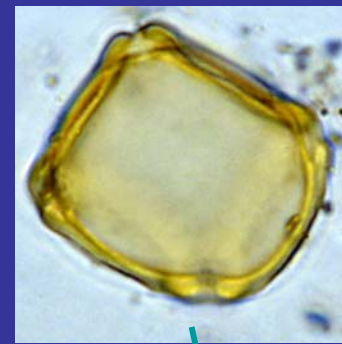
Microfossili marini

Molluschi marini

Molluschi

Pollini e resti

^{14}C

Datazioni
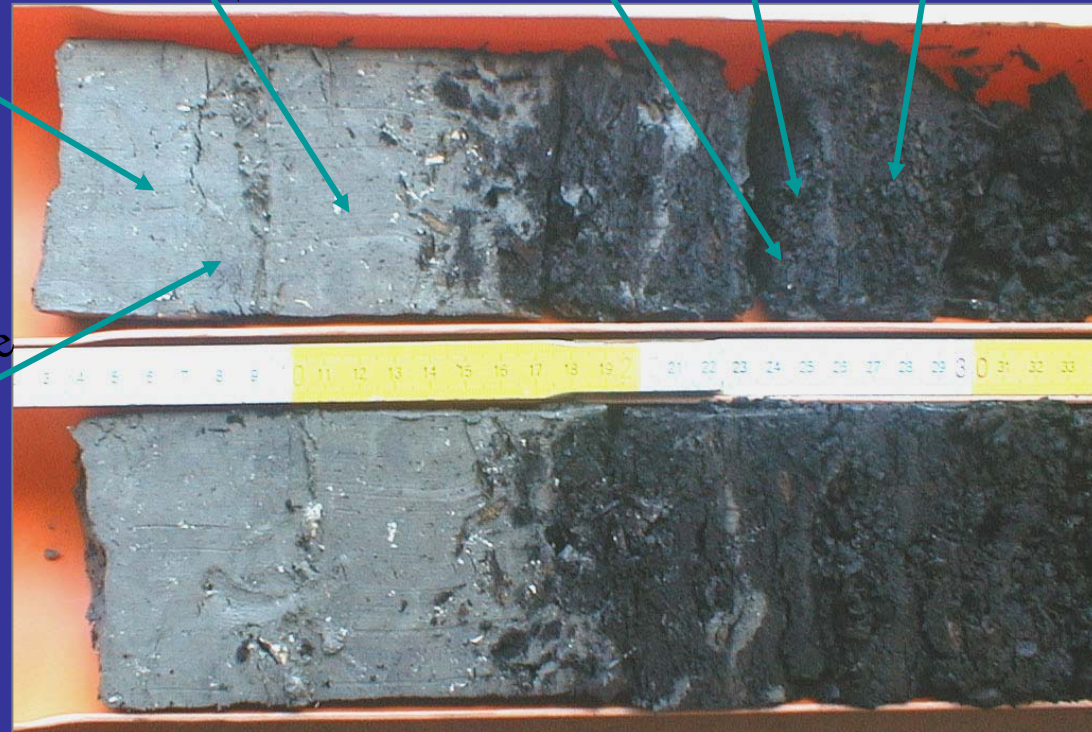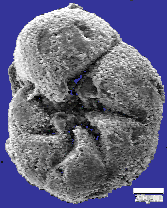
Petrografia sabbie
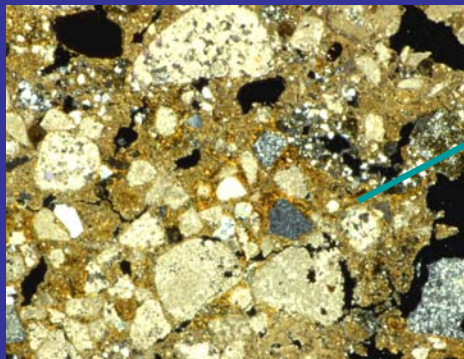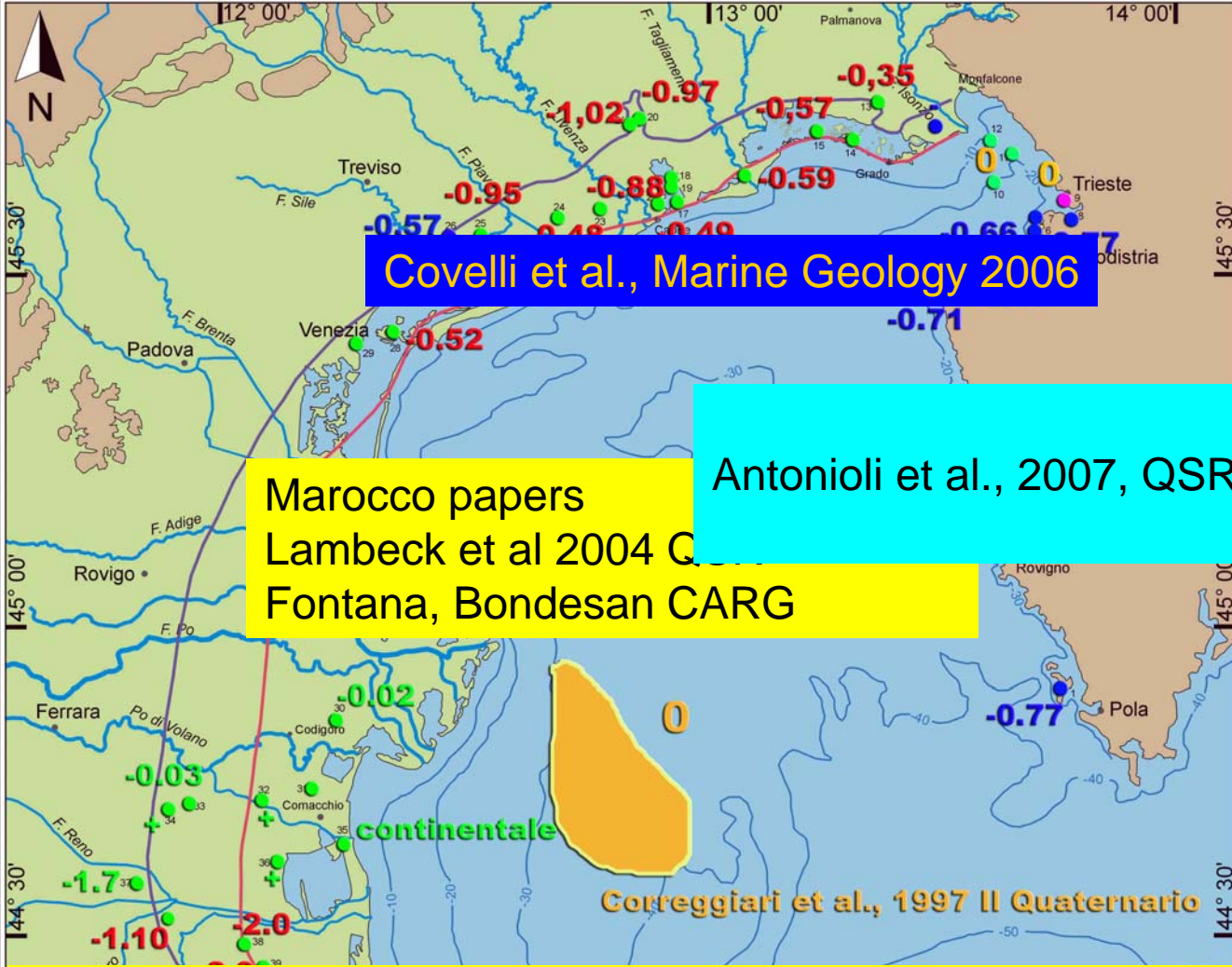
Covelli et al., Marine Geology 2006

