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Elevation of the last interglacial highstand in Sicily (Italy): A benchmark of coastal tectonics

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Abstract

Well-preserved MIS 5.5 terraces in Sicily are identified primarily by the index fossil *Strombus bubonius*, and dated by amino acid racemization (AAR), electron spin resonance (ESR), Uranium/Thorium (U/Th) and thermo luminescence (TL) methods. This review of published data and new results for the island of Sicily and neighbouring small islands of Egadi, Ustica and Lampedusa identifies areas of rapid uplift in the east (up to +175 m, elevation above sea level), slower uplift in the north (+29 m), and relative stability in the northwest (+2/+18 m). In contrast, about 250 km of the southern coastline of Sicily does not appear to contain MIS 5.5 outcrops. In eastern Sicily, correlation of MIS 5.5 highstands is based on *Strombus bubonius*, discovered at +86 m, and correlated with the inner margin terrace at +110 m, In the Taormina area, a fossiliferous marine conglomerate on a terrace with an inner margin at +115 m occurs in an area with undated terrace morphology and elevation data. Based on ESR methodology applied to fossils sampled at +105 m in Taormina, we attribute this terrace to MIS 5, probably 5.5. This age allows us to constrain the date of one point along a very long coastline that is otherwise undated. A newly discovered fossil beach (between +7 and +9 m) at Cefalù (north-central Sicily) attributed to MIS 5.1/5.3 using AAR analysis, permits correlation of MIS 5.5 to a +29 m-high tidal notch geomorphologically related to a terrace at the same elevation. Cefalù lies in an important position between the uplifted coastline of northeastern Sicily, and the more stable coastline of western Sicily. This compilation of MIS 5.5 data for all of Sicily reflects the active tectonics of eastern Sicily in contrast to the rest of the island.

1. Introduction

Sicily sits astride the African–European plate boundary and thus is an important area for understanding the complex effects of this active location. Much of the eastern coastline of Sicily is defined by a major fault system, juxtaposing crust of both continental and oceanic affinities. Gvirtzman and Nur (1999) attempted to model this complex tectonic setting, which also involves Mount Etna, Europe's most active volcano. Coastal sites on the eastern side are affected by progressive uplift through the Quaternary, whereas the northwestern coast is quasi-stable. Well-preserved sequences of marine terraces occur along these coasts including many assigned to the MIS 5.5 (Tyrrhenian). This correlation is primarily based on the distinctive *Strombus bubonius* warm water molluscan fauna (Gignoux, 1913; Issel, 1914) which now occur at elevations up to about +175 m (i.e. above sea level).

Marine isotope substage (MIS) 5.5 coincides with the last interglacial, and its geochronology is based on

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orbital tuning of high-resolution deep-sea oxygen isotope stratigraphy. According to this stratigraphy, the geochronological subunit MIS 5.5 occurred between Termination II (end of MIS 6) and the onset of MIS 5.4, spanning 133–115 ka (Shackleton et al., 2003). During this last interglacial period the global sea level rose to a level higher than the modern sea level (Waelbroeck et al., 2002; Siddal et al., 2003). Reconstructed sea-level curves, however, vary according to the location as a result of isostatic changes related to ice-sheet loading cycles, which can be on the order of several meters (Lambeck and Chappell, 2001; Lambeck et al., 2002; Potter and Lambeck, 2004). Along the Italian coasts, the average level attained by the sea during the MIS 5.5 is inferred to be ~+7 m (Lambeck et al., 2004). Elsewhere within the western and central Mediterranean Sea, the validity of sea level markers identified by previous researchers and the role of tectonic processes is discussed by Ferranti et al. (this volume).

However, the range of available data on distribution of MIS 5.5 elevations in Sicily is limited. Therefore this study assembles previous data, together with new results, to provide a comprehensive survey of the last interglacial highstand in Sicily. We aim to expand the information available on studied sections, provide more data on elevations of uplifted surfaces, and obtain new dates on a number of sections and marine fossils so that the dataset becomes statistically reliable enough to produce a model. The results are applied to comment on tectonic controls of uplift in the late Quaternary.

