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Sea-level change along the Italian coast for the past 10,000 yr

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Abstract

Relative sea-level change along the Italian coast and adjacent seas—the combined result of eustasy, glacio-hydro-isostasy and vertical tectonic motion—exhibits considerable spatial and temporal variability throughout the Holocene. The tectonic contribution can be evaluated from the elevation of MIS 5.5 shoreline-markers that are well developed in many localities and the eustatic and isostatic contributions can be predicted from models of ice sheets and earth rheology. Discrepancies between observed Holocene sea levels and model predicted values provide the information for refining the model parameters, including the tectonic rates of vertical movement. Recent and new Holocene and MIS 5.5 information from 30 sites in Italy has been evaluated and compared with model results to calibrate the predictive model. The resulting parameters for the earth rheology and for the eustatic (ice-volume equivalent) sea-level function are consistent with results from regions outside of the Mediterranean and reflect global values. Using the calibrated model parameters the relative sea-level change due to eustasy and the concomitant isostasy is predicted across the central Mediterranean region. Holocene tectonic rates of vertical motion are also given for the Italian coastal zone. At most sites where the MIS 5.5 shoreline occurs above or below its 'tectonically stable' position, the inferred rates of vertical crustal displacements are consistent with the assumption that average rates for the past $\sim$125,000 years are comparable to the average Holocene rates, but at some locations in eastern Sicily and southern Calabria the Holocene rates exceed the longer term average rates.
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1. Introduction

Sea-level change along the Italian coast is the sum of eustatic, glacio-hydro-isostatic, and tectonic factors. The first is global and time-dependent while the latter two also vary with location. The glacio-hydro-isostatic part exhibits a well-defined pattern and is readily predictable whereas the tectonic component exhibits a less regular pattern that is generally of shorter wave-length and also less predictable. Together, these components result in a complex spatial and temporal pattern of relative sea-level change around the central Mediterranean coast-line, observations of which provide information on earth-rheology, on rates of vertical tectonic movements, and on the global ice–ocean balance during glacial cycles.

Pertinent observations of sea-level change around the coast include the age–height relationship of geological deposits and archaeological structures whose positions relative to coeval sea level can be established. During the last decade, considerable new information (some un-published) has become available but much of this is for the later stages of the last global deglaciation. Thus the emphasis of the present study is on the Holocene period. This material can be used to calibrate the parameters defining the isostatic models if an independent assess-ment can be made of the tectonic rates of change. What we attempt to do in this paper is to evaluate the components contributing to sea-level change subsequent to the last deglaciation, develop a predictive model for the Late Pleistocene and Holocene changes in relative sea level for this part of the Mediterranean, and estimate rates of vertical tectonic motions. An important ques-tion is whether the various contributing components can be separated and whether valid predictive models for the relative change between the ocean and land surfaces can be developed.

The glacio-hydro-isostatic formulation for sea-level change resulting from the growth and decay of the large high-latitude ice sheets is well known and the broad pattern of change in the central Mediterranean has been

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established (Lambeck and Johnston, 1995; Lambeck and Bard, 2000). Apart from tectonic signals the dominant contribution to sea-level change in the Mediterranean is the eustatic part. However, while the region lies well beyond the margins of the former large ice sheets glacio-isostatic effects are significant. The important consequence of the large ice sheets is that for the entire length of Italy the crust is subsiding in response to the last deglaciation. (We ignore here any contributions from the Alpine glaciation. Simple order of magnitude estimates indicate that their magnitudes are smaller than those arising from the Eurasian and North American ice sheets, but that they may contribute in a minor way to subsidence of the crust along the North Adriatic coast. However see note added in proof below) The hydro-isostatic contribution results from the loading of the ocean floor by the meltwater entering into the Mediterranean and causes maximum subsidence within the central parts of the basin and relative uplift at the coast and inland. If the earth-rheology, the history of the global ice sheets, and the geometry of the ocean basins are known, then both isostatic effects can be evaluated. If the relevant parameters are only partly known, then observations of sea-level change can be used to improve the model parameters. Thus on the one hand the model can be effectively used as a formulation for interpolating between fragmentary observations of sea-level change across the region. But on the other hand, we also wish to have a model that yields parameters that are physically insightful about the earth rheology and the ice sheets.

Tectonically the Italian peninsula cannot be considered to be stable on Quaternary and longer timescales. It comprises $\sim$8000 km of coastline of which approximately 25% consists of low-lying plains, some of which are subsiding with a potential for flooding (Antonioli and Leoni, 2000; Antonioli et al., 2001a). Other areas, in particular the southern coastal zone of Calabria and eastern Sicily, are subject to uplift at rates reaching 1–1.4 mm year^{-1} (Monaco et al., 2001; Antonioli et al., 2003; Miyauchi et al., 1994). There are marked differences in local tectonic evolution between adjacent coastal zones: areas exhibiting an unstable behaviour even in recent times occurring adjacent to, and alternating with, areas that have been virtually stable since the middle Pleistocene. Other areas, such as the coasts of Tuscany, Sardinia, Campania and parts of Latium appear to have been stable for much of the later part of the Quaternary. Thus any analysis of the Italian sea-level data in terms of eustasy and isostasy must consider the possibility of vertical tectonic movement along the entire coastal sector. In this regard, an important observation in Italy and elsewhere in the Mediterranean is the elevation of the Last Interglacial (marine isotope stage MIS 5.5 or 5e) sea level. Here this level (named also *Tyrrhenian*) is characterized by several morpho- and litho-stratigraphic markers including prominent notches, lagoonal sedimentary facies, fossil beaches and terraces that often contain a typical warm-fossil association named *Senegalese fauna* including *Strombus bubonus* (Gignoux, 1913). This gastropod is found in the central and eastern Mediterranean Sea only at the time of the Last Interglacial highstand and it provides a unique marker of the MIS 5.5 horizon. Globally, in tectonically stable regions, Last Interglacial shorelines lie a few meters above present sea level (e.g. Stirling et al., 1998) but in some locations in Italy, such as Calabria, it occurs at more than 100 m. Elsewhere, such as along the northern shores of the Adriatic Sea, it occurs below present sea level. We use the position of this marker as an indicator of tectonic stability or otherwise and in the latter case we make a first-order correction for the tectonic contribution based on the assumption that long-term (10^5 years) rates of uplift and subsidence are representative of shorter time intervals ($\sim 10^3$ years). If adequately representative models can be developed then this assumption can be tested a posteriorily.

In this paper we first summarize the types of evidence available for sea-level change along the coast of Italy (Section 2) and discuss the data and tectonic stability for each location (Section 3). We next summarize the eustatic–isostatic model and its uncertainties (Section 4) and compare the model predictions with the observational evidence (Section 5) for stable, uplifting and subsiding sites. In Section 6 some of the nominal model parameters are re-evaluated based on the Italian data, primarily the global eustatic sea-level function and some local estimates of vertical crustal motion where the underlying assumption of uniformity of uplift throughout the last interglacial cycle does not appear to be valid. With these revisions, predictive models for the relative sea-level change and shoreline evolution across the region are presented for the interval from the Last Glacial Maximum (LGM) to the present. Section 7 summarizes the main results.

2. Sea-level indicators and their accuracies

A range of different sea-level indicators have been used which can be divided into biological, sedimentological, erosional and archaeological categories. The last have been discussed for the Mediterranean as a whole by Flemming (1969) and for some Italian locations by Schmiedt (1972) and Pirazzoli (1976) and we do not discuss the methodologies in any detail. Some of the biological evidence from the Italian region have received less attention and we comment briefly on these sea-level markers here. Most sea-level indicators refer to some specific part of the tidal range and while this is generally small in the Mediterranean, corrections to mean sea level have been applied where appropriate. Tidal amplitudes along the Italian coast are mostly between 0.25 and 0.44 m but locally can reach 1.2 m in the northern Adriatic at the time of highest astronomical tide.

2.1. Sea-level markers

2.1.1. Vermetids

Vermetids are a reef building species of gastropods from lower intertidal habitats. Because of their well-defined growth zone they provide highly reliable indicators of sea-level change and of tectonic movement (Laborel et al., 1994, 1996; Pirazzoli et al., 1996). In the Mediterranean Sea, the most common reef-forming vermetid species is the gastropod *Dendropoma petraeum* which can form reefs up to 10 m wide with a depth range of over 0.40 m. Along the Sicilian coast Antonioli et al. (1999a) identified platform-type reefs that are similar to coral fringing reefs and which correspond to the classical vermetid reefs described by Pérès and Picard (1964). Vermetids commonly colonize abrasion platforms generated by wave action and the edge of the resulting structure is frequently eroded, taking the shape of a continuous vertical wall 0.4–1 m high. The average age of a Sicilian reef is less than 600–700 years because their rapid growth results in a loss of stability and resilience against storm events. At their time of growth vermetid reefs are submerged during high tide but remain exposed during low tide so their position defines the mean sea level to within the tidal amplitude. For the fossil samples considered here we adopt error bars equal to the tidal amplitude plus 0.10 m (Antonioli et al., 1999a).

2.1.2. Cerastoderma glaucum

This Lamellibranchia is frequently found in the Italian coastal plain in lagoonal deposits both in outcrops and in cores. In association with other lagoonal species such as *Bittium, Rissoa* and *Hydrobia*, Lamellibranchia define a typical lagoonal environment (LEE) bottom (Pérès and Picard, 1964) whose position with respect to mean sea level is between 0 and −2 m (Gravina et al., 1989).

2.1.3. Lithophaga

These bivalves live only in calcareous rock, between low tide level and a depth of no more than 20 m. However, they live preferentially in the uppermost few meters, with 90% occurring in the first 2 m below tide level. They are commonly used as sea-level markers but unless their living position can be related to morphological indicators their associated uncertainty can be large (> 5 m). For example, observations from scuba-dive transects of sea-floor features below dated fossil outcrops determine the depth range of living species and, together with seabed profiles, determines the maximum depth limit of the fossils at the time of their growth (Antonioli et al., 2003). Where such supplementary observations have been made the lower limit is determined by the sea-floor profiles at the site.

2.1.4. Speleothems with marine overgrowth

For some limestone sections of the coast caves occur that are now flooded. During lowstands, speleothems formed but as the caves flooded during the sea-level rise their development ceased and they became encrusted with colonies of the marine worm *Serpula massiliensis*. These gregarious worms typically form thick marine crusts composed of calcitic tubes. At the time of sampling, modern serpulids were living on the outer surface of the speleothem. By dating both the first serpulid layer and the last continental layer, Alessio et al. (1996) obtained the time of submergence at the altitude of sampling. Because serpulid growth rates are very slow the ^{14}C ages are often time-integrated values and a linear growth model is adopted to arrive at a model age for the oldest encrustration (Alessio et al., 1992). In some speleothems the age of flooding is provided by Lithophaga that bored into the continental layer and were found to be completely covered by the overgrowth. In this case the age of the mollusc is considered to date the first marine colonization of the speleothem and the earliest stage of submersion (Antonioli and Oliverio, 1996). However, a hiatus of 2 or 3 ka is sometimes found between the ages of the continental deposits and the oldest recorded lithophaga so that the ages are limiting values only.

Lithophaga growth is relatively slow, typically 8 cm in 80 years and the results used in this study are only from specimens less than 3 cm in length. Thus age-of-growth uncertainty from sampling is at most 30 years, less than the typical ^{14}C measurement precision. The speleothem depths have been determined with a digital depth gauge that has a typical error of ± 0.1 m. Down-growing speleothems have been sampled near their lower limit and up-growing speleothems have been sampled near their upper limit and the maximum positional uncertainty is better than 0.5 m.

2.1.5. Cores containing marsh or biological markers

Biological markers from core samples have provided satisfactory results when the cores are from sandy sediments for which compaction has been minimal. In these cases the depth precisions are determined by the accuracy of the relationship of the biological marker to mean sea level. This is the case for the ENEA core (*1*) discussed below. However, because of a range of potential uncertainties associated with the interpretation of single core records we add an uncertainty of 1 m to all precision estimates. Where the cores are from marsh deposits compaction may be important and the positional uncertainty of the biological markers may be considerably increased, reaching as much as 10 m, unless the samples are from near the lower part of the marsh or peat deposit or unless compaction corrections are possible. This information is not always available in the older publications of sea-level data.

2.1.6. Fossil sand beach

In some localities, particularly the uplifting areas of southern Italy, fossiliferous sands have been identified. These contain gastropods and bivalves (*Bolma rugosa, Osilinus turbinatus, Hesaplex trunculus* species) that form biological associations characteristic of a lower mesolittoral cliff environment subjected to regular periods of immersion. They may also contain species (*Ostrea, Spondilus, Cerastoderma Cardium*) that do not show relevant ecological associations. Similar mixed associations occur along the modern infrashoreline zone at the same localities as the fossil outcrops. The error bars of these results could be as large as 10 m. Where possible, the same methodology as described for the lithophaga deposits has been used to reduce the uncertainty of the depth range of these deposits (i.e. using scuba-dive transect information) (Antonioli et al., 2003).

2.1.7. Beach rock

Beach rock is constituted from clastic shoreline deposits cemented by calcitic-magnesitic or aragonitic–carbonates in or near the intertidal zone, often at the interface of the freshwater–marine phreatic flow. This precipitation can be exceptionally fast, of the order of 10 years and, depending on local conditions, this interface may occur above or below mean sea level. In particular, supratidal cementation by carbonate cements is common and much debate still exists about the uppermost level of cementation. Also, dating the time of formation is associated with difficulties, and ages may be either too old because of contamination from older carbonate or they may be too young because of post-depositional alteration of the cement. Hopley (1986), in reviewing the suitability of beachrock as a sea-level marker, concludes that it is an unreliable recorder of sea level and while his discussion deals with low-latitude deposits we adopt a cautious approach in its use here. Numerous beach rock deposits have been preserved at different depths along the Sardinia-Corsica continental shelf with remarkable continuity of the outcrops (De Muro and Orrù, 1998). The thickness of the sampled deposits is mostly between 4 and 5 m and we provisionally adopt the error bars of $+1$ and -5 m for these results as given by De Muro and Orrù. This encompasses the likely uncertainty of the relation between formation and sea level.

2.1.8. Submerged archaeological remains

Flemming (1969), Schmiedt (1972), Caputo and Pieri (1976), and Pirazzoli (1976) have discussed the archaeological evidence for sea-level change in considerable detail. Different archaeological markers provide sea-level estimates with different accuracies and it is not possible to assign the same error bars to all data. For estimating the altitude of the Roman piscinae, for example, the architectural feature that relates directly to sea level must be identified and is not necessarily the same for all holding tanks (cf. the piscinae of Torre Astura and the fish tanks from Briatico). Such observations are corrected for tidal effects with an uncertainty of ± 0.20 m.