Antonioli et al., 2007, QSR

Marocco papers
Lambeck et al 2004 QSR
Fontana, Bondesan CARG

Amorosi et al., 1999 - Sedimentology (area di Ravenna)
Amorosi et al., 2003 - Journal of Geology (area di Ferrara)
Amorosi et al., 2005 - Marine Geology (correlazioni terra-mare

Data available for Ne-Italy

Tide gauges: 100 ys –
Tilt: 40 ys - Leveling (IGM): 50 ys -
Topex/Poseidon: 13 ys -
Continuous GPS: 4 ys.

1
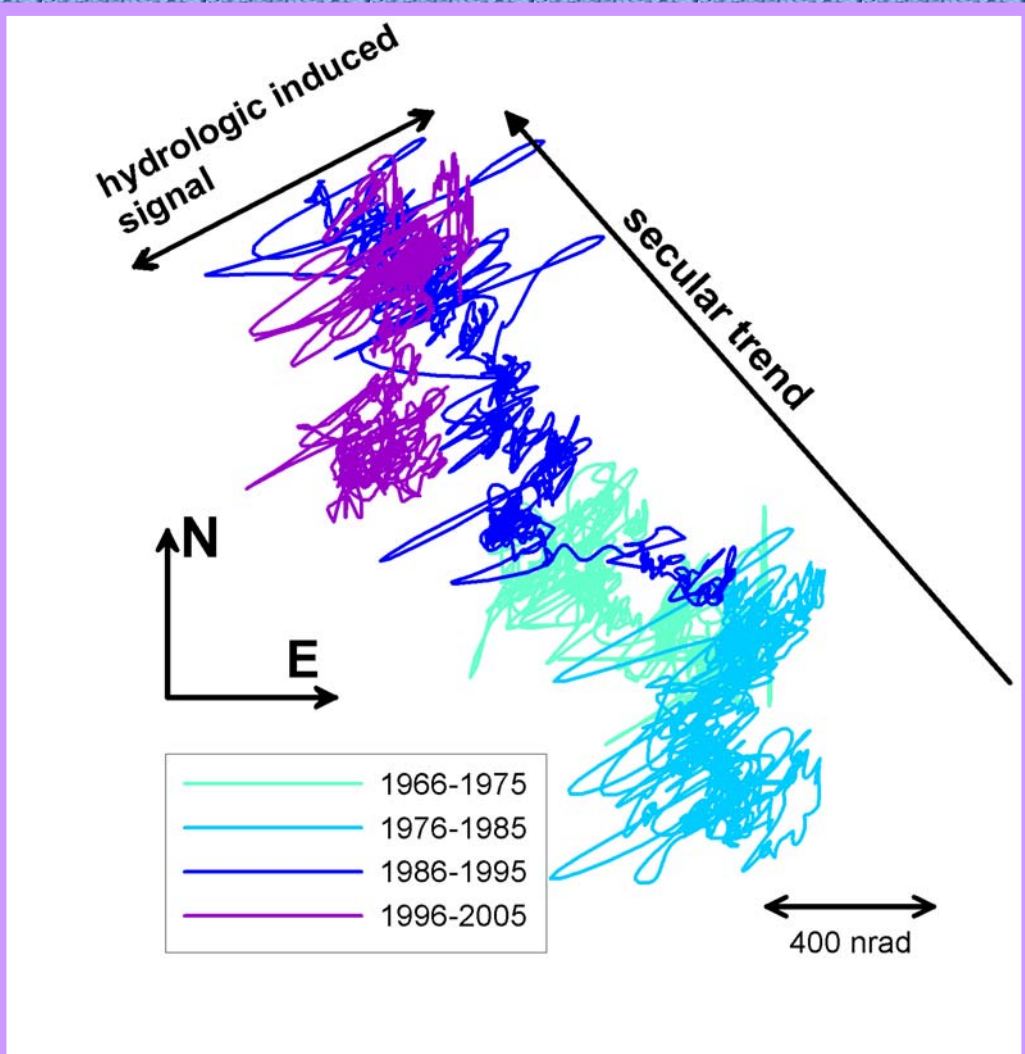
A long-base tiltmeter located in the Gigante Cave closet o Trieste has a secular trend which indicates a NW tilt.