In this paper, the coastline of Sicily is divided into four coastal sectors and islands (Fig. 1). In Sector 1, in western Sicily (and Egadi island), MIS 5.5 is recognized by terraces and notches at +7 to 12 m (Malatesta, 1957; Antonioli et al., 2002). Sector 2 extends for more than 250 km along the south coast where there is no evidence of the MIS 5.5 highstand. Sector 3 shows MIS 5.5 features at around +15 m, and differs from Sectors 2 and 4 as it lies on the Hyblean portion of Sicily, and is tectonically part of the African Plate. In northeastern Sicily (Sector 4), MIS 5.5 features are all above +100 m, and as high as +175 m on Mt. Etna volcano (north of Catania, Monaco et al., 2000). On the volcanoes of Ustica Island and the Aeolian islands, the MIS 5.5 higstand is found uplifted between +30 and +115 m (Hearty, 1986; Lucchi et al., 2004a, b). Lampedusa, the southern Italian island (on the African plate) contains fossil *Strombus bubonius* at about +3 m, and thus appears to be relatively stable (Segre, 1960).

Bordoni and Valensise (1998) compiled MIS 5.5 highstand data for Italian shorelines, reporting 15 sites in Sicily. In the present work we build on their work and report a comprehensive review of published papers on highstand elevations at 36 sites in Sicily, with new findings from Egadi, Ustica and Lampedusa Islands. We also present new age data for two important sites at Taormina and Cefalù (see Fig. 2 and sites 1 and 24 of Fig. 1).

2. Regional geologic setting

With respect to the MIS 5.5 history, Sicily is divided into four sectors (Fig. 1), and the setting of each is briefly described in this section. In general terms, Sector 1 shows good evidence of stability despite a complex history. Sector 2 is problematic because of rock preservation problems. However, both Sectors 1 and 2 are currently tectonically more stable than the east coast

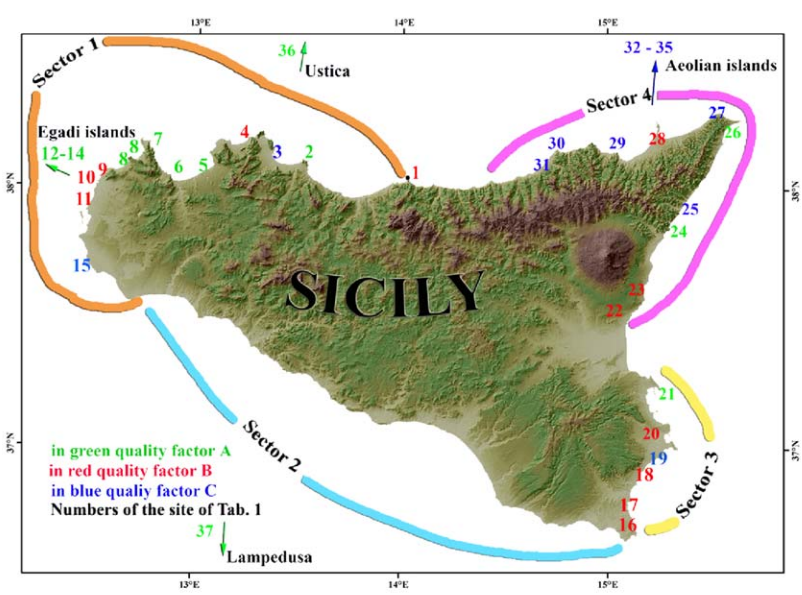

Fig. 1. DEM of Sicily showing how the coast is divided into sectors for this paper. Numbers are site numbers in Table 1, and are in different colours for the different geomorphological quality factors. (A = excellent, B = intermediate, C = low).

(Sectors 3 and 4). Also, the eastern Sicily coastline can be further divided into the following segments, from N to S, and there are differences in tectonic behaviour: NE Sicily, part of the Appennine–Maghrebian Chain; Mount Etna volcanic region; Catania Plain foredeep area. The geological background to the range of coastal features are summarized below.

2.1. Sector 1—NW area

The NW sector of Sicily (including the Egadi Archipelago, sector 1 of Fig. 1) represents the emerged western edge of the Sicilian–Maghrebian Chain, which originated from the deformation of the Meso-Cenozoic Northern African continental margin. The geological setting of the area (Fig. 2) is characterized by overthrust tectonic units referable to the Panormid carbonate platform and its margins, or units belonging to other palaeogeographic domains (such as the Trapanese basin; Giunta and Liguori, 1972; Catalano and D'Argenio, 1982; Abate et al., 1991, 1993). Stacking of SE-verging thrust sheets in the Middle–Upper Miocene and in the Middle Pliocene tectonic phases led to brittle rocks being emplaced over more ductile rocks.