3. Observed sea-level change and tectonic uplift

Table 1 summarizes the evidence for change in the land–sea intersection at the 30 Italian sites. Data from Tunisia has also been included because this site increases the north–south extent of the region and potentially provides information for testing the isostatic models for glacio-hydro-isostatic rebound. Site locations are given in Fig. 1. The MIS 5.5 (or 5e) shoreline is well developed along long sections of the Italian coast and its present elevation is used to establish whether significant tectonic uplift or subsidence has occurred because, in tectonically stable regions and away from former ice sheets, its position is typically a few meters above present sea level (Stirling et al., 1998). Along the northern and central Tyrrhenian coast (southern Tuscany, northern and southern Latium, Campania, Sardinia) the marine notches and inner margin terraces corresponding to the MIS 5.5 highstand occur from within a few meters up to 4–10 m above present sea level (Hearty and Dai Pra, 1986; Antonioli et al., 1999b; Carobene and Pasini, 1982). (An uncorrected uniform uplift of 10 m since the Last Interglacial introduces an error of ~ 1 m in the elevation of early Holocene sea levels.) Thus here the tectonic movement since the Last Interglacial appears to have been small and the Holocene data from these localities is assumed to be largely free from vertical tectonic movement. (We distinguish between movements of the crust driven by various tectonic processes other than the isostatic response to the ice–ocean loading. The tectonic component includes, for example, subsidence driven by sediment loading.) In southern Italy the MIS 5.5 highstand reaches some of the highest altitudes in the Mediterranean: 175 m in Sicily (Monaco et al., 2001) and 162 m in Calabria (Miyauchi et al., 1994). In contrast, along the Adriatic coast, particularly the central and northern parts, considerable tectonic subsidence has occurred because coastline features attributable to the MIS 5.5 stage are found only in cores at depths of -100 m to -120 m below present sea level (Amorosi et al., 1999). Fig. 1 summarizes the information on the elevation of the MIS 5.5 shoreline in Italy. The tectonic vertical movement and its uncertainty estimate is based on a nominal age of 124±5 ka and elevation, in the absence of tectonics, of 7±3 m above present sea level. This elevation is higher than global estimates of this level because the Italian sites lie relatively close to the former ice margins and the present MIS 5 shorelines in the Mediterranean may lie a few meters higher than for localities much further from the former ice margins (cf. Potter and Lambeck,

Table 1

1—*Versilia Plain*

Ages (cal yr BP)*	Age error (± yr)	Altitude (m)	Altitude error (±m)		Marker	Ref.
2227	99	−1.0	3.0	3.0	Marsh	1
2812	37	−2.1	3.0	3.0	Marsh	
4166	78	−2.5	0.5	2.5	*Cerastoderma*	
4247	97	−2.6	5.0	5.0	Wood	
4660	115	−2.7	0.5	2.5	*Cerastoderma*	
4665	130	−3.0	5.0	5.0	Wood	
6200	84	−4.0	5.0	5.0	Wood	
5863	33	−7.5	5.0	5.0	Marine shell	
6626	49	−8.9	0.5	2.5	*Hinia sp.*	
7050	86	−9.5	0.5	2.5	*Cerastoderma*	
7605	40	−10.5	0.5	2.5	*Cerastoderma*	
7813	53	−15.3	0.5	2.5	*Venus sp.*	
7844	60	−15.8	3.0	3.0	Infralittoral shell	
7870	53	−27.3	3.0	3.0	Infralittoral shell	
9422	91	−29.5	5.0	5.0	Wood	
9904	111	−29.9	3.0	3.0	Marsh	
9622	177	−32.1	0.5	2.5	*Cerastoderma*	
10146	90	−34.0	0.5	2.5	*Cerastoderma*	
> 53000		−69.2	0.5	2.5	*Cerithium*	

2—*Castiglioncello*

Ages (Archaeological attribution; BC)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
300	100	−1.65	0.5	0.5	Quarry	2

3—*Argentarola Island*

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
6500	285	−3.5	0.25	0.25	Serpulids overgrowth on submerged speleothems	3, 4, 5, 6
6590	185	−6	0.25	0.25		
6770	190	−9.5	0.25	0.25		
7360	200	−14.5	0.25	0.25		
8300	150	−16.0	0.25	0.25		
9590	120	−18.5	0.25	0.25		
8036	55	−18.5	0.25	0.25		
9727	50	−18.5	0.5	0.5	Speleothem	
11199	80	−18.5	0.5	0.5	"	
11638	65	−18.5	0.5	0.5	"	
8810	80	−21.5	0.5	0.5	"	
9430	170	−21.5	0.25	0.25	Serpulids	

4—*Gravisca*

Ages (Archaeological attribution BC)	Age error (± yr)	Altitude (m)	Altitude error (±m)		Marker	Ref.
400	100	−1.67	0.5	0.5	Walking surface	7, 8
300	100	−1.47	0.5	0.5		

5—*Punta della Vipera*

Ages (Archaeological attribution; AD)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
0	100	−0.40	0.2	0.2	Roman piscinae	7, 8, 9, 10

Table 1 (*continued*)

6—*Roma (Tevere Plain)*

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
5346	50	−3	3.0	3.0	Marsh	11
6658	70	−3.5	5.0	5.0	Wood	
5982	50	−4	5.0	5.0	Wood	
5855	60	−7.8	3.0	3.0	Marsh	
8572	80	−9.2	0.0	10	Wood	
8572	70	−9.35	0.0	10	Wood	
8844	70	−9.5	5.0	5.0	Clay	
10222	100	−22	0.0	10	Wood	
9745	50	−30.1	3.0	3.0	Marsh	
9676	60	−30.9	3.0	3.0	Marsh	
10669	90	−31	0.0	10	Wood	
11644	80	−31.5	5.0	5.0	Clay	
11009	80	−31.5	0.0	10	Wood	

7—*Anzio*

Ages (Archaeological attribution; AD)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
110	100	−0.56	0.2	0.2	Roman piscinae	7, 8, 9, 10

8—*Torre Astura*

Ages (Archaeological attribution; AD)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
50	100	−0.39	0.2	0.2	Roman piscinae	7, 8, 9, 10

9—*Fondi*

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
7483	150	−1.8	0	2	Cerastoderma	12
7388	120	−2.98	3	3		13
8028	130	−3.55	3	3		
8069	120	−4.28	3	3		
8028	120	−5.25	3	3		
8142	110	−15.8	3	3	Infralittoral shell	
8614	120	−19.6	3	3		
8406	110	−23.1	3	3		
8629	110	−33.7	3	3		

10—*Volturno*

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
4765	265	−3	3.0	3.0	Marsh	14
6580	270	−4	3.0	3.0	"	
5620	290	−6	3.0	3.0	"	
6290	330	−7	3.0	3.0	"	
7450	180	−8	3.0	3.0	"	

11—*Pozzuoli*

Ages (uncal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
1348	60	6.9	2	2	Lithophaga	15
660	75	6.9	4	4	Astroides	

12—*Palinuro Cape*

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
8223	71	−27	0.25	0.25	Serpulids	3, 16
8680	65	−41.5	0.25	0.25	Serpulids	
8560	63	−41.5	0.25	0.25	Lithophaga	
13915	167	−41.5	0.5	0.5	Speleothem	
9865	155	−47	0.25	0.25	Serpulids	
10253	72	−48	0.25	0.25	Lithophaga	

Table 1 (*continued*)

13—*Briatico (Scoglio Galera)*

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
1806	40	0.0	–	–	Wood	17
0 A.D. Archaeological attribution	100	0.0	0.2	0.2	Roman piscinae	

14—*Scilla*[a]

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
2668	164	3	0	2	Spondylus	18
3318	103	3.4	0	2	Spondylus	
3901	125	3.4	0	2	Hesaplex	

15—*Taormina*

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
4399	320	3.4	0	2	Cladocora	19
3331	510	2.0	0	2	Lithophaga	
5963	390	1.5	0	2	Lithophaga	
2936	150	2.1	0	2	Lithophaga	
2168	180	1.5	0	1	Bolma Rug.	20
2229	150	2.8	0	0.2	Vermetid	
1791	160	1.9	0	0.2	Vermetid	

16—*Zafferano Cape*

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
9528	130	>-25	0	6	Patella shell (food remain)	21

17—*S. Vito Lo Capo*

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
188	35	−0.3	0	0.2	Vermetid	22
430	37	−0.4	0	0.2	Vermetid	

18—*Marettimo Island*

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
9564	79	−24	0.25	0.25	Lithophaga	23

19—*Orosei (Cala Liberotto)*

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
9938	58	−33	1.0	5.0	Beachrock	24

20—*North Sardinia*

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
180	50	0	1.0	5.0	Beachrock	24
830	83	−0.3	1.0	5.0	Beachrock	
1780	70	−1	1.0	5.0	Beachrock	
2169	107	−2	1.0	5.0	Beachrock	
2256	107	−3	1.0	5.0	Beachrock	
1963	75	−3,5	1.0	5.0	Beachrock	
2263	109	−4	1.0	5.0	Beachrock	
5126	163	−7	1.0	5.0	Beachrock	
6774	106	−15	1.0	5.0	Beachrock	
8356	74	−17	1.0	5.0	Beachrock	
9705	179	−29	1.0	5.0	Beachrock	

21—*Caccia Cape*

Ages (Archaeological attribution; yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
7000	200	−8.5	3.0	10.0	Submerged Neolithical Burial	25

Table 1 (*continued*)

22—*Capo Rizzuto*

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
2990	50	0.6	0.5	0.5	Algae reef	26

23—*Sibari*

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
5316	70	−3.0	3.0	3.0	Marsh	27
9362	70	−38.0	3.0	3.0	Marsh	
11129	142	−55.0	3.0	3.0	Marsh	

24—*Egnazia*

Ages (Archaeological attribution AD)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
0	100	−3	1.0	1.0	Flooded harbour (catenae)	28

25—*North Adriatic Sea*

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
9263	60	−28.8	3.0	3.0	Marsh	29
9340	60	−30.2	3.0	3.0	Marsh	
9351	50	−33	3.0	3.0	Marsh	
9838	60	−32.8	3.0	3.0	Marsh	
9384	50	−30.4	3.0	3.0	Marsh	
9991	60	−34	3.0	3.0	Marsh	
9814	70	−35.2	3.0	3.0	Marsh	
10003	60	−32.3	3.0	3.0	Marsh	
10160	90	−37.6	3.0	3.0	Marsh	
10015	70	−37.2	3.0	3.0	Marsh	
10172	60	−38.3	3.0	3.0	Marsh	
10197	80	−42.5	3.0	3.0	Marsh	
10197	80	−39	3.0	3.0	Marsh	
10371	60	−39.6	3.0	3.0	Marsh	
10422	60	−31.1	3.0	3.0	Marsh	
10448	60	−33	3.0	3.0	Marsh	
10499	60	−38	3.0	3.0	Marsh	
10629	80	−45.9	3.0	3.0	Marsh	
10695	100	−47.9	3.0	3.0	Marsh	
10695	60	−35.1	3.0	3.0	Marsh	
10803	70	−38.7	3.0	3.0	Marsh	
11597	70	−43.4	3.0	3.0	Marsh	
11754	60	−41.6	3.0	3.0	Marsh	
11834	60	−42.2	3.0	3.0	Marsh	
12147	80	−43	3.0	3.0	Marsh	
13111	60	−52.9	3.0	3.0	Marsh	

26—*Conselice*

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
5924	50	−9.0	0.5	2.5	Cerastoderma	30
6680	60	−9.8	3.0	3.0	Peat	

27—*Caorle Lagoon*

Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
1953	120	−1.16	0.5	2.5	Lagoon. shell	31
5894	270	−3.18	3.0	3.0	Peat	
6717	515	−6.04	3.0	3.0	Peat	
8448	655	−7.78	3.0	3.0	Peat	
3464	245	−2.78	3.0	3.0	Peat	
6197	480	−4.16	3.0	3.0	Peat	
6798	150	−5.97	0.5	2.5	Lagoon. shell	

Table 1 (*continued*)

28—*Tagliamento*						
Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
4746	160	−7.3	0.5	2.5	Lagoon. shell	32

29—*Grado Lagoon*						
Ages (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
869	290	−0.9	0.5	2.5	Lagoon. shell	33
3657	290	−4.1	3.0	3.0	Peat.	
5855	225	−8.3	0.5	2.5	Lagoon. shell	
639	140	−3.3	0.5	2.5	Lagoon. shell	

30—*Aquileia*						
Ages (Archaeological attribution; AD)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
150	100	−0.80	0.5	0.5	Roman remain	34

31—*Djerba (Tunisia)*						
Ages (mean of 12) (cal yr BP)	Age error (± yr)	Altitude (m)	Altitude error (± m)		Marker	Ref.
5488	290	+0.40/+1.0	3	3	Infralittoral shell	35
1846	290	0	3	3	Infralittoral shell	

References: (1) Antonioli et al. (1999c); (2) Galoppini et al. (1996); (3) Alessio et al. (1996); (4) Antonioli et al. (2001b); (5) Bard et al. (2002); (6) Antonioli et al. (2004a,b); (7) Leoni and Dai Pra (1997); (8) Antonioli and Leoni (1998); (9) Schmiedt (1972); (10) Pirazzoli (1976); (11) Belluomini et al. (1986); (12) Antonioli et al. (1988); (13) Devoti et al. (2004); (14) Barra et al. (1996); (15) Morhange et al. (1999); (16) Antonioli and Oliverio (1996); (17) Esposito et al. (2004); (18) Antonioli et al. (2002 submitted); (19) Stewart et al. (1997); (20) Antonioli et al. (2003); (21) Antonioli et al. (1994); (22) Antonioli et al. (1999a); (23) Antonioli et al. (2002a); (24) De Muro and Orrù (1998); (25) Antonioli et al. (1998); (26) Pirazzoli et al. (1997); (27) Cherubini et al. (2000); (28) Auriemma (2002); (29) Correggiari et al. (1997); (30) Preti (1999); (31) Galassi and Marocco (1999); (32) Marocco (1991); (33) Marocco (1989); (34) Pirazzoli (1998); (35) Jedoui et al. (1998).

[a] For this site there is also an unpublished age of a flowstone, dated at 2370 cal BP, that covers the fossil material and consistent with the ages in this table.

* All radio carbon dates have been calibrated using the Bard (1998) and Stuiver et al. (1998) calibrations.

2004). These values are consistent with observations from Sardinia which is believed to have been tectonically stable during the recent glacial cycles and where the MIS 5.5 shoreline is typically found at 7–10.5 m in the east and at about 4 m in the northwest and at about 5 m in the south (Cala Mosca) where the Tyrrhenian (MIS 5.5) section was established by Gignoux (1913) (see comments on sites 19–20 below). With the following notation

$$\Delta H = H_{5.5} - \delta H_{5.5},$$

where $H_{5.5}$ is the elevation above mean sea level of the observed MIS 5.5 shoreline and $\delta H_{5.5}$ is the elevation of this shoreline in areas of tectonic stability, the uplift rate u and its variance σ_u^2 is given by

$$u = \Delta H / T_{5.5}, \qquad \sigma_\delta^2 = \sigma_{\Delta H}^2 / T_{5.5}^2 + (\Delta H / T_{5.5}^2)^2 \sigma_{T5.5}^2, \tag{1}$$

$T_{5.5}$ is the age of MIS 5.5 with standard deviation $\sigma_{T5.5}$ and $\sigma_{\Delta H}^2$ is the variance of the tectonic uplift ($= \sigma_{H5.5}^2 + \sigma_{\delta H5.5}^2$). We adopt the following values: $T_{5.5} = 124.5$ ka, $\sigma_{T5.5} = 5$ ka, $\delta H_{5.5} = 7$ m, $\sigma_{\delta H5.5} = 3$ m. $\sigma_{H5.5}$ is typically 3–5 m but at some sites may be larger.

1. ENEA Core, Versilia: A 70 m long core has recently been drilled in the Versilia Plain of Northern Tuscany yielding one of the more complete Holocene sea-level records for Italy (see Table 1). The first 34 m of the core contained sandy and thin marsh Holocene lagoonal sediments (Antonioli et al., 1999c) with ages from 2.23 ka near the surface to 10.15 ka cal. BP at −34 m. The age constraints are based on ^{14}C ages of marsh and lagoonal fossils shells, the greater part of which consist of the mollusc *Cerastoderma glaucum*. The lower portion of core intersects a lagoonal deposit at −69 m that contains *Cladocora* with conventional U–Th ages of (132–129±15) ka (Antonioli et al., 1999c). (TIMS age measurements are planned.) For the present this observation is interpreted as sea level at ∼−70 m at ∼130 ka BP, in agreement with the pre-Last Interglacial sea-level curve of Lambeck and Chappell (2001), indicating that the Versilia area is tectonically stable.