This is in agreement with the geological (MIS 5.5 and Holocene) data that shows a crustal tilt to the W
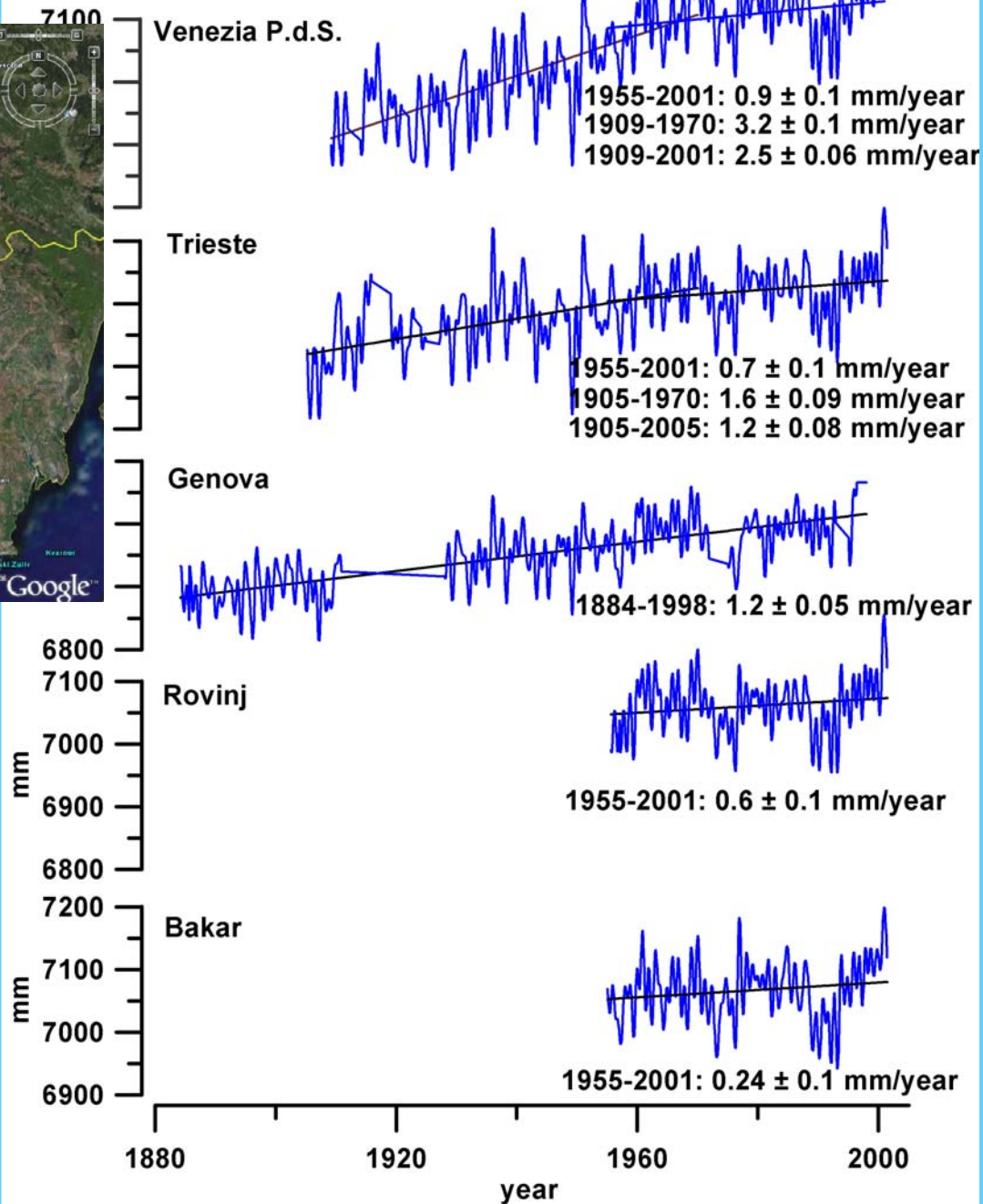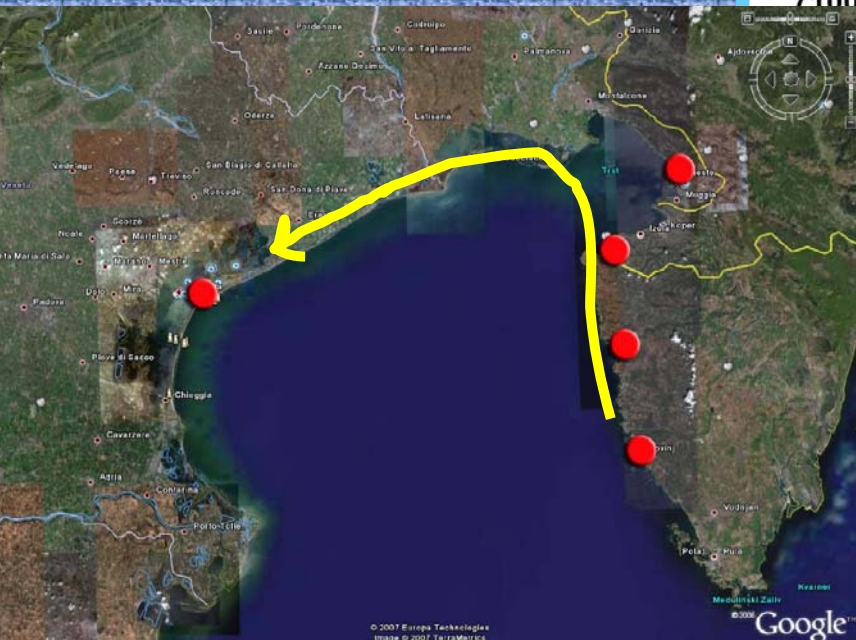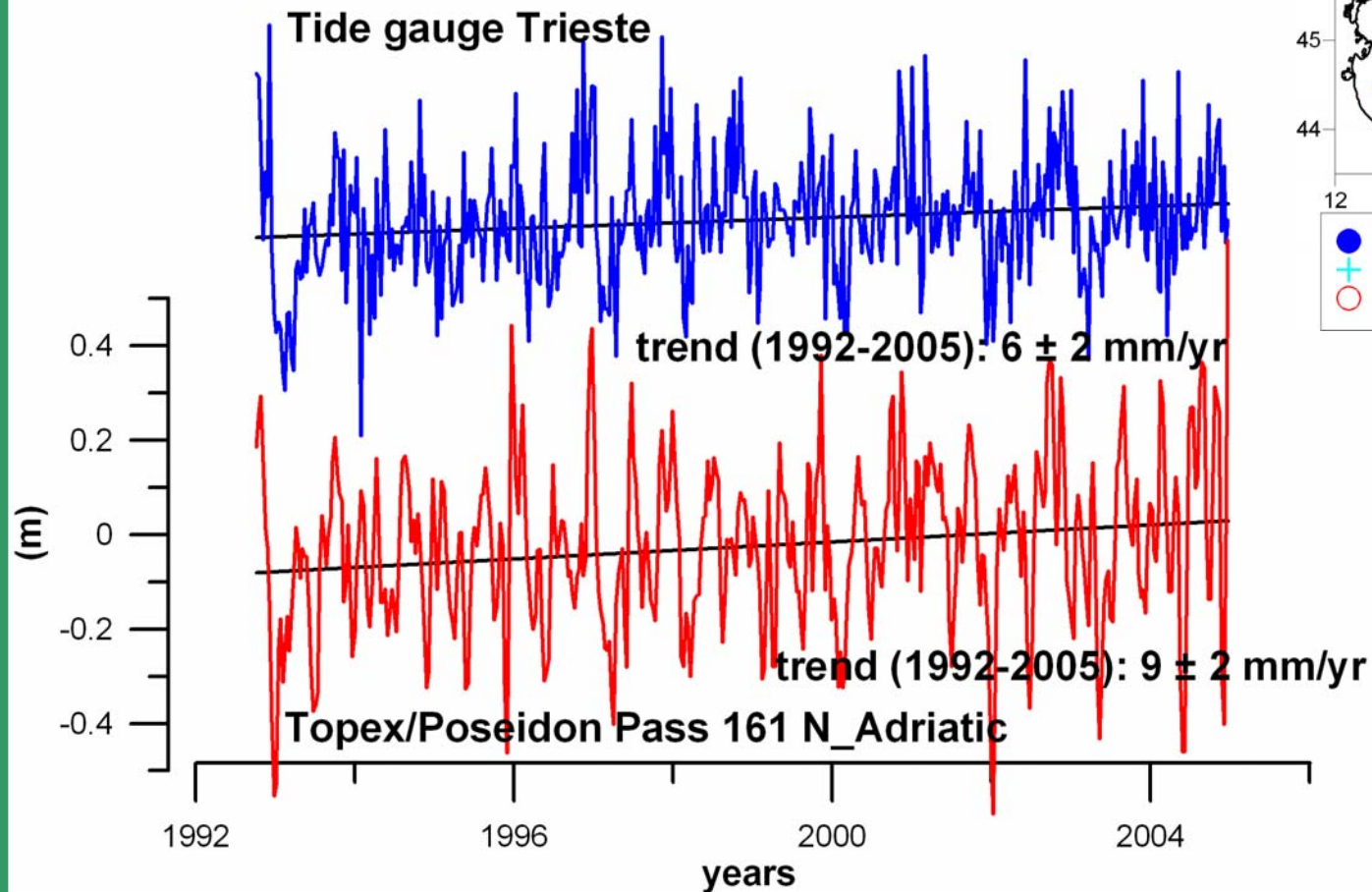
Height along leveling line.
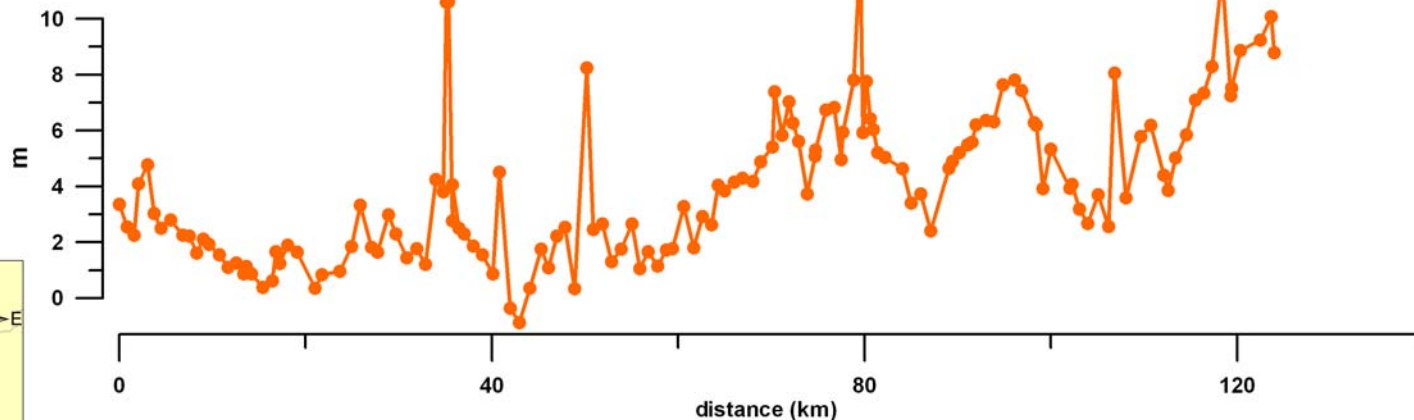
Vertical movement at consecutive time intervals.