Quaternary disjunctive and strike-slip tectonics, occurred mainly along NW–SE, NE–SW, N–S and E–W oriented normal fault systems producing differentially uplifted blocks, thus yielding alternating structural highs and basins (D'Angelo et al., 1997). In the Capo San Vito promontory (Figs. 1, 2, and 4), this structural pattern is reflected by the occurrence of subsided sectors, presently occupied by coastal plains (Castelluzzo and Cornino Plains; Abate et al., 1991) and structural highs. Moreover, the recent tectonics create favourable conditions for the onset of both deep-seated and surficial gravitational slope deformation, particularly along the eastern flank of the peninsula (Agnesi et al., 1995). The Capo San Vito promontory and the Egadi islands are characterized by Mesozoic and Tertiary units composed of carbonates, evaporites and siliciclastic deposits, overlain unconformably by late orogenic clastic deposits (Abate et al., 1991, 1997). Several sub-horizontal erosion surfaces, interpreted as raised marine terraces, are present at different heights up to 85 m along wide coastal tracts of western Sicily. Their formation has been considered to be of Middle–Upper Pleistocene age since they cut not only carbonate rocks and marlstones of Mesozoic age but also terrigenous, evaporitic and calcarenitic formations of Late Miocene to Lower Pleistocene age (D'Angelo and Vernuccio, 1996). Cefalù is included in this sector and comprises a coastal cliff with preserved beach deposits at +9/12 m, dated here to