2. Castiglioncello: The archaeological site, consisting of a pre-roman sandstone quarry, of Castiglioncello

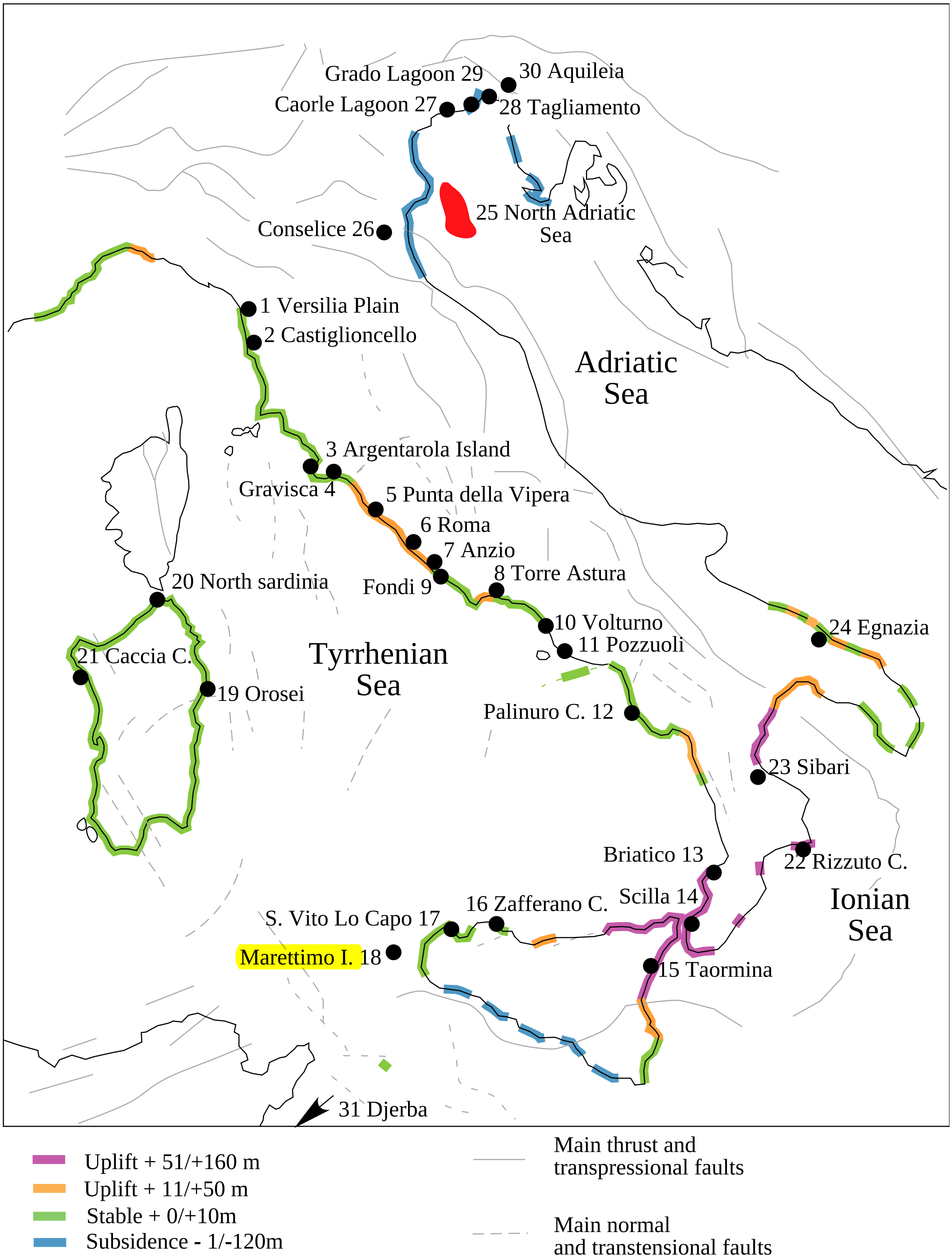


Fig. 1. Locations of the Italian sea-level sites (numbers correspond to Table 1) and the summary of the elevations of the MIS 5.5 shorelines relative to present sea level. Dashed colour coded lines refer to areas where the information is uncertain. The red area 25 defines the Adriatic core site locations. The principal faults are also shown.

lies in the rocky coastal zone of northern Tuscany (Galoppini et al., 1996). The quarry is carved down to 1.7 below present sea level and is archaeologically related to the Late Hellenistic period at ~2.3 ka BP (−300 AD). The altitude of the MIS 5.5 shoreline is a few meters above present sea level (Nisi et al., 2003) and we assume that the area has been tectonically stable.

3. Argentarola: The evidence here comes from speleothems found in a submerged cave in stratified dolomitic limestone bedrock on the small island of Argentarola located near the Argentario Promontory. The samples were collected by scuba diving at depths from 3.5 to 21.7 m measured with a digital depth gauge and corrected for a tide range of 0.24 m. Age control is provided by radiocarbon ages on marine and continental layers of the speleothems and range from 6.5 to 9.6 ka cal. BP (Alessio et al., 1996; Antonioli et al., 2001b; Bard et al., 2002). The Tyrrhenian sea level has been identified 7 km from the island by well-carved marine notches at 5.3 m above present sea level, indicating that the Argentario promontory is located in a tectonically stable area.

4. Gravisca: Archaeological remains consisted of a footway that now occurs at -1.47 m. Its historical attribution fixes its age at -300 to -400 AD (Leoni and Dai Pra, 1997). The MIS 5.5 sea level here is identified by inner margin deposits at an elevation of ~ 10 m and this site is considered to have been either tectonically stable or subject to an insignificant uplift of $0.02 \pm 0.03\ \mathrm{mm\,yr^{-1}}$.

5. Punta Della Vipera: Many Roman piscinae were studied and measured by Schmiedt (1972), Pirazzoli (1976) and Leoni and Dai Pra (1997). For Punta Della Vipera the measured altitude is given as ~ -0.40 m and its date of construction is 0 AD. The elevation of the MIS 5.5 transgression (inner margin sediments) reaches 30–35 m (Nisi et al., 2003) and we consider this area to have been tectonically active with an uplift rate of $0.23 \pm 0.05\ \mathrm{mm\,yr^{-1}}$.

6. Tevere Plain, Rome: The data at this site comes from cores drilled 2 km apart, east from the present-day coastline of the prograding Tevere Plain near the silted-up ancient Roman harbour. Belluomini et al. (1986) used sea-level markers consisting of ^{14}C-dated peat, marsh and wood fragments found between -3 and -31 m. The corresponding calibrated ages are in the interval 5.9–11 ka cal. BP. The tectonic history of the Rome Plain is unclear. Some 30 km to the north within the plain there are sites where the MIS 5.5 inner margin reaches an altitude of about 35 m (Nisi et al., 2003). This is consistent with a result by Karner et al. (2001) who measured the 5.5 inner margin adjacent to the plain at 25 m elevation. We suggest that the tectonics can be characterized by a continuous but slow rate of uplift (since MIS 22 and correlating with regional volcanic activity) of $0.15 \pm 0.05\ \mathrm{mm\,yr^{-1}}$.

7. Anzio: The archaeological marker is a now-flooded ancient harbour works consisting of remains of caissons used in the construction of piers (Auriemma, 2002). Its historical age is 110 A.D. and indicative of a sea-level change of -0.56 m (Leoni and Dai Pra, 1997). The altitude of the 5.5 transgression here occurs at ~ 10 m above present sea level (Nisi et al., 2003) and we assume that the site is effectively stable (uplift of $0.02 \pm 0.05\ \mathrm{mm\,yr^{-1}}$).

8. Torre Astura: The Roman piscinae of Torre Astura, 50 km south of Rome, were studied by Schmiedt (1972), Pirazzoli (1976) and Leoni and Dai Pra (1997). Pirazzoli estimated sea level at time of construction as -0.50 m compared with -0.39 m by Leoni and Dai Pra whose value we adopt here. The historical age is ~ 50 AD. The position of the MIS 5.5 highstand is consistent with an absence of tectonic movement (Nisi et al., 2003) and we assume that the principal contribution to sea-level change here is the eustatic-isostatic contribution.

9. Fondi: Fondi Plain, 110 km south of Rome, is a small coastal plain with outcropping Holocene lagoonal deposits. Samples containing *Cerastoderma* at -1.8 m previously gave an ^{14}C age of about 7.5 ka cal. BP (Antonioli et al., 1988). More recently a core was drilled near the outcrops that intersected marine sediments that filled a palaeo-valley carved during the LGM (Devoti et al., 2004). Marine shells between -3 and -33.7 m yielded calibrated ages in the interval 7.4–8.6 ka cal. BP. Within the limestone bordering the plain, undated marine notches occur at $+7.3$ m, in contrast to lagoonal deposits of MIS 5.5 age in a core within the plain itself at -6.5 m (Antonioli et al., 1988). If these notches are of MIS 5.5 age, then the latter are indicative of a slow subsidence of the plain at $\sim -0.11 \pm 0.03\ \mathrm{mm\,yr^{-1}}$ relative to its limestone promontories. The Fondi observations in the time interval 7.5–8.7 ka fall into two distinct depth ranges (see Table 1), possibly indicating that the infralittoral shells may be from a greater depth range than assumed above for the fossil sand beach deposits, or that the ages for the shallow group of observations have been contaminated.

10. Volturno: The Volturno River coastal plain formed during the Holocene as a complex of beach-ridges and flat back-barrier depressions with lagoonal sedimentation. Lagoonal facies have been found in a core located at 2.5 km from the present beach over a depth range of 10 m. Radiocarbon ages of peats found in this core are given by Barra et al. (1996) and the calibrated ages span the interval from 4.8 ka at -3 m to 7.4 ka BP at -8 m. Romano et al. (1994) published data on the MIS 5.5 highstand showing elevations fluctuating from -50 up to $+50$ m depending on whether the evidence came from near the centre of the plain or from the adjacent limestone outcrops and, as for Fondi, the plain appears to have subsided relative to the adjacent promontories. The core site used here is from a locality within the plain and near its edge and a nominal value of zero uplift is adopted for the present.

11. Pozzuoli: The Pozzuoli coastal area is famous for its episodic vertical movements, which over the past 2000 years have reached several meters in amplitude, within the active volcanic caldera of the Phlaegrean fields near Naples. Biological sea-level indicators were documented up to 7 m above present on the Roman columns (cf. Lyell, 1877) and have been dated more recently by Morhange et al. (1999). Because of the irregular nature of these movements the information from this site is not used in the sea-level analysis but we return to it in the discussion section.

12. Palinuro (Scaletta cave): The Palinuro promontory is a morphostructural high with peaks of 170 m that merges landward into the main carbonate relief of the southern Apennines. Speleothems from the Scaletta cave were sampled at depths between 27 and 48 m and yielded ages from 8.4 to 10.2 ka cal. BP (Alessio et al., 1996; Antonioli and Oliverio, 1996). All of the sampled speleothems showed a marine crust of serpulids over karstic material and in some *lithophaga* occurred as the first marine colonizers of the karstic speleothem during the sea-level rise. The accuracy of the depth measurements, including depth-gauge uncertainties, tidal corrections and sampling position, are estimated to be ± 0.5 m. A precision survey of morphological and stratigraphical relationships indicates that the Palinuro Cape is tectonically quasi-stable (Antonioli et al., 1996a). The Tyrrhenian (MIS 5.5) sea-level marker elevation is well developed at 10 sites where well-carved marine notches occur at elevations of 2.1–2.2 m above present mean sea level. Thus, we assume a slow subsidence of about -0.04 ± 0.03 mm yr^{-1}, a rate that is consistent with tectonic stability.

13. Briatico: The evidence from this archaeological site on the Tyrrhenian coast of Calabria consists of fish tanks that are characteristic of the Roman epoch. The archaeological age of this feature is 0 AD, consistent with a radiocarbon age (1.88 ka cal. BP) of wood used in repairs to the foundations of one of the tanks. The mean sea level at this epoch is estimated to have been the same as its present value (Esposito et al., 2004). A MIS 5.5 inner margin was found in terraces at 65 m above sea level (Miyauchi et al., 1994) yielding an average tectonic uplift rate of 0.47 ± 0.04 mm yr^{-1}. Well-carved marine notches also occur within the tanks and post-date their construction. In so far as sea levels at other stable sites indicate that levels during the Late Holocene occurred below present, this indicates that the uplift continued into recent time at a rate about equal to the a-tectonic sea-level rise.

14. Scilla: At three locations at this site in southern Calabria, Antonioli et al. (2004a, b) identified Holocene fossiliferous beach deposits at elevations between 3 and 3.4 m above present sea level with ^{14}C ages of between 2.7 and 3.9 ka cal. BP. The inner margin of an impressive terrace related to the MIS 5.5 highstand by Miyauchi et al. (1994) occurs at 125 m above sea level, giving a tectonic uplift rate of 0.95 ± 0.06 mm yr^{-1}. A lower limit of the positional uncertainties of 2 m for the non-infralittoral sampled fossils has been established from subsurface morphology transects.

15. Taormina: Data from Taormina, eastern Sicily, have been reported by Stewart et al. (1997) and Antonioli et al. (2003). Dated samples of lithophaga, cladocora and vermetids from 1.8 up to 5.9 ka cal. BP occur at 1.5–3.4 m above sea level. The error bars for the intertidal Vermetids *Dendropoma* is ± 0.10 m. Observations along scuba transects provide a lower limit for the non-infralittoral fossils of about 2 m below the sample position. The MIS 5.5 highstands, consisting of an inner margin of a terrace with fossiliferous conglomerates (dated by Antonioli et al., 2002b), lie above the Holocene uplifted fossils at 115 m, giving an uplift rate of about 0.87 ± 0.06 mm yr^{-1}.

16. Capo Zafferano: A deposit of shell remains (*Patella ferruginea* with *Trochus* sp.) associated with stone artifacts (weapons, scrapers, etc.) of Mesolithic age has been identified in an emerged karstic cave. Underwater investigation of the site, now completely isolated from the sea by steep walls, indicate a submerged terrace at -20 m that formed a continuous strip around the promontory and which provided access to the cave during Mesolithic time. The observation is an upper limit estimate, consisting of remains of Neolithic occupation in a cave only accessible from the rock platform. The site is west facing and today is subject to storm-wave action up to 6 m above sea level. Thus for the deposits to have survived, the human occupation would have corresponded to a time when the platform was at least this high above sea level. The shells give an age of 9.5 ka cal. BP. Antonioli et al. (1994) also identified the MIS 5.5 transgression at Capo Zafferano from Tyrrhenian deposits at 3 m that correlate with a marine notch at 7 m. Thus the area is assumed to have been tectonically stable.

17. San Vito lo Capo: Antonioli et al. (1999a) collected two vermetid reef samples from San Vito lo Capo (Sicily) at -0.3 and -0.4 m with ^{14}C-determined ages of 0.2 and 0.4 ka cal. BP from ~ 2 cm thick samples. At the time of sampling, modern *Dendropoma* were living on the top of the reef. The northwest coast of San Vito lo Capo has been subjected to an average, long-term uplift of only $\sim 5 \times 10^{-3}$ mm yr^{-1} for the past 125,000 years (Antonioli et al., 1999b) and in the first instance we consider this to be a stable site.

18. Marettimo Island: The island of Marettimo is located in the archipelago of the Egadi (Sicily). In the southern portion of the island a submerged karstic system has been preserved consisting of a wide horizontal tunnel. Inside the cave Antonioli et al. (2002a) sampled, at a depth of 24 ± 0.5 m, a stalactite covered by serpulids and containing *Lithodoma*. The ^{14}C-based age of the latter is 9.6 ka cal. BP. Fossiliferous sand and conglomerates, containing *S. bubonis*, occur in small borders along the shoreline of the island at between 2 and 10 m above sea level and these establish that the marine notches carved from 5 to 8.20 m correspond to MIS 5.5. Thus, Marettimo Island appears to have been stable since the Last Interglacial.

19–20. Orosei and northern Sardinia: A great number of well-conserved palaeo-shorelines have been discovered in northern Sardinia on the continental shelf up to depths of −120 m. De Muro and Orrù (1998) observed beach deposits (sandstone and conglomerates) on an erosional platform of crystalline bedrock at depths ranging from 0 to 55 m from two main localities; Orosei (19), and northern Sardinia (20). Beach rock has been sampled at a number of sites on the northern Sardinia continental shelf where it does not exhibit active erosive morphologies. The chronology has been established from ^{14}C dating of the carbonate matrix that was considered to correspond to early-stage magnesium-calcite cementation, with samples ranging in age from 0.2 up to 9.7 ka cal. BP at progressively deeper depths of 0–29 m below present sea level. Because the matrix ages must be considered as uncertain and likely to be younger than measured, we have adopted large lower limit uncertainties for the depth estimates and we adopt the depth error bars of +1 and −5 m published by De Muro and Orrù (1998). Pleistocene marine deposits and notches that correlate with MIS 5.5 occur at elevations of 3.5–10.5 m along the coastline and Sardinia is assumed to be tectonically stable.