Linea 34
1951-1989
1952-1989
1989-2002
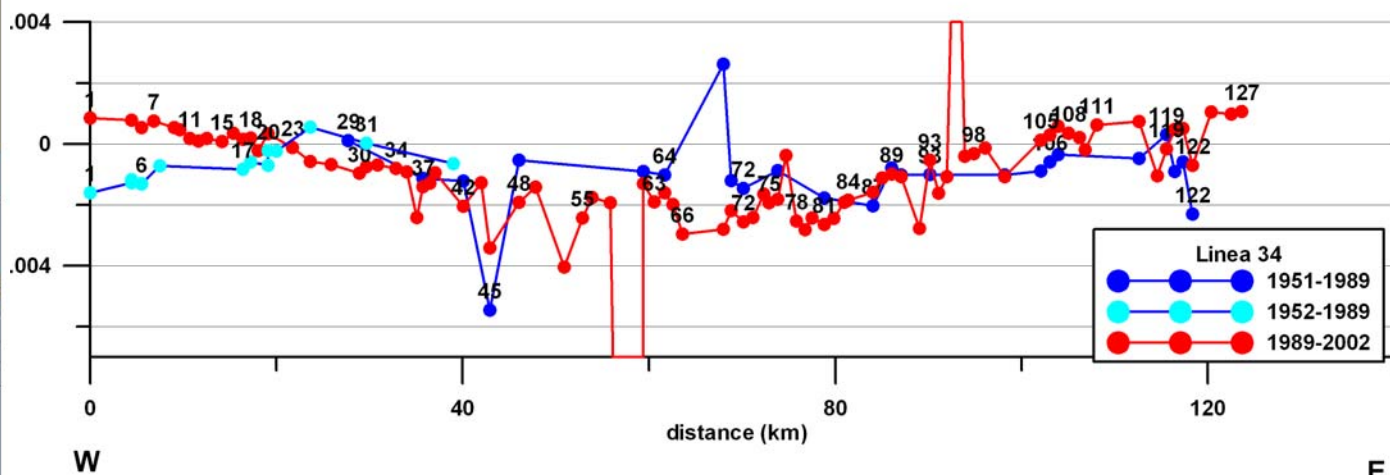
Vertical movement rates (mm/yr) from leveling along coast. Tectonic subsidence is documented in the middle of the line, increased by anthropogenic effects
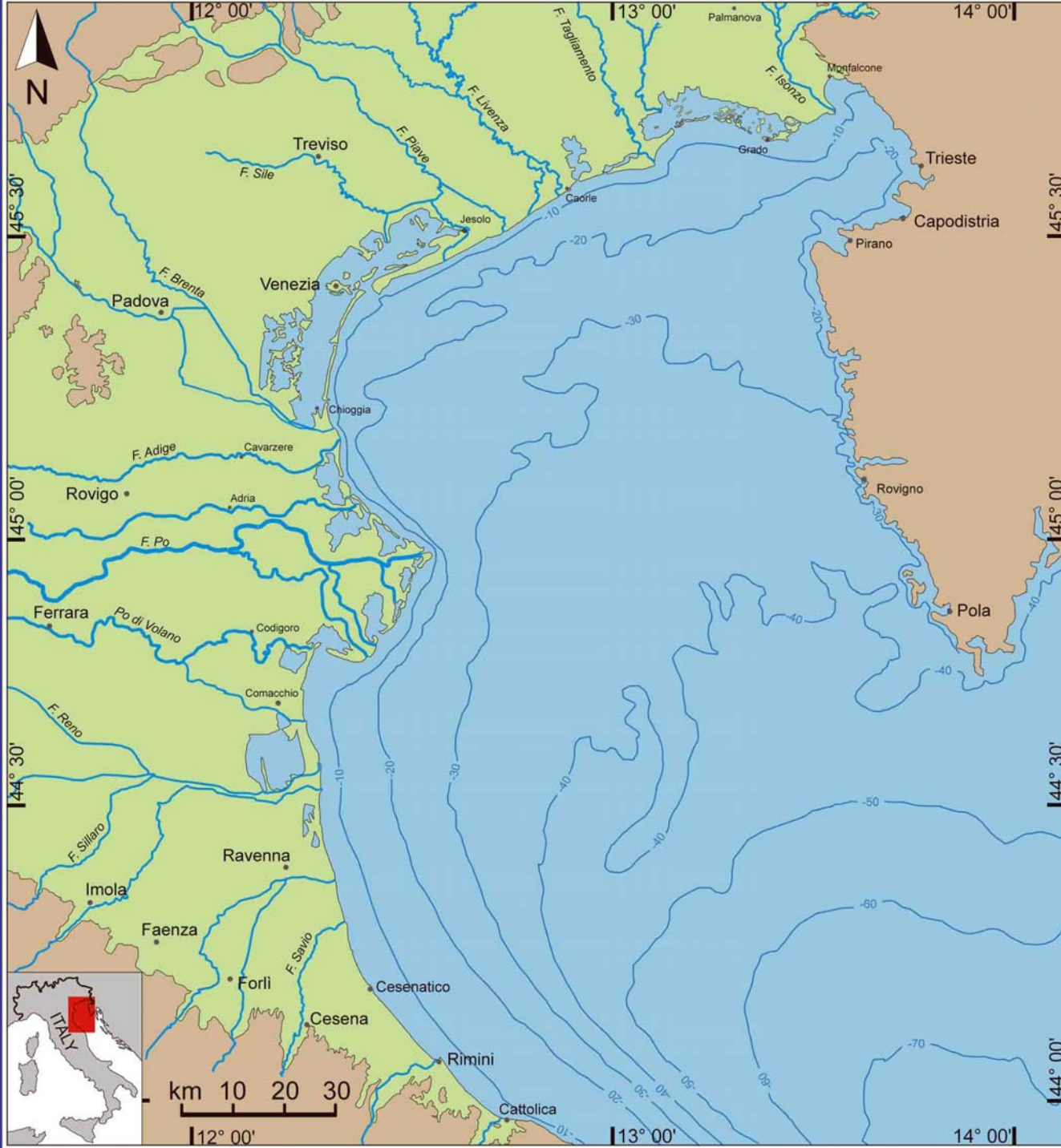
Data: Istituto Geografico Militare.