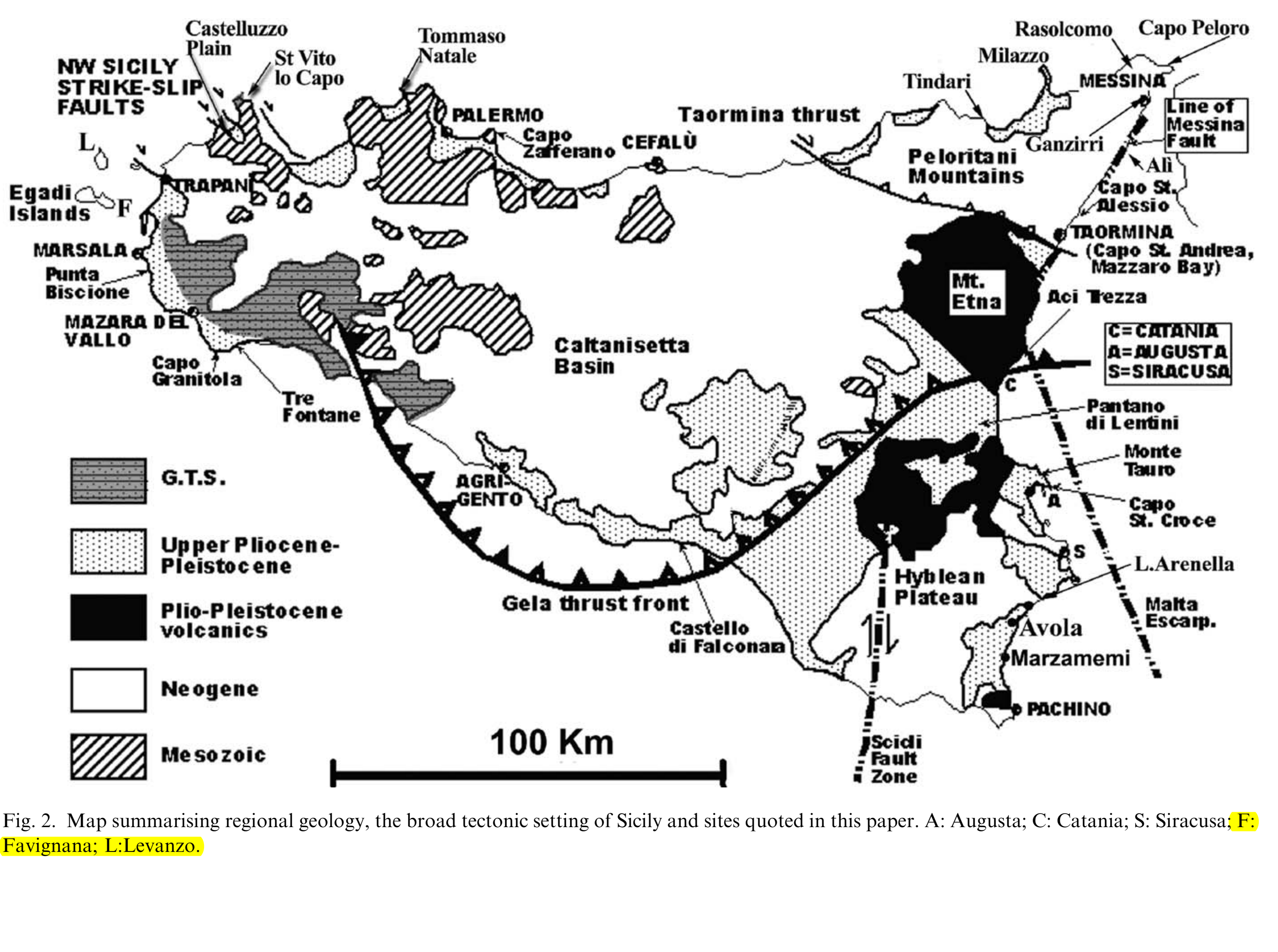

Fig. 2. Map summarising regional geology, the broad tectonic setting of Sicily and sites quoted in this paper. A: Augusta; C: Catania; S: Siracusa; F: Favignana; L:Levanzo.

Tyrrhenian age, and therefore is in a zone of minor tectonic activity.

2.2. Sector 2—southern coastline

In contrast to the tectonic controls that operate in northern and northeastern Sicily, with southward thrust progradation, the southern region apparently does not record tectonic uplift. The southern coastline west of the Hyblean Block consists of low cliffs composed of poorly resistant lithologies that do not preserve evidence of previous sea-level positions. However, because MIS5.5 sea level was higher than modern sea level, terraces should be preserved inland of the low cliffs in some localities. Therefore either the poor resistance of the rock has led to erosion of any uplifted remains, or alternatively it is possible that MIS 5.5 record is submerged below modern sea level.

2.3. Sector 3—SE coastline

Sector 3, the Hyblean Plateau is part of the Pelagian Block and forms the northern margin of the African Plate, therefore experienced a different tectonic history from the rest of Sicily. The area underwent collision with northern Sicily in Early Miocene to Pliocene times (Grasso and Pedley, 1990), but because the Pelagian Block is essentially a rigid mass, it has suffered brittle deformation, but has not developed the complex thrust system of the Maghrebian region to the north. Thus the tectonic background has led to reduced rates of vertical tectonic motion, and this is reflected in the limited uplift recorded in coastal sites, that are described in this paper.

2.4. Sector 4—northeastern area

Northeastern Sicily including Calabria is situated at the southern margin of the Tyrrhenian microplate (Gvirtzman and Nur, 1999). The area, called the Appennine–Maghrebian Chain, is composed of sedimentary and metamorphic rocks within a southward-verging system of thrusted nappes developed above the northward-dipping African plate. The resulting tectonic depression has created a foredeep along the northern margin of the African continental crust that is occupied by early Quaternary marine clays. These clays form the substrate for much of the eastern and southern flanks of the Mount Etna volcanic edifice and are known as the sub-Etnean clays. Farther to the south, the African crust is represented at the surface by the platform carbonates and clastics of the Hyblean plateau which make up southeastern Sicily. In the Tyrrhenian Sea north of Sicily, a subducted margin is marked by the Aeolian Islands volcanic arc. Overall, this tectonic regime imposes north–south compression to the northeastern Sicily region (Lanzafame and Bousquet, 1997). Field relationships between rocks of the Appenine–Maghrebian Chain and the early Quaternary marine clays indicate that thrusting in this compressional regime continued until at least mid-Pleistocene times (Lanzafame and Bousquet, 1997), while active regional uplift is indicated by several lines of evidence. In particular, the early Quaternary marine clays are now found several hundred metres above sea level (Romano, 1979), and well-developed uplifted Tyrrhenian marine erosional platforms occur at about 130 m at Taormina in Sicly, as well as in Calabria on the eastern side of the Messina Straits.