21. Cape Caccia–Grotta Verde: Cape Caccia is a mainly limestone promontory located on the north-western side of Sardinia. The Grotta Verde is a large cave at the end of which is a lake that is directly connected to the sea. A now-submerged Early Neolithic burial site has been discovered at −8.5 m. The archaeological style of a nearby settlement allows the age to be established as 7.0±2 ka BP (Antonioli et al., 1996b) and local sea level was lower than −8.5 m at this time. The promontory, bordered by steep cliffs, is cut by a notch associated with characteristic MIS 5.5 fauna at between 3.5 and 5.4 m above mean sea level. Also, two phreatic speleothems, located at 4.2–4.3, metres above present sea level have been sampled in Nettuno Cave (500 m from Grotta Verde) and U–Th TIMS dated at ~117±2 and 120±2 ka, respectively (Tuccimei et al., 2000). Thus we conclude that this promontory has also been tectonically stable (or very slowly subsiding at $-0.02\pm0.03\,\mathrm{mm\,yr^{-1}}$d) during the last glacial cycle.

22. Capo Rizzuto: The site of Chiacolilli, located near Capo Rizzuto bordering the Ionian sea, was investigated by Pirazzoli et al. (1997) who sampled and dated a calcareous algae in growth position that covered beach rock at an altitude of 0.6 m. Radiocarbon analysis provided an age (uncorrected for δ^{13}C) of 2.7 ka cal. BP. The inner margin of MIS 5.5 terraces, a few km from coastline occurs at an altitude between 84 and 110 m (Bordoni and Valensise, 1998) yielding an average uplift rate of about $0.73\pm0.11\,\mathrm{mm\,yr^{-1}}$.

23. Sybaris: Archaeological excavations on the alluvial plain of Sybaris have led to the identification of three superimposed levels of occupancy from the 6th to the 1st century BC: ancient Sibari, the Hellenistic town of Thurium, and Roman Copia. This plain forms a graben that runs in an ENE-WSW direction, bordered by regional fault systems. The upper part of this depression is filled with ~400 m of deposits consisting of sands including fine clay-sands and peat levels at various depth. A core from the plain yielded ^{14}C-based ages in the interval 5.3–11.1 ka cal. BP for peats and marsh deposits from depths of 3–55 m below sea level (Cherubini et al., 2000). The inner margins of MIS 5.5 terraces occurs at an altitude of 115 m (in Bordoni and Valensise, 1998) giving an uplift rate of $0.87\pm0.06\,\mathrm{mm\,yr^{-1}}$. However the core sites lie within a fault-bounded plain while the inner margin observations lie inland from the plain so that this tectonic uplift estimate may be too high.

24. Egnazia: Egnazia is an old town located near Brindisi (Apulia) with periods of occupation from proto-historic age to late ancient-medieval time. Auriemma (2002) identified a caisson used in harbour construction that bears a well-defined relationship to mean sea level and whose historic age is Roman or about 2030 yr BP. Its positional relationship indicates that sea level at this time was 3 m below present level (data uncorrected for tide). The MIS 5.5 inner margin altitude in this area is unclear and lacks an age determination. Values of between 4 and 30 m above sea level are given in Bordoni and Valensise (1998). For the present we adopt a mean elevation of 15 and slow uplift of $0.08\pm0.11\,\mathrm{mm\,yr^{-1}}$.

25. North Adriatic cores: The northern part of the Adriatic Sea is characterized by a shallow sea-bottom morphology (at 30–50 m depth) with sediments deposited by the Po River in the immediate offshore area. The low shelf gradient and the lower sediment input near the central part of the basin results in significant landward shifts of depositional environments at times of sea-level rise. In consequence, successive backstepping sequences do not completely overlap. Furthermore, transgressive deposits are not always covered by younger highstand sediments and they can, therefore, be selectively sampled using conventional gravity and piston coring (Correggiari et al., 1997). Sediment cores from a number of sites have yielded 23 depth–age data points within the depth interval from 26 to 52 m with radiocarbon-based ages of 9.3–12.9 ka cal. BP. The sample depths within any core are mostly within 1 or 2 m below the sea floor and never exceed 5 m, even for the oldest samples, indicating low sedimentation rates at these localities.

The coastal zone of the northern Adriatic Sea appears to be mostly a region of subsidence with MIS 5.5 deposits always occurring below present sea level. For example, in cores near the coast at Ravenna, Last

Interglacial (the age is based on palynological analyses) beach sands were identified at -120 m (Amorosi et al., 1999) indicating a subsidence rate of 1 mm yr^{-1}. Bondesan et al. (1995) established a long-term subsidence rate of $\sim$1.1 mm yr^{-1} for the Padana Plain of the Po delta and Kent et al. (2002) found MIS 5.5 deposits at -79 m within a core drilled near Venice, giving a subsidence rate of 0.69 ± 0.06 mm yr^{-1}. Further to the east, near Trieste, the MIS 5.5 levels have been reported at ~ -20 m (Pirazzoli, pers. comm.) giving an average subsidence rate of $\sim$0.15 mm yr^{-1}. Thus there is no simple spatial pattern for the subsidence within and along the coast of the North Adriatic Sea other than that the rates decrease with distance from the Po Delta. Offshore subsidence rates can be expected to be less than the coastal values because the rates of sediment deposition are much less than in the now-onshore part of the Po Delta itself. In the absence of specific evidence from the core sites we assume a value of zero and use the comparison of the data with the model predictions to test this hypothesis.

26. Conselice: An inland core from the alluvial Po Plain at Conselice reached Holocene marine sediment and indicates that between 6 and 7 ka BP the coastline occurred more than 26 km inland from its present position. This data set provides an interesting reconstruction of local sea-level rise. Two samples (Preti, 1999) define sea level below -9.8 m at 6.7 ka and above -9.0 m at 5.9 ka. The subsidence for this locality, based on the core of Amorosi et al. (1999) discussed above, is assumed to be 1.0 ± 0.25 mm yr^{-1}.

27. Caorle lagoon; 28. Tagliamento Lagoon; 29. Grado Lagoon: Several cores have been drilled in different lagoons between Venice and Trieste in which lagoonal shells and marsh deposits have been identified. Radiocarbon analyses indicate ages from 0.9 to 9 ka cal. BP at elevations of -0.90 to -8.30 m (Marocco, 1991, 1989; Galassi and Marocco, 1999). Shell species have not always been identified but, because most of the sea-level markers are based on the peat or marsh horizons, we assume here that they are associated with lagoonal environments. Because of this uncertainty positional error bars of ± 3 m are adopted. Pirazzoli (1998) noted that because Pleistocene emerged shorelines are lacking for this region, the possibility for slow tectonic subsidence should not be ignored. From the evidence discussed above we have assumed a linear gradient in the subsidence rate from 0.7 mm yr^{-1} near Venice to 0.15 mm yr^{-1} near Trieste, giving 0.45, 0.37, 0.28 mm yr^{-1} for the subsidence at Caorle, Tagliamento and Grado lagoons, respectively. Nominal precision estimates of ± 0.2 mm yr^{-1} have been adopted for all sites.

30. Aquileia: This is a Roman epoch town from the first half of first century AD and the sea-level marker is from its fluvial harbour connected to sea level. The upper surface of paving stones of the quay is now close to modern water level and the relative sea level at time of construction must have been 0.8 m lower than today (Pirazzoli, 1998). Recent research (including scuba-dive transects) in the adjacent Trieste limestone cliffs by Antonioli confirms the absence of older sea levels higher than present. A well-developed submerged marine notch has been found at -2.2 m at localities between Trieste and the Croatia coast that appears to be of Holocene age and this is consistent with subsidence for this section of the coast. For the present we adopt the above linear interpolation to give -0.28 ± 0.2 mm yr^{-1} for Aquileia.

31. Djerba (Tunisia): Because a diagnostic feature of the models for the prediction of sea level during the Holocene is the gradient of isobases orthogonal to the former ice sheet margins we have included one site from Tunisia as a further test of the validity of the models. The evidence is from Holocene deposits on Djerba island (Gabès Gulf) at 0 and 1 m above present sea level (Jedoui et al., 1998). Ages and elevations for the individual shells sampled are not given but they range from 1.8 ka cal. BP (based on the mean of two ages at $\sim$0 m elevation) to 5.5 ka cal. BP (the mean of 7 ages between 0.4 and 1.0 m elevation). The shells are not from lagoonal species and not all shells appear to be in their in situ position, they suggest that sea levels for the southern Tunisia coast may have been higher than present-day level. Since the MIS 5.5 highstand has been identified here by silici-clastic units of up to 3 m elevation overlain by carbonate-rich deposits containing *Strombus bubonis* up to 5 m above present sea level (Jedoui et al., 2003), the coast appears to be tectonically stable and the observations may provide a useful check on predictions of the north–south isostatic sea-level gradient.

4. Predicted sea-level change data

Local measurements of sea-level change provide the temporal variation of the relative position of the sea surface and the adjacent land. They contain, therefore, information on both the vertical movement of the land and the vertical displacement of the ocean surface. The latter results from change in ocean volume, change in geometry of the ocean basins, and redistribution of water within the basins. On the time scale of the glacial cycles the primary reason for the regional fluctuations in sea level within the Mediterranean basin is the exchange of mass between the ice sheets and the oceans as climate oscillates between cold and warm conditions. The resulting pattern of change is complex because of the deformation of the Earth under the changing surface load of ice and water and the associated gravitational changes. These are the glacio-hydro-isostatic effects. In the case of the Italian coast the principal glacio-isostatic contribution is the Earth's response to the loading and unloading of the Northern Hemisphere ice sheets. During loading, a broad and shallow bulge develops out to several thousand kilometers from the centres of the ice sheets and this subsides during the deglaciation phase (cf. Lambeck, 1995; Lambeck and Johnston, 1995). Like much of the Mediterranean, Italy is located on this bulge and relative sea levels here rise during the Holocene even after ice volumes have stabilized. The principal hydro-isostatic effect is the changing load on the sea floor as ice sheets grow or shrink, with the consequence that the sea floor subsides during and after deglaciation while larger land bodies tend to be uplifted. To these effects must be added lesser isostatic components that result from the global changes in the planetary shape, rotation and gravity during the glacial cycle.

Numerical models with high resolution have been developed over recent years that give realistic representations of the spatial variability of the sea-level change and shoreline evolution if the history of the ice sheets through time is known (Lambeck and Johnston, 1998; Lambeck et al., 2003). One unknown in these models is the rheological response function of the Earth. This is usually inferred from observations of sea-level change themselves. Likewise, the hypothesis that the ice model is adequately known can be tested by comparing observed and predicted sea levels. However, such comparisons require that any land uplift or subsidence from non glacio-hydro-isostatic causes is not important or, if it is, that it can be independently assessed. As illustrated by the above examples, the assumption of zero tectonic contributions cannot be justified for many segments of the Italian coast. But, if the predictions can be calibrated with observational data from stable sites, we can use the model to infer the tectonic rates at the unstable localities. We use, as discussed above, the observation of the position of the Last Interglacial shoreline (MIS 5.5) to assess whether a section of the coast is likely to be tectonically stable or not. The so-calibrated model can then be used as an interpolation devise to estimate tectonic rates from uplifting or subsiding regions where we do not have satisfactory independent estimates of vertical tectonic rates or to test the hypothesis of uniform rates of vertical movement.

The isostatic model allows for a high-spatial and temporal resolution of the ice–water load with a rigorous definition of the distribution of the meltwater into the oceans to include:

(i) Conservation of water–ice mass and the requirement that the ocean surface remains an equipotential (Farrell and Clark, 1976).
(ii) The global deformation of the sea floor and its associated redistribution of ocean water during the glacial cycle (Nakada and Lambeck, 1987; Mitrovica and Peltier, 1991).
(iii) Migration of shorelines as sea levels rise and fall (Lambeck and Nakada, 1990).
(iv) Rigorous treatment of ice on the shelves as it changes from being grounded to floating as it thins or as sea levels rise (Lambeck and Johnston, 1998; Lambeck et al., 2003; Mitrovica and Milne, 2003).
(v) Contributions from glaciation-induced changes in the Earth's rotation (Milne and Mitrovica, 1998).

As previously demonstrated, the spatial variability of sea level around the Italian coast is significant (Lambeck and Johnston, 1995) and it will generally not be permissible to combine data from different localities into a single sea-level curve without first establishing that such variability is less than the observational accuracy. This is illustrated in Fig. 2a for predictions at sites at different distances from the former Scandinavian ice sheet. Compare, for example, the predictions for sites *29*, *1*, *7*, *15* (the numbers refer to the site numbers in Section 3). Here the differences for Early Holocene time are of the order of 15 m, with the northern sites yielding systematically higher sea levels than the southern sites. Within smaller regions, the spatial variability is also not wholly negligible as is shown by the results in Fig. 2b for localities in Sardinia. These results represent differences in prediction from their mean value for the 12 individual sites within the observation group *20*. Differences here never exceed 0.5 m for the last 14 ka but they become larger when Orosei, on the east coast of Sardinia, is included. Thus, rather than combining observational data into single sea-level curves when we compare the observations and predictions, the comparisons are made for the location of each observation. Of note is that the predicted levels for all Italian sites never rise above present sea level at any time during the Lateglacial and Holocene intervals. Thus any observations of Holocene shorelines higher than present sea level provide an immediate diagnostic for tectonic uplift.

The earth- and ice-model parameters used in the above prediction have previously been found to give a good description of the sea-level change in the Mediterranean region and have been defined by Lambeck et al. (2002). Estimates of the accuracy of these predictions are based on the accuracy of the earth- and ice-model parameters where the latter include (i) the uncertainty arising from the descriptions of the individual ice loads, and (ii) the uncertainty of the ice-volume equivalent sea-level function describing the globally averaged sea-level change. The earth-model uncertainty is estimated by predicting sea levels at the measurement sites for a range of earth models that encompass the probable values and calculating the root-mean-square values of the departures from the mean. The adopted range is 50–80 km for the lithospheric thickness (H_l), $(2–4) \times 10^{20}$ Pa s for the upper-mantle viscosity (μ_{um})

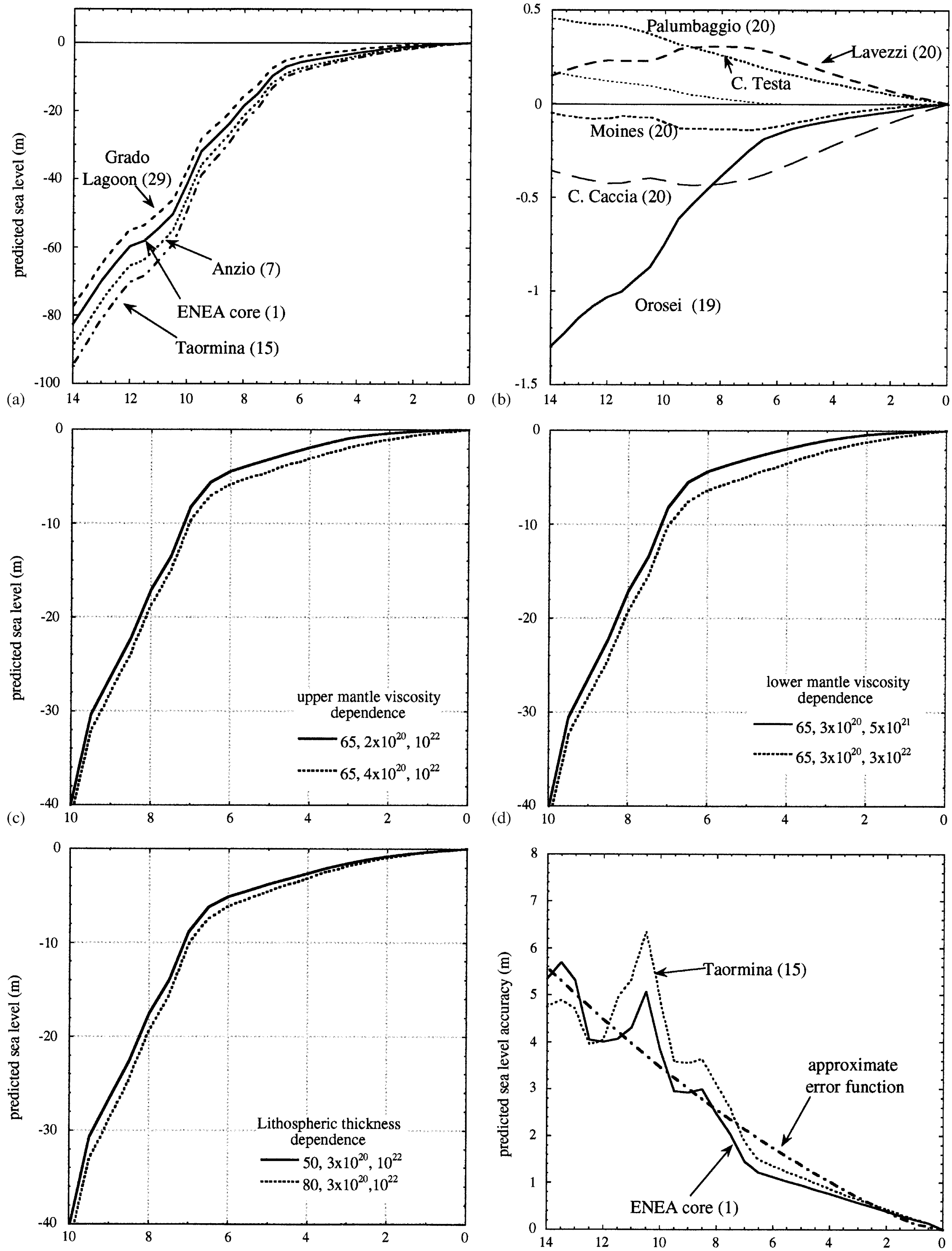


Fig. 2. Predicted sea levels, based on nominal earth- and ice-model parameters and glacio-hydro-isostatic theory, for four sites in Italy characterised by their increasing distance from the former northern polar ice caps from Grado lagoon in the North Adriatic to Taormina in Sicily. (See Fig. 1 for locations.) (b) Departures of predicted sea levels at five locations in northern Sardinia from the mean predicted value for all 12 locations (*20*), and the predicted departure from this mean for the east Sardinia site at Orosei (*19*). (c–e) Predicted earth-model dependence of sea level for the Versilia Plain core site (*1*). The six earth models defining the parameter space are characterised by three parameters, an effective elastic thickness of the lithosphere (km), the effective upper mantle viscosity (Pa s), and the effective lower mantle viscosity (Pa s). The range of parameter used covers values that are representative of solutions for the Mediterranean and other regions. (c) upper mantle viscosity dependence, (d) lower mantle viscosity dependence, and (e) lithospheric thickness dependence. (f) The error function at two sites for the predicted sea level resulting from uncertainties in the earth- and ice-model parameters and the adopted approximate error function (dashed line) for the interval 0–14 ka BP.