Topex/Poseidon: Pass 161 (2002-2005), (TU Delft, RADS).
Problematic result: Tide gauge has unexpected smaller increase.
Reliabilityof T/P is questionable: shortness of observation of T/P, shallow waters in upper Adriatic
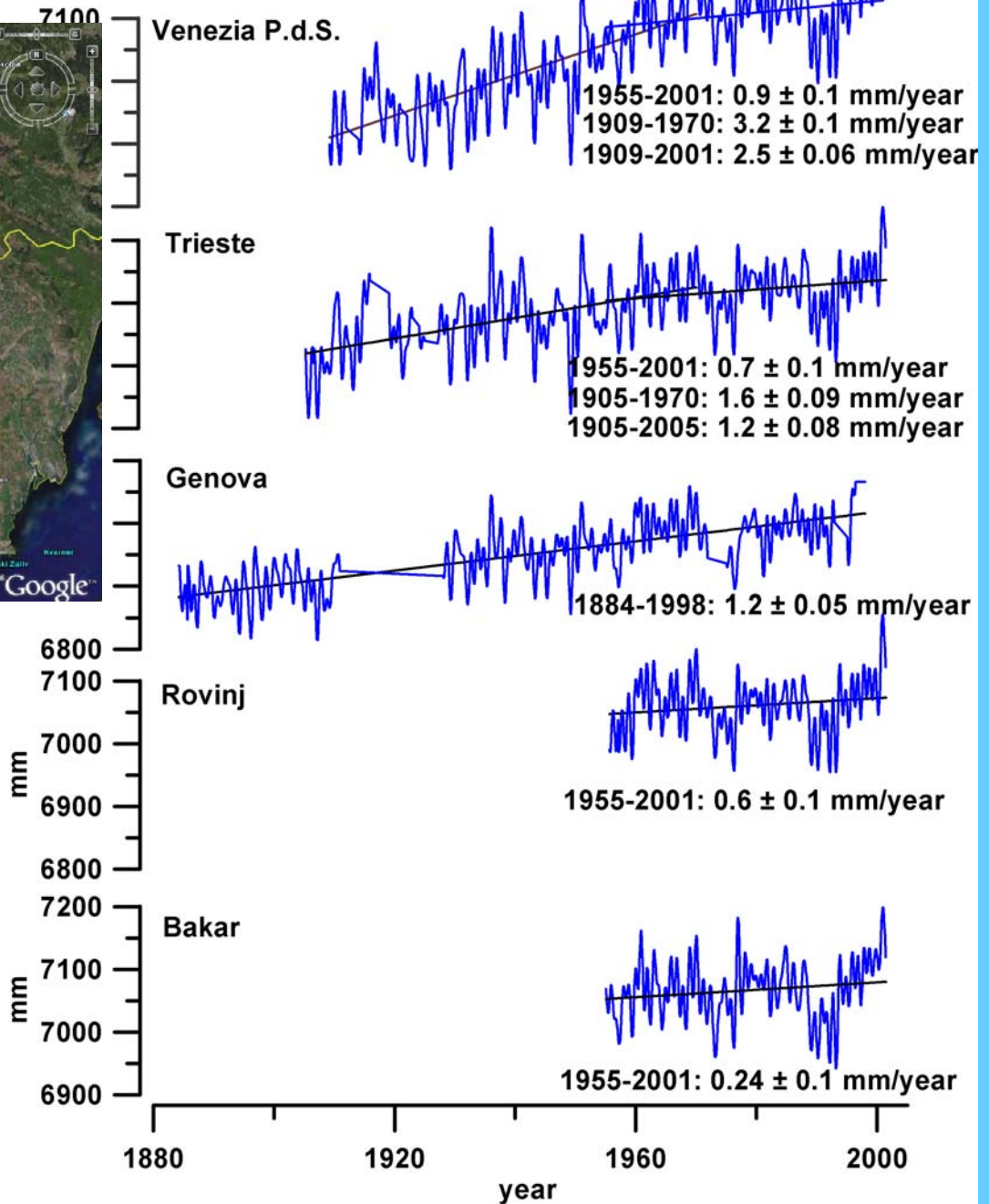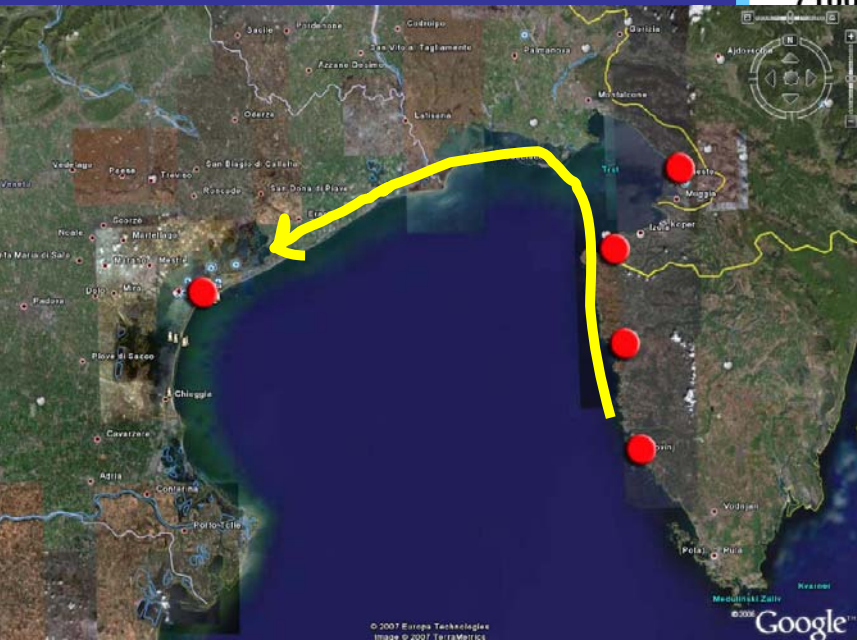
.
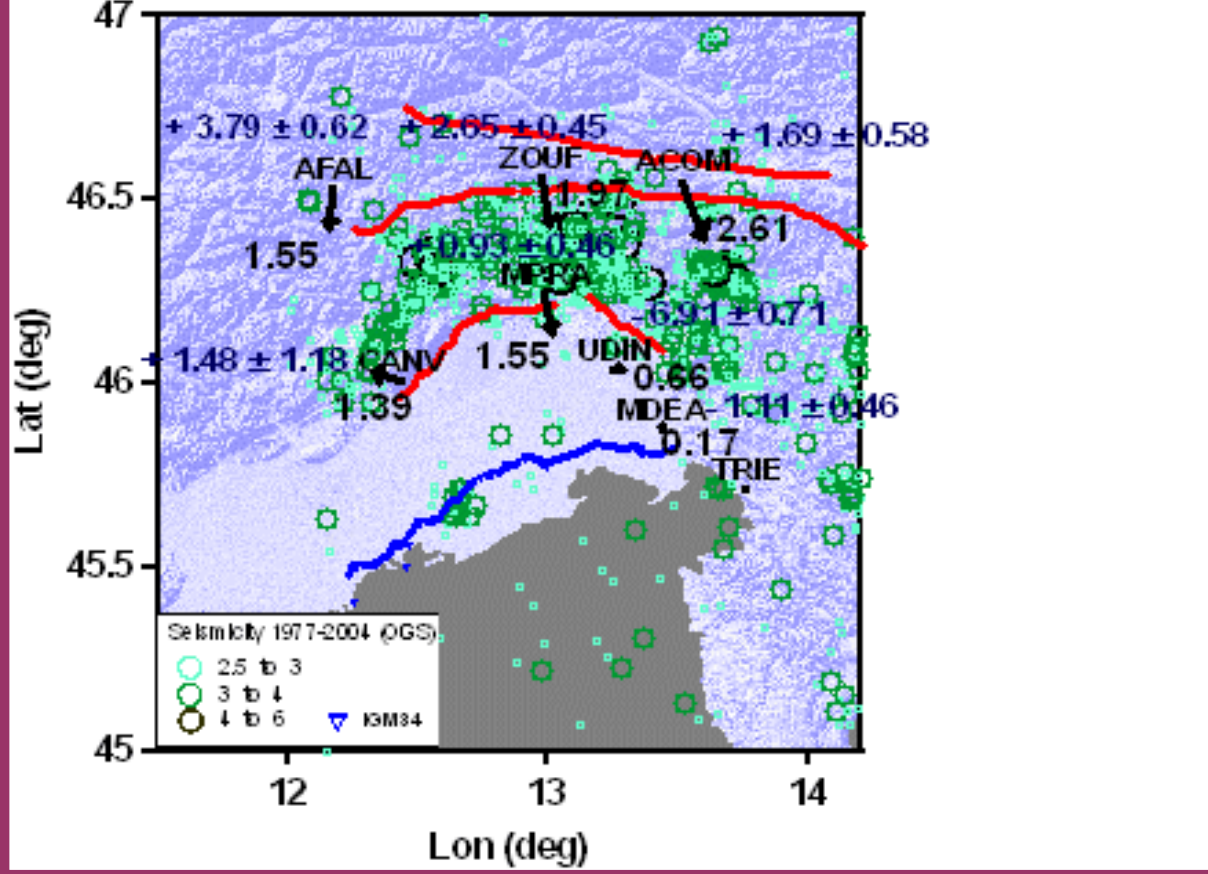