and (5–30) $\times 10^{21}$ Pa s for the lower-mantle viscosity (μ_{lm}). The range of predicted values for these effective model parameters are shown in Fig. 2(c)–(e) for the ENEA core locality (site 1). The major variation in this parameter range occurs for the lower mantle viscosity (Fig. 2d) reflecting the role of deep mantle flow towards the former areas of glaciation during the deglaciation phase. But the dependence on upper mantle viscosity is also important, even within the relatively narrow range of values with which this parameter is defined in rebound analyses. Models of low viscosity—for either the lower or upper mantle—yield predictions that lie higher than those for high viscosity models, and the comparison of results in Figs. 2c and d indicate some of the trade-offs that can occur at sites, with low μ_{lm} models leading to similar predictions at Versilia as low μ_{um} models. These trade-offs change with location from north to south but for the restricted positional range full separation of parameters may not be achieved and in this case we adopt μ_{lm} values determined from more global analyses where such separation has been more effective (Lambeck et al., 1998).

The ice-volume-equivalent sea-level function (or eustatic function in the absence of any other contribution to ocean volume change) is taken from Lambeck et al. (2002) for epochs from the LGM to 7 ka, Lambeck (2002) for the last 7 ka, and Lambeck and Chappell (2001) for the period before the LGM. The contributions to the uncertainty of the sea-level prediction arising from the limitations of the individual ice models are estimated in the same way as in Lambeck and Bard (2000); using a range of different ice models for North America and Europe to predict the sea levels at the Italian sites. For North America two models have been used that represent upper and lower limits to the ice models that are consistent with sea-level data from that region. One is based on the Licciardi et al. (1998) model and the second is based on a modified version of ICE-1 from Peltier and Andrews (1976). For the European ice sheet, the isostatic corrections have been predicted for three different models that span the permissible range in so far as agreement with the rebound data from Scandinavia is concerned (Lambeck et al., 1998). The influence of the uncertainty of the ice model is then estimated from the range of the sea-level predictions at the individual sites using different combinations of ice-sheet models. The precision of the global equivalent sea-level function is based on the root-mean-square scatter obtained from the combination of the isostatically corrected sea-level data from far-field sites discussed in Lambeck et al. (2002).

The different model errors are added in quadrature to provide an estimate of the total prediction uncertainty σ_{pred} for each locality and for each epoch. Fig. 2f illustrates the total prediction uncertainty for two localities (*1*, *15*). (These estimates tend to be conservative because they ignore the trade-off that occurs between some of the parameters.) At both, the maximum values are reached for $T \sim 14$ ka and the error functions are representative for the other Italian sites as well. For convenience we use a spatially averaged σ_{pred} for all sites within the Italian Peninsula of

$$\sigma_{pred} = -0.13 + 0.24T + 0.012T^2, \quad 1 > T > 14\,\text{ka}, \qquad \sigma_{pred} = 0.12T, \quad T < 1\,\text{ka}. \tag{2}$$

5. Comparison of predicted and observed sea levels

5.1. Tectonically stable sites

The most comprehensive data set is from the tectonically stable Versilia Plain (*1*) and Fig. 3a illustrates the comparison between the predicted and observed values where the former are represented by the upper and lower limits defined by σ_{pred}. With the exception of the single point at 7.87 ka BP, agreement between the observed and predicted values is within the combined observational and model uncertainties and the model describes well the observed sea-level change in the time interval spanned by the data. The exception corresponds to one of three samples of very similar age (Table 1), but with the other two corresponding to a higher horizon. The sediments and some foraminifera of the 7.81 ka BP sample are indicative of a lagoonal environment and provide a more precise indicator than the infralittoral shells at 7.87 ka which can live in deeper water, although they do occur here in association with other shallow-water species.

The Argentarola Island data (3) display greater discrepancies between observations and predictions (Fig. 3b). The five ages for samples from −18.5 m indicate that the terrestrial speleothem ages, corresponding to a time before emergence, are significantly older than the two ages of the encrusted serpulid at the same position. Thus the hiatus between the two types of samples may be as long as 2000 years and we do not use the terrestrial ages when serpulid or lithophaga ages are available. But the serpulid ages also exhibit some anomalies, with the sample at 21.5 m depth giving an older age than the terrestrial speleothem sample from the same location, and possibly the ages are too old because of contamination by older carbon from the speleothems.

Agreement between observations and predictions for the archaeological data from the four tectonically stable sites from the northern Tyrrhenian coast (*2*, *4*, *7*, *8*) is generally satisfactory. The two younger data points from Anzio and T. Astura lie higher than the predicted values by about 0.2–0.5 m (Fig. 3c), consistent with the functions of the two piscinae being filled at highest tidal levels.

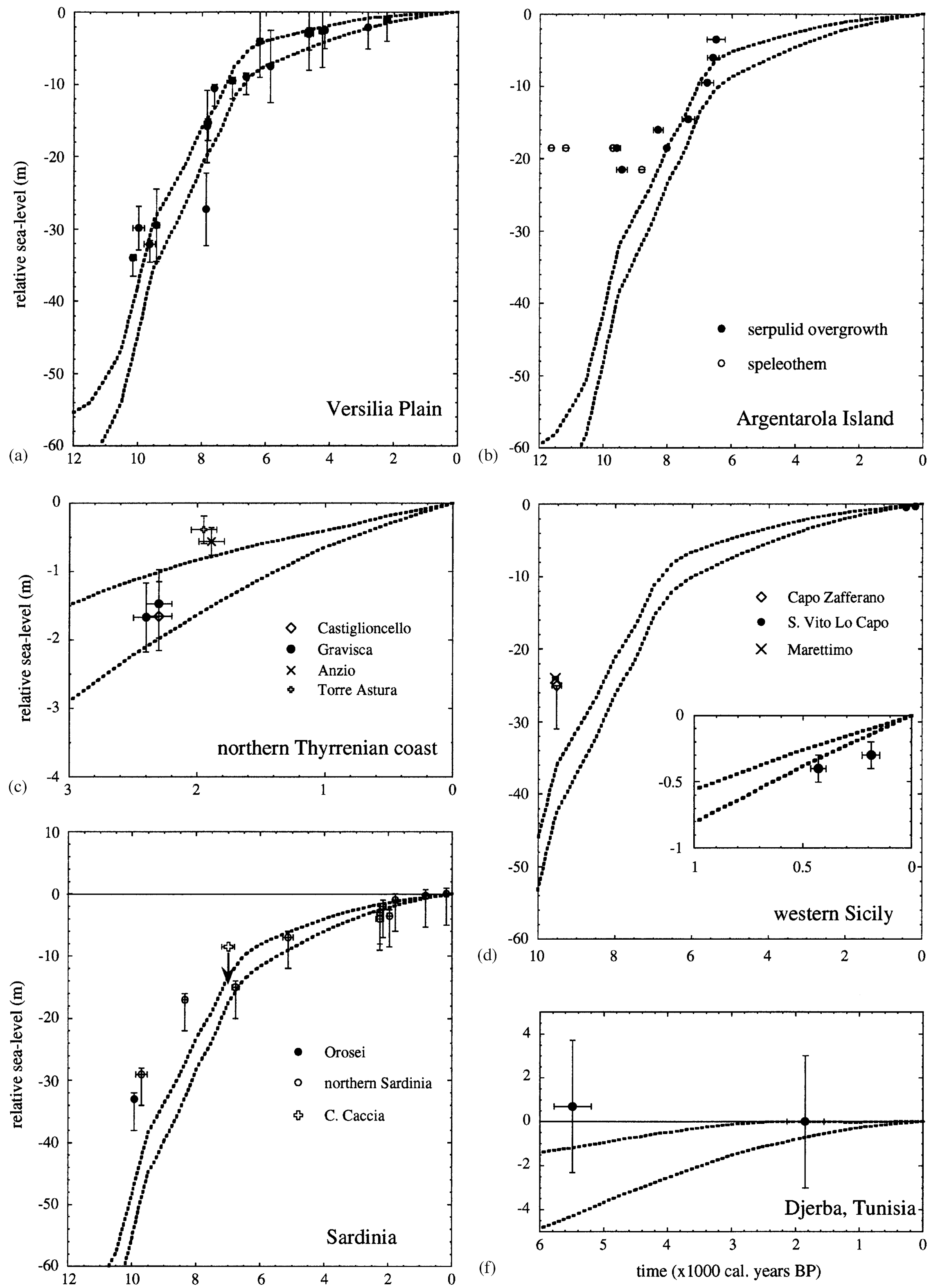


Fig. 3. Comparisons of observed (points with error bars) and predicted sea levels at tectonically stable sites. The upper and lower limits of the latter are shown by the dashed lines. For Argentarola, both the terrestrial and marine ages for the speleothems are indicated. The inset in (d) is for the S. Vito Lo Capo data points. Where results from several sites have been grouped into a single panel for illustrative convenience only, the predicted sea levels for the time interval of observations vary by much less than their uncertainties and the predicted values shown correspond to representative sites within each group: Gravisca in (c), S. Vito Lo Capo in (d), and northern Sardinia in (e).

The comparisons for the three sites from western Sicily (*16*, *17*, *18*) that have been assessed as being tectonically stable are illustrated in Fig. 3d. The observation from Capo Zafferano (16) at ~9.5 ka BP is, as discussed above, an upper limit estimate and the observation suggests that the cave was occupied when the platform was well above the zone of storm-wave action. The Marettimo (18) observation from the same depth is from lithophaga within a speleothem. The speleothem age itself is much older, ~24 ka BP, and indicative of a long hiatus between its growth and the subsequent marine colonisation. The lithophaga age is similar to that of the Mesolithic site at Capo Zafferano and this implies that either the lithophaga age is too old or that the assumption of tectonic stability for Marettimo is invalid. The MIS 5.5 shoreline is, however, well developed here at an elevation that is consistent with tectonic stability and either the lithophaga ages are unreliable or the site has undergone periods of almost compensating uplift and subsistence. The two observations from San Vito Lo Capo (*17*) both lie near the lower limit of the predicted values (see inset, Fig. 3c).

The younger beach rock observations from eastern (*19*) and (*20*) northern Sardinia yield age–depth results that are consistent with the model predictions but before about 8000 BP the three observed depths are consistently higher than the predicted values for the epoch of observation. This suggests one of several possibilities: inappropriate isostatic–eustatic model parameters, beach-rock ages that are too old, or that the older beach rock formed at supra-tidal elevations. The archaeological observation at ~7 ka from Caccia Cape (*21*) is an upper limit and is compatible with the beach rock observation from the north coast. The evidence at ~10 ka BP from both Marettimo (Fig. 3d) and Sardinia could point to the predictions being too deep, but this would be inconsistent with the Versilia Plain results for the same epoch (Fig. 3a). Also, the observed spatial variability is too large to attribute these discrepancies to the choice of model parameters.

The two observations from Djerba (*31*), Tunisia, (Fig. 3f) indicate that here there has been little sea-level change over the past 6000 years, consistent with the predictions that Late Holocene levels here occur higher than in Italy (compare the predictions in Fig. 3f with those for the other sites). The marine shells used to date the deposits are not in situ and it is possible that they represent storm deposits in which case their elevations may be too high.

5.2. Tectonically uplifting sites

Figs. 4a and b illustrate the comparisons of observed and predicted sea levels for areas undergoing tectonic uplift as discussed in Section 4. Both observed and tectonically corrected observations are illustrated. The accuracy estimates of the latter, $\sigma_{\mathrm{t.c.obs}}$, include the uncertainty in the tectonic correction according to

$$\sigma_{\mathrm{t.c.obs}} = (\sigma^2_{\mathrm{obs}} + u^2\sigma^2_t + t^2\sigma^2_u), \tag{3}$$

where σ_{obs} is the standard deviation of the observed position at time t, u and σ_{u} are the rate and its precision of tectonic uplift given by (1), and σ_{t} is the precision of the age determination at time t. The comparisons for the Rome plain (*6*) are illustrated in Fig. 4a along with the result for Punta della Vipera (*5*). As in Fig. 3 upper and lower estimates of the predictions are illustrated. A number of the core samples are dated wood fragments found in clay horizons that correspond to upper limits to sea level. Also, depending on the source of the wood fragments the ages may predate the time of first flooding. The other data are from salt marsh deposits that are indicative of levels above but close to sea level. These latter observations are mostly in good agreement with the model values back to about 10,000 years BP whereas the clay-wood samples lie consistently above their corresponding predicted values. In view of the latter corresponding to upper-limiting heights and lower-limiting ages we adopt the salt marsh results in preference to the clay-horizon results.

The comparisons for eastern Sicily (*15*) and southern Calabria (*13*, *14*, *22*, *23*, *24*) are shown in Fig. 3b. The spatial variability of the model predictions across this region is small when compared with observational uncertainties and the predictions shown correspond to the average value for these sites. The tectonically corrected observations for Sybaris (*23*) lie near the lower limit of the predicted values and this may indicate that the assumed uplift rate is too high. At the other locations the tectonically reduced observations all lie near the upper limits of the corresponding model predictions.