GPS station velocities in mm/yr relative to station TRIE (Trieste). Blue: vertical rates, black: horizontal rates.
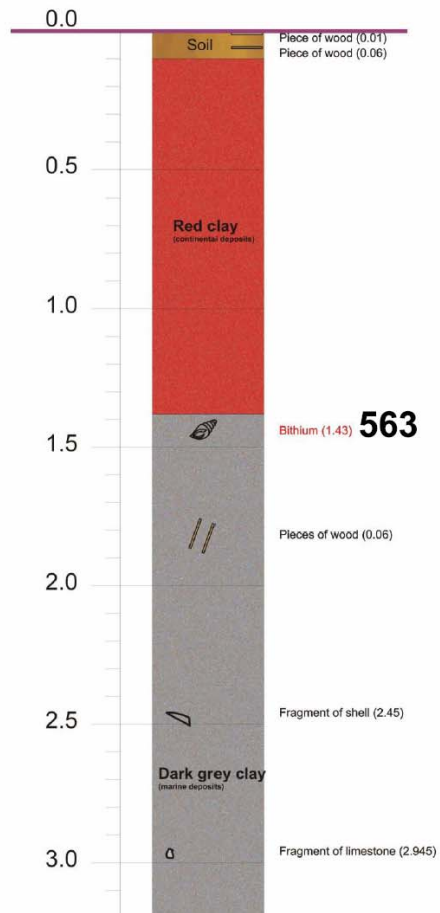
Result: Friuli plain subsiding, pedemountain area uplifting. Friuli plane and Trieste belong to Adria plate, in relative movement to Eurasia.
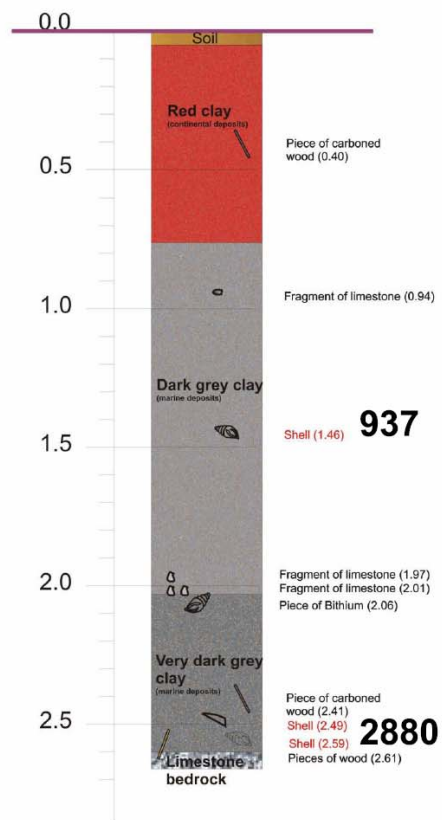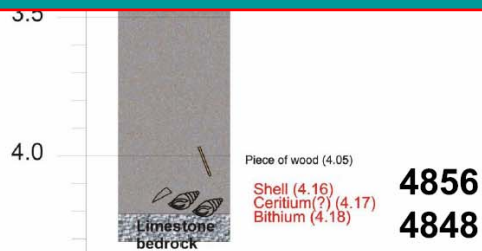
S1 - Rovinj