5.3. Subsiding sites

Figs. 4c and d summarize the comparisons of observed and predicted sea levels for sites subject to possible subsidence. At Palinuro (*12*) (Fig. 4c) the subsidence rate discussed above is small and may not be significant. The terrestrial age for the speleothem at 13.9 ka is too old when compared with the serpulid and lithophaga ages of ~8.6 ka from the same depth and is indicative of a long hiatus between the last preserved terrestrial deposits and the subsequent marine growth. Thus we do not consider this observation further. With the exception of the samples from this depth, the other observations from this cave site are consistent with the model predictions. At Fondi (*9*) (Fig. 4c), the comparisons between observations and the model values are satisfactory for the four older points. For the younger data, however, the observed values lie consistently at much shallower levels than recorded elsewhere at the

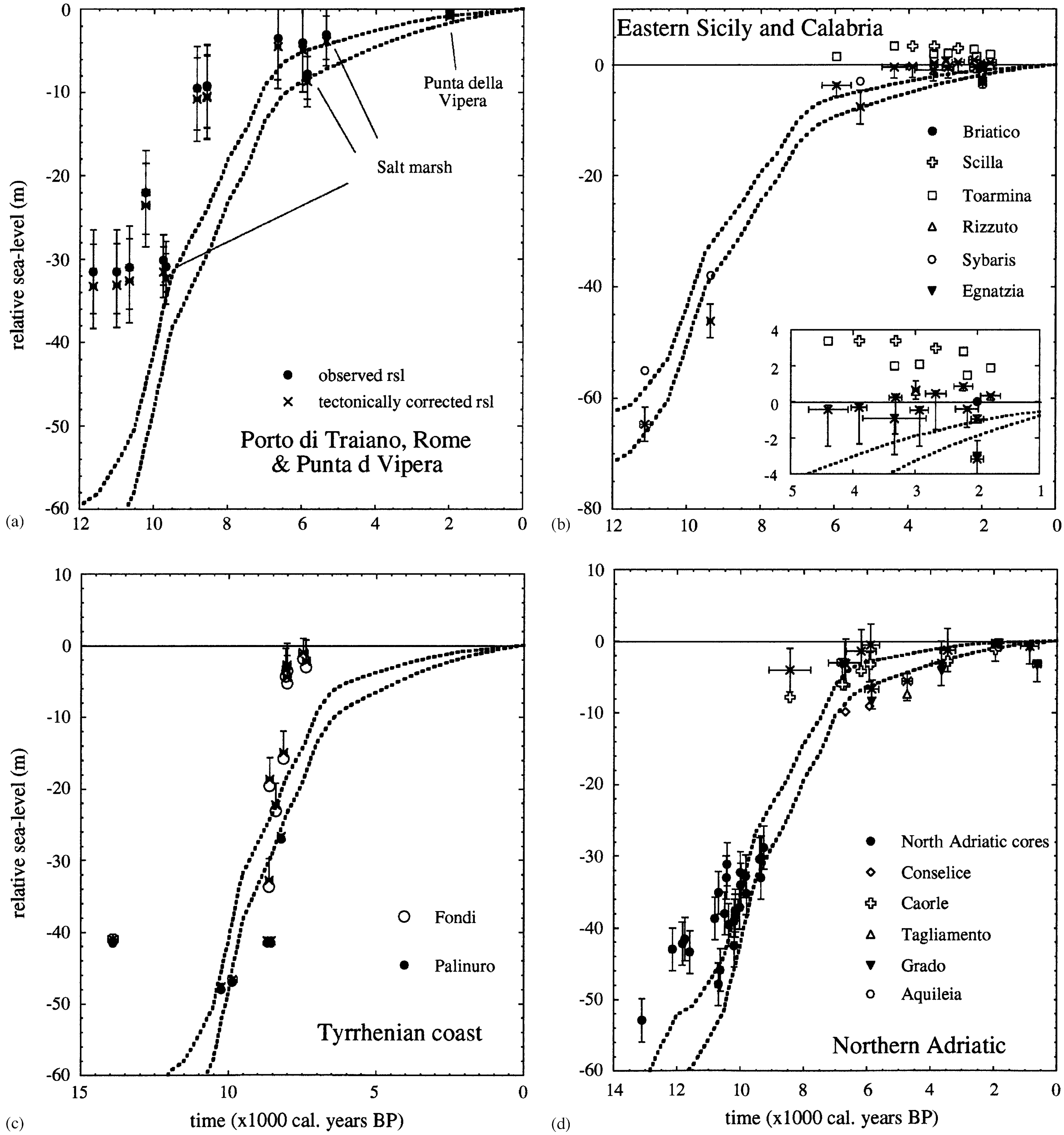


Fig. 4. Same as Fig. 3 but for sites of known tectonic uplift (a, b) or subsidence (c, d) where the tectonic contributions are based on the position of the MIS 5.5 shoreline. The uncorrected observed values are indicated by solid circles or other symbols and the tectonically corrected values are shown as crosses. Only the error bars for the tectonically corrected values are shown. In (a) the salt marsh samples are labelled and the other samples are the terrestrial peats. In (b) the inset is an expanded part of the results in the interval 1–5 ka BP. For the Palinuro speleothem results (c) both the terrestrial (old) and marine (young) ages are shown for the depth of ~40 m. The predicted limits shown are for Traiano in (a), Rizzuto in (b), Fondi in (c), and the centre of the northern Adriatic core sites in (d).

same epoch and occur well above the predicted values for this and other sites along the Tyrrhenian coast. Possibly this is indicative of irregular tectonic movement across the Fondi basin although the observed sea levels in the older group are consistent with the long-term subsidence rate inferred from the MIS 5.5 position. Alternatively it reflects a problem with the data interpretation because these results are from lagoonal deposits within a glacial-epoch paleo-valley that is fed by springs from the surrounding Tertiary limestone deposits and the ^{14}C ages of the lagoonal sediments may have been contaminated by old carbon.

The other region of reported subsidence is from the northern Adriatic region. The core observations (*25*) are reported as marsh deposits and represent upper limits to sea level. The model values illustrated in Fig. 4d are based on the assumption of zero subsidence and the observed limits are generally consistent with this assumption. Not all of the deposits could have been near sea level at the ages indicated since data points with the same age of ~10.1 ka occur over a depth range of ~10 m, consistent with the present gradient of the sea floor and core-site locations. With the exception of the Caorle Lagoon data, the observed sea levels at coastal and inland sites lie below the predicted values but, once corrected for subsidence, agreement is much improved. The older of two tectonically corrected observations at Conselice lies a few meters above the upper limit of the predictions and this is consistent with it being a terrestrial peat. The observations from Grado Lagoon and Tagliamento are mostly from shells in lagoonal deposits and correspond to lower limits, and the results are consistent with the model predictions. The tectonically corrected Caorle observations lie consistently above the predictions. Most of the data points correspond to peat ages but the lagoonal shell data point at 6.8 ka BP lies near the upper limit of the predicted value, suggesting that the assumed subsidence rate may have been too high.

6. Discussion

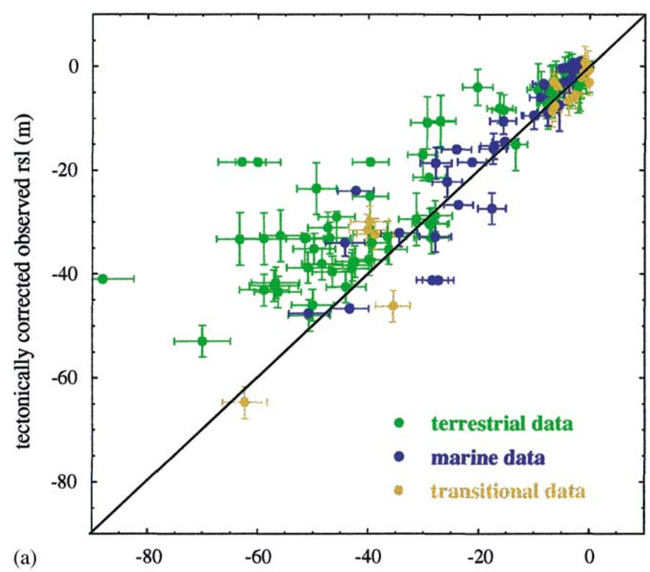
6.1. A summary of the comparison of observations and predictions

The comparison of the observed and predicted sea levels is summarized in Fig. 5a as a plot of predicted (horizontal axis) versus the tectonically corrected observed (vertical axis) values. If model corrections as well as predictions were perfect then the upper limiting observations (the terrestrial markers) should lie above the 1:1 line and the lower limiting observations (the marine markers) should lie below this line. Largely this condition is satisfied, indicating that the model provides a reasonable representation of the eustatic–isostatic sea-level change for this part of the Mediterranean. Nevertheless some significant discrepancies occur that suggest that refinement of the model parameters is warranted. As shown in Fig. 2c the choice of earth-model is not critical within a wide range of parameters encompassing results from earlier studies. A more critical choice is the eustatic sea-level function. The nominal global function used in the above comparisons is based on analyses of sea level from regions far from the former ice sheets and the isostatic component contributions are based partly on crustal rebound analyses of the formerly glaciated areas, but the uncertainty of this function remains substantial. Thus we first investigate whether the present data set can be used to improve upon this function in the interval from 0 to 12 ka BP.

6.1.1. The eustatic sea-level function

The observed relative sea level at any location φ and time t is written schematically as

$$\Delta\zeta_{\rm obs}(\varphi,t) = \Delta\zeta_{\rm e}(t) + \Delta\zeta_{\rm I}(\varphi,t) + \delta\zeta_{\rm e}(t) + \Delta\zeta_{\rm T}(\varphi,t) \quad (4)$$



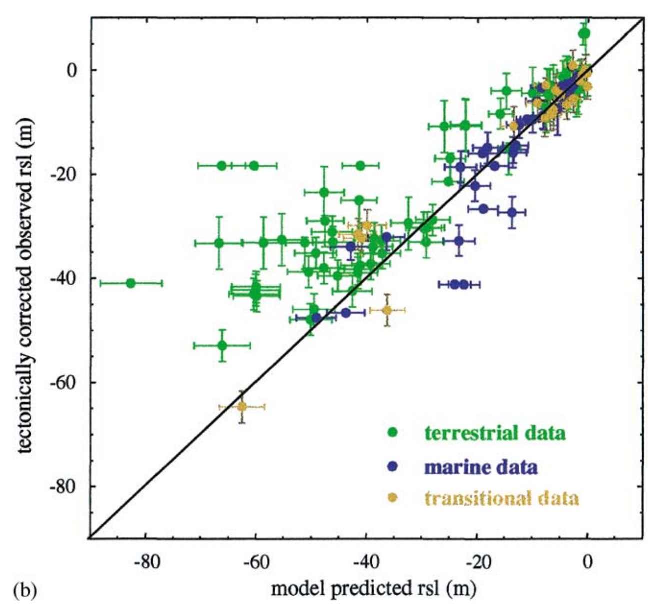


Fig. 5. Tectonically corrected observed sea levels versus model predicted values. The observed data is illustrated separately for the upper-limit terrestrial data, the lower-limit marine data, and the transition zone data. (a) Model predictions based on the nominal eustatic and isostatic model parameters and (b) model predictions based on the revised 'Italian' eustatic sea-level function.

where the first two terms on the right-hand side represent the eustatic and isostatic model-dependent contributions, respectively. The third term $\delta\zeta_e(t)$ represents a corrective term to the nominal eustatic term $\Delta\zeta_e(t)$ used to compute the isostatic term $\Delta\zeta_I(\varphi, t)$ and the last term is a tectonic contribution. Eq. (4) may be reorganized as

$$\begin{aligned}\Delta\zeta_e(t) + \delta\zeta_e(t) &= \Delta\zeta_e^*(t) \\ &= \Delta\zeta_{obs}(\varphi, t) - \Delta\zeta_I(\varphi, t) - \Delta\zeta_T(\varphi, t) \\ &= \Delta\zeta_{obs}(\varphi, t) - \{\Delta\zeta_{pred}(\varphi, t) - \Delta\zeta_e(t)\} - \Delta\zeta_T(\varphi, t)\end{aligned} \quad (5)$$

with

$$\sigma_{\Delta\zeta_e^*} = (\sigma^2_{t.c.obs} + \sigma^2_{\delta\zeta I}), \quad (6)$$

where $\Delta\zeta_e^*(t)$ is the observationally derived estimate of the eustatic sea level and $\Delta\zeta_{pred}(\varphi, t)$ is the sea-level prediction based on the nominal eustatic sea-level function. The variance of the tectonically corrected observed sea level is given by (3) and $\sigma^2_{\sigma\zeta I}$ is the variance of the isostatic correction (2). The function $\Delta\zeta_e^*(t)$ is compared with the nominal function (dashed line) in Fig. 6a. A notable Holocene discrepancy between the two estimates occurs in the interval from ~7 to ~9.5 ka where a number of marine-based estimates lie systematically above the nominal function.

The property of the eustatic sea-level function is that it is independent of location and the results for the Italian coastline can be directly compared with the results from other localities. The most complete records of Holocene sea-level change remain those from Barbados (Fairbanks, 1989; Bard et al., 1993), Huon (Chappell and Polach, 1991) and Tahiti (Bard et al., 1996) to which have been added data from Christchurch, New Zealand (Gibb, 1986; Lambeck et al., 2002). This 'global' result, corrected for isostatic and tectonic effects, is illustrated in Fig. 6b where the eustatic sea-level function is defined as the upper limit to the isostatically corrected coral indicators from these three localities. These estimates also lie a few meters above the nominal function in the mid-late Holocene interval. Thus we adopt as best estimate for the interval 10.5–7 ka BP the weighted mean of the Italian and global estimates, where the former is represented by the smoothed function illustrated in Fig. 6a.

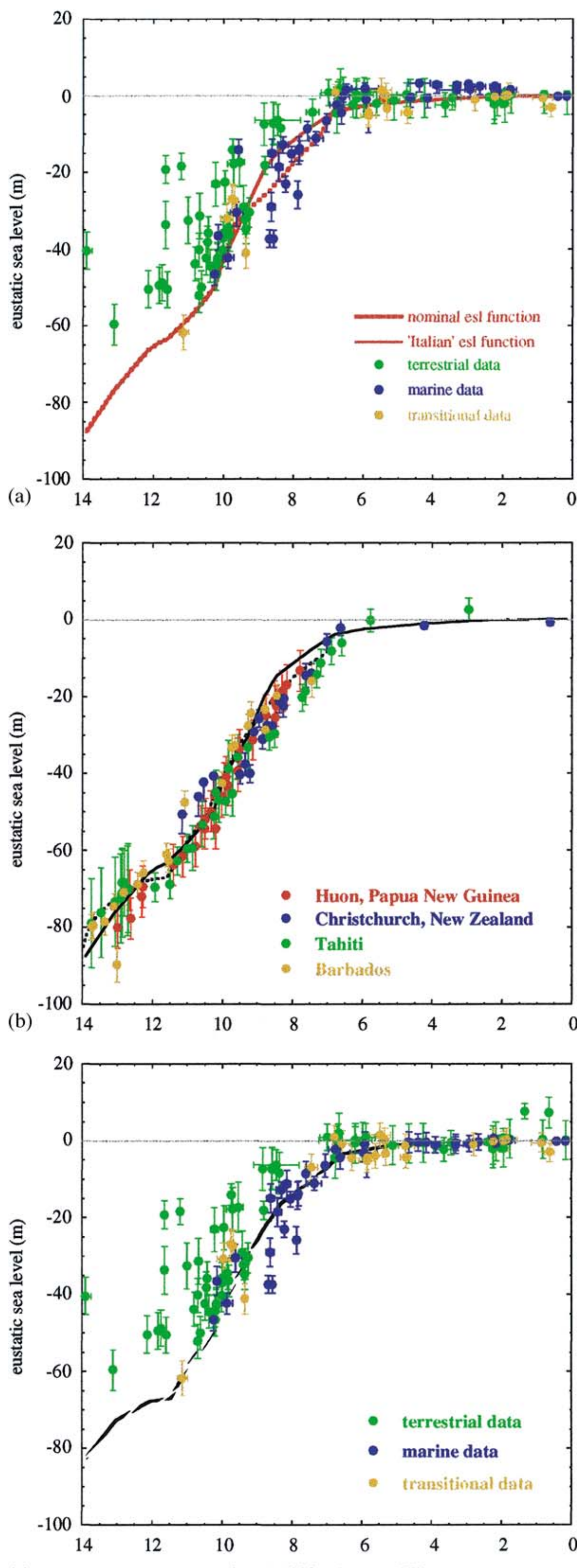
Modification of the eustatic sea-level function has the consequence of also modifying the isostatic corrections but, as the corrections to the former are relatively small and the isostatic corrections for the Italian sites represent about 10–15% of the total sea-level signal, these further corrections are second-order effects. As to which ice sheet needs to be modified to accommodate the change in the global ice volume cannot be answered from sea-level observations far from the former ice margins. Thus, we have made the adjustment by partitioning the change between the distant ice sheets of North America and Antarctica. With the so-modified ice models the predicted sea levels at the Italian sites have been revised and compared with the tectonically corrected observations as before (Figs. 5b and 6c).

Despite these modifications to the isostatic model the previously identified isolated anomalous points persist, such as the marine and transitional data points in the interval ~10.3 to ~9.4 ka BP that lie above the lowest continental points within the same time interval and well above the revised predicted levels. This may be a consequence of misidentification of the depositional environments—that the marsh deposits were terrestrial deposits rather than salt marsh, for example—but unfortunately many of the older cores are not available for re-examination.

6.1.2. Tectonic vertical movement estimates

A second group of anomalous points occurs in the interval 0–5 ka where a number of marine data points lie higher than coeval terrestrial data points. These correspond to the tectonically uplifted sites of Taormina (*15*), Scilla (*14*) and Capo Rizzuto (*22*). In all three cases the predicted rates of uplift are based on the elevation of the MIS 5.5 shorelines and on the assumption of uniform rates of uplift but the results here suggest that recent uplift rates may have been higher than the long-term averages. The difference between the tectonically corrected data—based on the long-term averages—and the predicted values are illustrated in Figs. 7a and b for Taormina and Scilla. For both sites the differences for the individual data points exhibit systematic trends that indicate that uplift rates for the past 6000 years have been about 100% greater than the long-term averages. This will be investigated separately and here we use the revised rates estimated from Fig. 7 of, respectively 1.72 ± 0.22 and $1.97 \pm 0.33\,mm\,yr^{-1}$. The Capo Rizzuto evidence suggests a recent uplift rate of $1.15 \pm 0.25\,mm\,yr^{-1}$ that may have been about 50% greater than predicted from the MIS 5.5 data although this is based on a single data point.

Estimates for the vertical tectonic rate at Volturno (*10*) are ambiguous as discussed above, with estimates of the elevation of the MIS 5.5 shoreline fluctuating between ± 50 m (Romano et al., 1994), depending on whether the location is within the coastal plain or on the adjacent ridges. The comparison of observed and predicted values, with the former based on the assumption of an absence of vertical tectonics, suggests in fact that the area has been subject to some uplift over the past 8000 years (Fig. 7c). The observations here are from peat and marsh samples and are assumed to mark the upper limit of sea level. From this evidence the estimated rate of uplift is $0.35 \pm 0.29\,mm\,yr^{-1}$, consistent with the upper limit of the observed MIS 5.5 elevation and, at the level of observational accuracy, the location is effectively stable.



The North Adriatic offshore data, comprising peats that are assumed to correspond to upper limits of sea level, are consistent with the assumption of zero tectonic movement with all observed data points lying above or within the predicted range (cf. Fig. 4). Likewise, the observed coastal and inland data points are in broad agreement with the model values, assuming subsidence, to within the uncertainties of both values (Fig. 8). Possibly the assumed subsidence rate for Caorle Lagoon is too high and that for Grado Lagoon is too low but the data is insufficient to estimate improved subsidence rates and we retain the assumed rates based on the sparse evidence from the location of the Last Interglacial sea levels across the region. The implication of these results is that the subsidence caused by loading from the Po River sediments is restricted to the inland and coastal zone and that it is not important for the offshore sites.

6.1.3. Further comments on comparisons

One feature of the nominal eustatic sea-level function, and one that has been retained in the present solution, is that ocean volumes have continued to increase into Late Holocene time and this has been attributed to the continued melting of the Antarctic ice sheet after the completion of the melting of the northern ice sheets (Nakada and Lambeck, 1988). This is consistent with the recent results by Stone et al. (2003) that demonstrate that significant melting has occurred in at least one part of Antarctica. The eustatic sea-level curve for this post-northern hemisphere glacial period is therefore important for constraining the total changes in ice volumes. Most analyses have indicated that much of this decay occurred before about 2000–3000 years ago (Lambeck, 2002) and this is consistent with the Italian evidence (Fig. 9) that supports eustatic levels below present values in the interval 7–5 ka BP but the present Italian data is not sufficiently accurate to establish better constraints on this function for the more recent interval.

Some of the comparisons indicate differences that exceed the uncertainties associated with both the observed and predicted sea-levels values and this may point to either limitations of the tectonic values adopted or to data problems. For most of these sites the comparisons are based on one or two observations only

Fig. 6. Observed sea-level data, tectonically and isostatically corrected, corresponding to the eustatic or ice-volume-equivalent sea level function. (a) The 'Italian' solution. The data is grouped according to whether they are terrestrial, marine or transitional indicators. The dashed line illustrates the nominal eustatic function used in the model corrections and the solid line illustrates the best estimate based on the Italian data. (b) The 'global' solution based on data from Huon Peninsula, Barbados, Tahiti, and New Zealand. The solid line illustrates the 'Italian' solution and the dashed line the solution inferred from the coral data (Lambeck et al., 2002). (c) The second iteration Italian solution based on the revised eustatic sea-level function from the combined global and Italian data sets.

and the following comments are more suggestions for follow-up work than confirmed facts. As noted above, the evidence from Fondi (*9*) indicates a local relative sea level that approached present-day values soon after 8 ka BP, inconsistent with evidence from all other localities. The early part of the record, $t > 10.2$ ka, is consistent with the model predictions (Fig. 10) and we conclude that the ages for the younger material have been contaminated by older radiocarbon carried by ground water from the limestones bordering the plain. The predictions for the Pozzuoli site (*11*) indicate levels at 0.8 and 0.4 m below present for the two epochs of observation (Table 1). Thus the integrated tectonic displacements here have been at least 7 m over the past 1400 years. The notches, with widths approximately equal to the tidal range, recorded within the Roman fish tanks of Briatico (*13*) imply that sea-level rise here has kept up with the tectonic uplift for much of the last two millennia. The predicted isostatic sea-level rate for the past two millennia is $0.78 \pm 0.20\,\mathrm{mm\,yr^{-1}}$ and higher than the long-term average at $0.47 \pm 0.04\,\mathrm{mm\,yr^{-1}}$ based on the elevation of the MIS 5.5 levels and this difference suggests that here the assumption of constant uplift during the glacial cycle may not be valid. Thus for this site we adopt a Holocene rate of $0.63 \pm 0.20\,\mathrm{mm\,yr^{-1}}$, the mean of the two estimates.

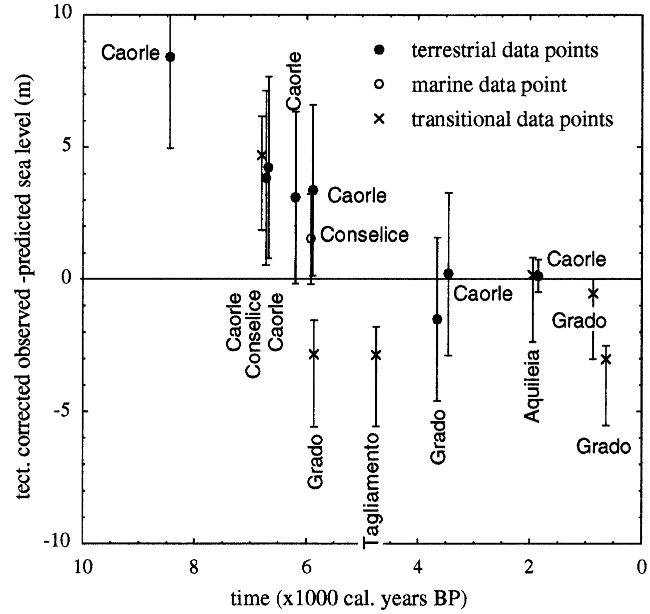


Fig. 8. Tectonically corrected observed sea levels less the corresponding predicted values (using the nominal tectonic rates discussed in text) as a function of time for the North Adriatic lagoonal, coastal and inland sites (26–30).

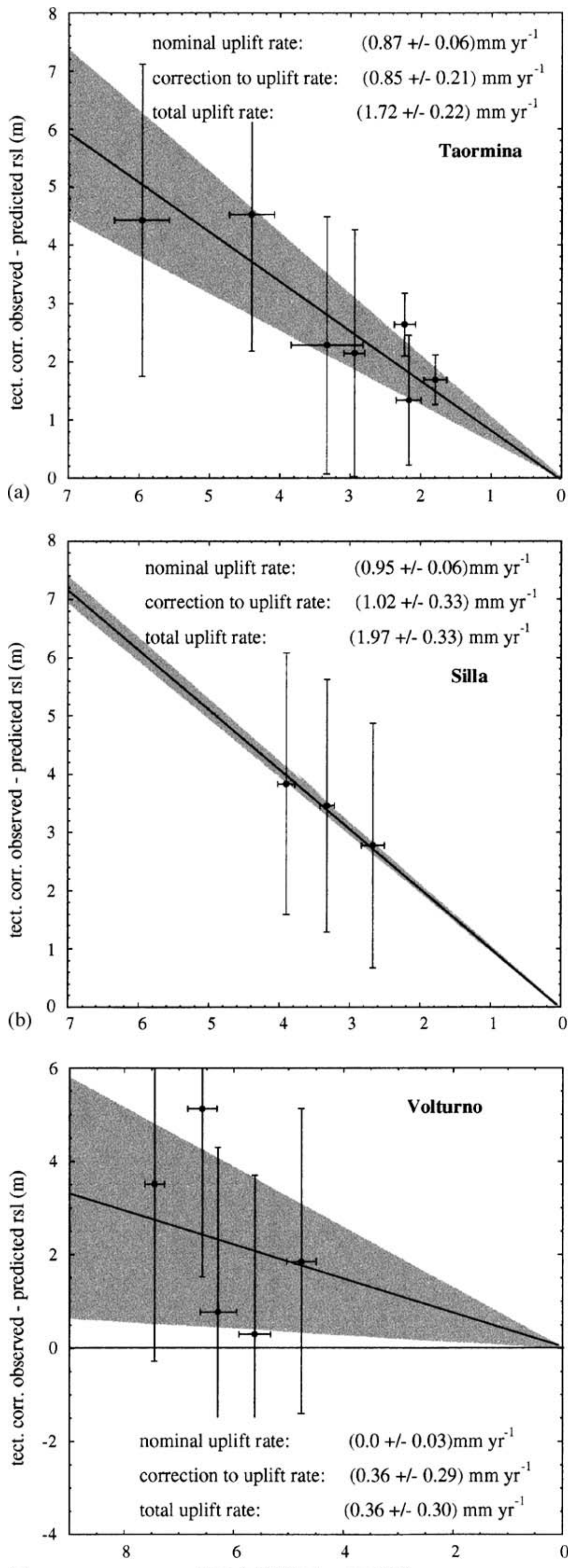


Fig. 7. Comparison of the tectonically corrected observed sea-levels and predicted values at three locations (*15*, *14*, *10*). The tectonic corrections are based on the MIS 5.5 inferences (the nominal uplift rates). The vertical axes correspond to the difference between the corrected observed values and the predicted values and systematic departures from zero indicate that the 'nominal' tectonic rates may need revision. The corrections to the 'long-term' rates are given by the linear regression lines. The shaded zones define the error estimates.

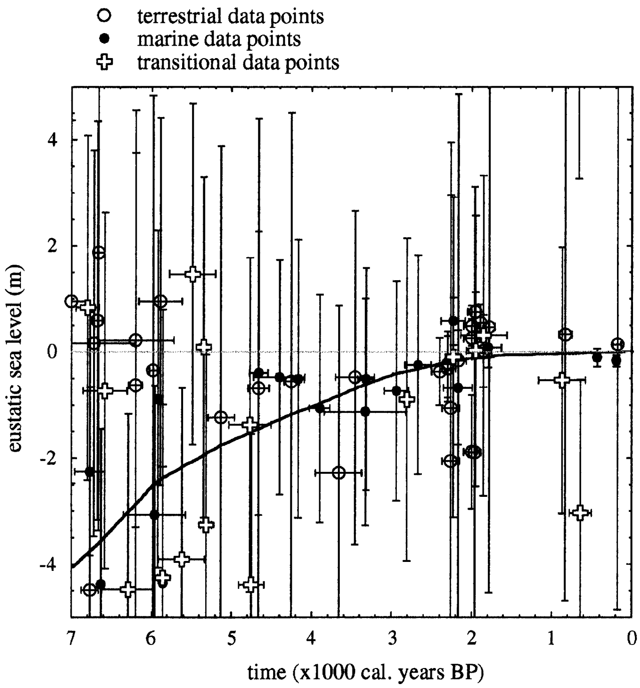


Fig. 9. The estimated eustatic sea-level change from the Italian data for the past 7000 years. The observational data has been grouped according to whether they are terrestrial, marine or transitional indicators of sea level. The solid line refers to the 'global' estimate from Lambeck (2002).

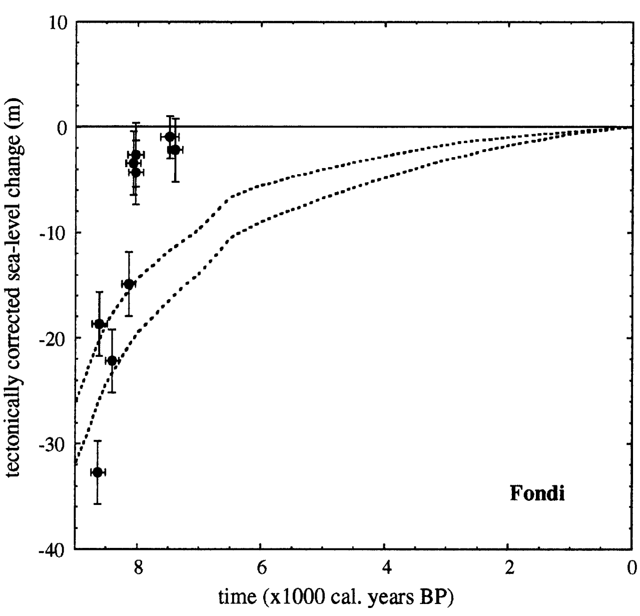


Fig. 10. Comparison of the tectonically corrected observed sea levels with the predicted values at Fondi (*9*).

In the discussion of the data from Sybaris (*23*) it was noted that the plain was fault bounded and that the tectonic correction was based on the elevation of MIS 5.5 features inland from the plain. However, the agreement between tectonically corrected and predicted sea levels is satisfactory and the estimated tectonic rate appears to be representative of the plain. At Egnazia (*24*) the tectonically corrected observation lies below the model-predicted value and this would suggest that this site was one of subsidence rather than of a slow uplift as assumed above.

Fig. 11 summarizes our best estimates of the tectonic vertical motions for the Holocene period. The results are based on the MIS 5.5 evidence where there is agreement between these rates and the Holocene data, or on the Holocene averages where the estimates for the two epochs are significantly different. These results must be considered preliminary because of the varying quality of some of the data used and because in the northern Adriatic they are based on interpolations between uncertain data points. However, the results do reveal some trends that can be regionally characterized as follows. (i) Subsidence along the northern Adriatic coast, ranging from $\sim 1\,\mathrm{mm\,yr^{-1}}$ in the Po River delta at Conselice (*26*) to about $0.3\,\mathrm{mm\,yr^{-1}}$ at Grado (*29*) and Aquilleia (*30*) but relative stability offshore (*25*). (ii) Primarily coastal stability along the Tyrrhenian coast from the plain of Versillia (*1*) to Palinuro (*12*) although small regions of uplift occur at Punta della Vipera (*5*) and the Rome Plain (*6*) and again at Volturno (*10*) and Pozzuoli (*11*) and subsidence may occur at Fondi (*9*). Evidence from the French Mediterranean coast indicates that this zone of stability extends at least as far as Marseilles (Lambeck and Bard, 2000). (iii) Uplift in eastern Sicily, Calabria and Basilicata with uplift rates increasing from near zero at Egnazia (*24*) to a maximum of $\sim 2\,\mathrm{mm\,yr^{-1}}$ at Taormina (*15*) in the Messina Strait. (iv) Tectonic stability in western Sicily and Sardinia. The sea-level evidence from Corsica also points to tectonic stability of this island on the Holocene time scale (Lambeck and Bard, 2000).