Depth	Layer	Finds
0.0		Piece of wood (0.01)
	Soil	Piece of wood (0.06)
0.5		
	Red clay (continental deposits)	
1.0		
1.5		Bithium (1.43) **563**
2.0		Pieces of wood (0.06)
2.5	Dark grey clay (marine deposits)	Fragment of shell (2.45)
3.0		Fragment of limestone (2.945)
4.0		Piece of wood (4.05)
	Limestone bedrock	Shell (4.16) **4856** / Ceritium(?) (4.17) / Bithium (4.18) **4848**

SM1 - Santa Marina

Depth	Layer	Finds
0.0	Soil	
0.5	Red clay (continental deposits)	Piece of carboned wood (0.40)
1.0		Fragment of limestone (0.94)
1.5	Dark grey clay (marine deposits)	Shell (1.46) **937**
2.0		Fragment of limestone (1.97) / Fragment of limestone (2.01) / Piece of Bithium (2.06)
2.5	Very dark grey clay (marine deposits)	Piece of carboned wood (2.41) / Shell (2.49) / Shell (2.59) **2880** / Pieces of wood (2.61)
	Limestone bedrock	

Legend:
- Gastropods
- Fragments of shells
- Piece of wood
- Limestone fragments

Faivre, Ghilardini, Fouache, Antonioli Furlani, Kovacic in prep