6.2. *Predictions of sea-level change and shoreline evolution*

With the above revisions of the tectonic corrections for Taormina and Scilla and with the revised eustatic function, the comparison of the observed and predicted sea-level changes are in good agreement as illustrated in Fig. 6c. The latter provide a satisfactory description of central Mediterranean sea-level change for tectonically stable regions or for those regions for which tectonic uplift or subsidence rates have been independently determined. Thus the model should serve as a useful interpolation for sea level between the fragmentary pieces of observational evidence. Fig. 12 illustrates the results for the isobases of sea-level change at selected epochs for the Italian Peninsula and its adjacent seas. They are based on the revised eustatic sea-level function and the accuracy estimates can be estimated from (2). Results for other epochs are available at http://wwwrses.anu.edu.au/geodynamics. The dominant

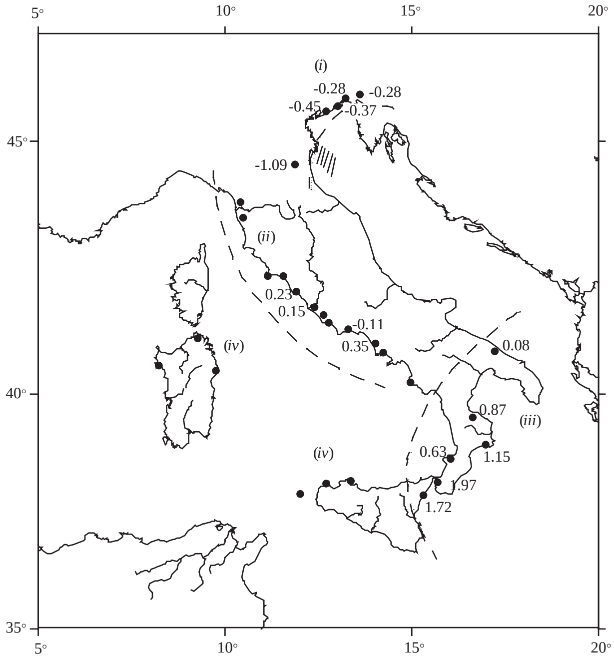


Fig. 11. Estimates of the average vertical tectonic uplift and subsidence rates (mm/year) for the Holocene interval. Sites without numbers correspond to localities where the tectonic signals are zero or less than the estimated precision of the vertical rates. The shaded zone in the North Adriatic corresponds to the core sites for which Holocene subsidence is effectively zero. The tectonic signature falls into four broad categories: (i) subsidence along the North Adriatic coast, (ii) predominantly tectonic stability along the central and northern coast of Tyrrhenian Italy but with local areas of some uplift or subsidence, (iii) uplift in southern Italy, including eastern Sicily, and (iv) tectonic stability in western Sicily and Sardinia.

pattern of the sea levels for all epochs is determined by the hydro-isostatic contribution, with the sea basin floor subsiding under the additional water load. Thus observed sea levels from the island sites such as Pantelleria, between Sicily and Tunisia, Marettimo and Sardinia, should exhibit lower levels than sites on the Italian Peninsula for the same epoch. Along the central Tyrrhenian coast, between about Argentarola and Palinuro, the isobases are nearly parallel to the shore and data from different locations can be combined into a composite regional sea-level curve if desired. But this is not the case for the Adriatic coast where the glacio- and hydro-isostatic contributions combine to produce a well-defined north–south gradient such that levels in the northern Adriatic lie persistently above those further south. (See Fig. 7 in Lambeck and Johnston, 1995, for the separate approximate evaluation of the two components. Note that the contour labelled -1.5 in Fig. 7b for $T = 2$ ka should read -0.5 m.) The isobases also follow the general outline of the North African coast but, because of indentation in the coastal geometry, the site at Djerba (Tunisia) becomes effectively an inland site and the predicted levels in the Gulf of Gàbes lie above those for northern Tunisia. In fact, if Late Holocene sea-level indicators have been preserved along the section of coast between Tunis and Tripoli they should provide a good test of the isostatic model. Nowhere within the region are sea levels from stable coasts predicted to occur above present sea level at any time during the Holocene, and the mid-Holocene highstands characteristic of equatorial latitudes of Africa (Faure et al., 1980) are absent here because the glacio-isostatic effect is still sufficiently large to counteract the hydro-isostatic effect.

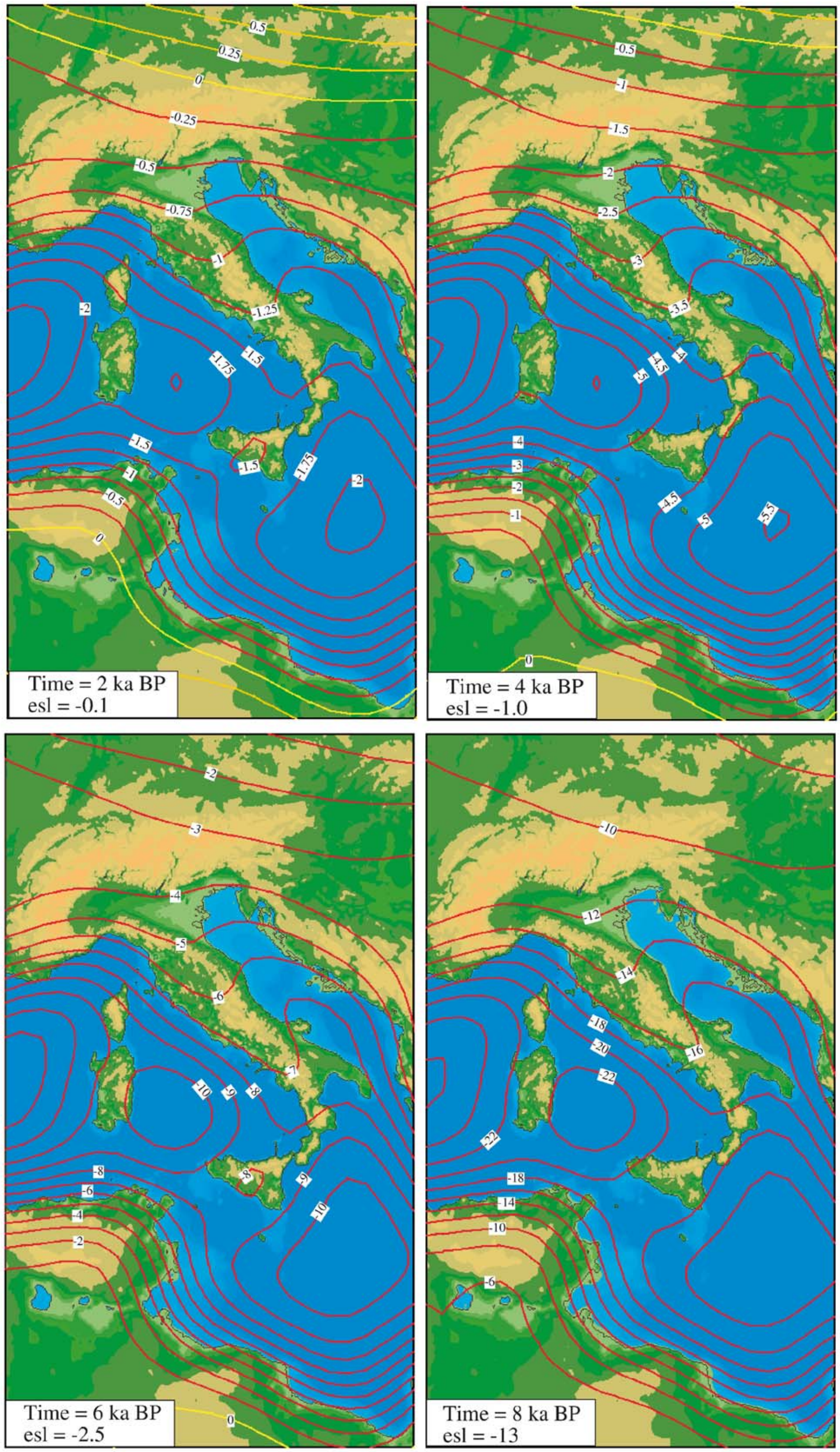
The palaeo shorelines are obtained from the relationship between water depth $h(\varphi, t)$ at time t and location φ relative to that $h(\varphi, t_0)$ at time t_0

$$h(\varphi, t) = h(\varphi, t_0) - \Delta\zeta_{pred}(\varphi, t),$$

where $\Delta\zeta_{pred}(\varphi, t)$ is the eustatic–isostatic prediction of the change in sea level at time t since the time t_0 (Fig. 7). The palaeo shoreline location is then given by the contour $h(\varphi, t) = 0$. The water depths used here are from the DTM compilation on a 2.5' grid and the results are devoid of detail in the smaller and shallow embayments. During the LGM, at 20 ka BP (Fig. 12) the predicted isobases range from about -120 m in the Gàbes Gulf (Tunisia) to -150 m in the middle of the basin and extensive exposure of the shelves occurs in the North Adriatic as well as along parts of the North African coast and marine LGM deposits will not occur on these shallow parts of the shelf. Of potential importance is the shallow basin, possibly isolated from the Mediterranean at some time during the LGM, that forms at latitude $\sim 43°$N. Cores from this feature may provide important constraints on LGM sea levels and ice volumes in much the same way as did the cores from the Bonaparte Gulf of northwestern Australia (Yokoyama et al., 2000). The sub-aerially exposed shelves in the northern Adriatic persist for much of the Lateglacial period. The location of the southernmost sample, dated at 13–11 ka BP, for example, would have been about 13 m above coeval sea level at its time of formation and would have remained sub-aerially exposed until ~ 10.9 ka. At 10 ka the isobases range from about -55 to -35 m below present level but the shallowest values occur where the sea has not yet encroached. Only by about 8 ka does the Adriatic take its present form (Fig. 12). At 6 ka BP the sea levels begin to approach present-day values but the spatial variability remains significant, coastal levels ranging from ~ -2 m at Gàbes to ~ -9 m in Sicily and Calabria. At the Roman period, ~ 2 ka BP, levels fluctuated from about -0.5 in the north of the Adriatic to as low as -1.8 m in parts of Sardinia.

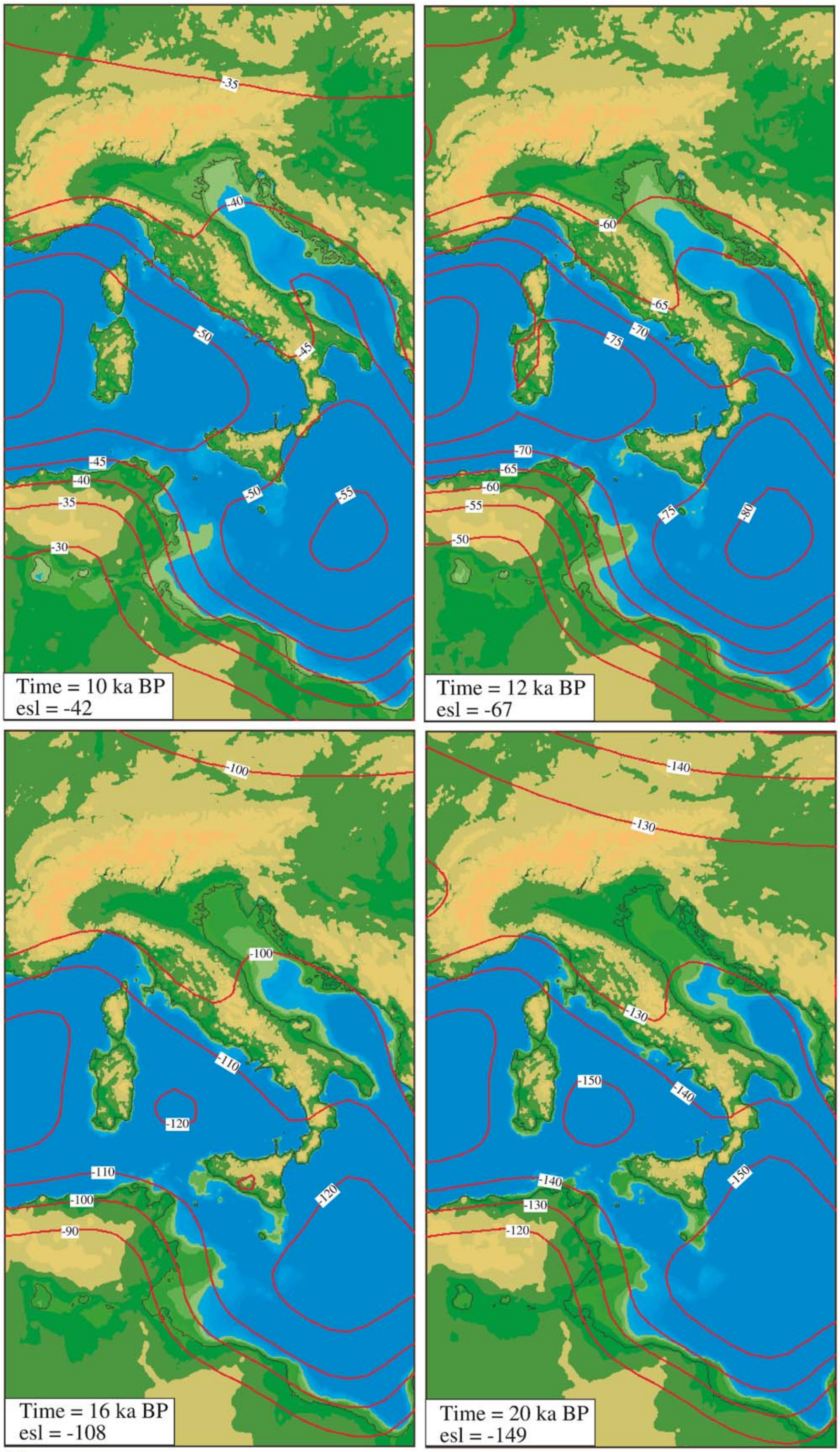
7. Conclusion

Even in the absence of the tectonic processes, relative sea level is spatially variable along the length of the



(a)

Fig. 12. Palaeogeographic reconstructions at nine epochs for the central Mediterranean region. The red (negative) and yellow (zero and positive) contours refer to the sea level change. Palaeo water depths are indicated by the change in shades of blue at depths of 25, 50, 100, 150 and 200 m. The ice-volume-equivalent sea level (esl) values for each epoch are given in meters.



(b)

Fig. 12 (*continued*).

Italian Peninsula and across its adjacent seas because of glacio-hydro-isostatic effects and sea level cannot be represented by a single time-dependent curve for the region. The latitudinal dependence is mostly a consequence of the Earth's delayed response to the past deglaciation of the northern ice sheets but this is modulated by the response to the concomitant change in water load to produce the variability illustrated in Fig. 12. The spatial differences are significant throughout and greater than many of the observational uncertainties. At all sites eustatic–isostatic sea levels have not exceeded their present level at any time in the Holocene and where observations indicate highstands then the location has been subject to tectonic uplift.

For many of the coastal locations considered in this study it has been possible to make first-order corrections for the tectonic contributions to relative sea-level change with the assumption that average uplift or subsidence rates have remained the same for the Holocene as for the entire last glacial cycle. Predictions of the total relative sea-level change based on this assumption and on the eustatic–isostatic model predictions are broadly consistent with the observational data from most of the 31 sites considered. This agreement holds for the entire range of biological and archaeological sea-level markers considered. In particular, the model predictions are consistent with the observations from the most complete record, the Plain of Versilia. Where major discrepancies do occur, such as at Fondi or Marettimo, they cannot be attributed to any aspect of the eustatic–isostatic model because other data from nearby localities and for similar epochs do lead to agreement with the model predictions. At these sites the model predictions can be used to test hypotheses about the environmental conditions at time of deposition or formation. At least at two sites, Taormina and Scilla, and possibly at Capo Rizzuto, the comparisons indicate that the assumption of uniformity of the tectonic uplift may not be valid, that the average rate for the Holocene has been about twice the average rate for the past 125,000 years. For the remaining sites subject to uplift, as established from the elevation of the MIS 5.5 shorelines, this assumption appears to be valid within the resolution of the data. For sites where the MIS 5.5 evidence is ambiguous, such as Volturno and Marettimo, the comparisons can be used to identify which observations are most likely to be the correct ones.

Some systematic discrepancies between observed and model-predicted sea levels from stable sites have been identified, and the observational data for the region, particularly that from tectonically stable sites, provide constraints on the eustatic sea-level function that are consistent with the evidence from other localities. Rapid global melting continued until about 7000 years ago but ocean volumes continued to increase until at least 3000 years ago (Fig. 6).

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Note added in proof

In a more recent rebound solution mountain glaciations have been included using the limits and ice volumes defined by G.H. Denton and T.J. Hughes (The Last Great Ice Sheets, Wiley, NY, 1981). The contribution to sea level change is significant only in the Northern Adriatic and the Gulf of Genova with amplitudes of 4–5 m at 12ka BP and 1–12 m at 6 ka BP.

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