This compressional framework is transected by a number of seismogenic structures of regional tectonic importance. Of these, the largest is the Malta Escarpment, a structure that intersects the African margin on the southern side of the Mediterranean at a high angle. It strikes NNW–SSE and defines the eastern and southeastern edge of the Sicilian continental shelf, marking the boundary with the oceanic-affinity crust of the Ionian Sea to the east. Dip-slip displacement on the Malta Escarpment amounts to some 3 km, and where it intersects the coast of Sicily on the eastern side of Mount Etna a series of active faults (the Timpe fault system) produce scarps up to 200 m and fault planes displaying both dip-slip and right oblique slip kinematic indicators (Lanzafame and Bousquet, 1997; Monaco et al., 1997). This major structure, although its continuity is disrupted by interactions with other faults, has been interpreted as passing through northeastern Sicily as a series of structures which ultimately displace the Aeolian arc by approximately 6 km in a right-lateral sense (Lanzafame and Bousquet, 1997).

The most important structure which intersects the faulting associated with the Malta Escarpment is the NNE–SSW striking Messina fault system. The 1908 Messina earthquake was attributed to a blind fault in the Messina area (Valensise and Pantosti, 1992), and although there is uncertain linkage between the faults along the linear NE Sicily coast north of Etna, the uniform strike of these faults provides good reason to consider them as a group. This system defines the northeastern coastline of Sicily bordering the Straits of Messina, and produces fault scarps in the mid-Holocene age surface of the Chiancone deposits on the eastern side of Mount Etna and coast-bounding faults in the Taormina area. These faults are thought to meet the onshore expression of the Malta Escarpment (Timpe faults) in the eastern Etnean area (Lanzafame et al., 1997), but we stress that the Malta Escarpment-Timpe faults and Messina fault system are different fault groups.

3. Data

The first four authors of this paper have together examined the coastline of all Sicily, to re-evaluate

MIS 5.5 (also called *Tyrrhenian*) deposits and features. Thus the work is based on field observations of more than 60 sections, permitting personal comparisons with literature-based work. Many warm fauna Tyrrhenian sections have been published for Sicilian coasts but some of these sites present uncertain ages, elevations and error bars with respect to sea level. There are also many kilometres of coast, for example along the northeast coastline, with no published Tyrrhenian sections. Table 1 summarizes published and new data for Sicily coasts, including two sections with new data emphasized (Taormina and Cefalù). Sites are also discussed where there are varying views on the history of the sites, for example in the Augusta and Taormina areas.

3.1. Sector 1

NE of Cefalù (site 1 of Tables 1 and 2; Fig. 1) town (Mesozoic limestone promontory), we discovered some well preserved *Glycymeris* fossils shells in little caves on the Cefalù town-harbour route at an elevation between +6.9 and 9.9 m (Fig. 3F). The shells appear to be well preserved and retain their original colour. We analysed the shell using an AAR method (Wehmiller and Miller, 2000), and the data are shown in Table 2. Comparing these results with Fig. 1 of Hearty et al. (1986a, b; location map of the Western Mediterranean showing isotherm of present day mean annual temperature) and Fig. 3 (map of the contoured *Glycymeris* alle/ille ratios from last interglacial deposits), these deposits at this elevation represent the Aminozone A–C of Hearty et al. (1986a, b), correlated for Sicily with the MIS 5.3/5.1 highstand. We correlate a tidal notch at +29 m in a cave on the promontory with the MIS 5.5 highstand. The notch appears at the same elevation as a terrace carved on the granodiorite promontory named "La Kalura", ca. 1 km east of the Cefalù promontory, with an inner margin at about +30 m. The consequent uplift rate is 176 mm/ka, assuming an elevation of −10 m for MIS 5.1 (Waelbroeck et al., 2002, elevation confirmed for Italian seas by Antonioli et al., 2004a) we obtain the same uplift rate.

At Capo Zafferano (site 2 of Table 1) Antonioli et al. (1994) measured at an elevation of +7 m a tidal notch well connected with fossil *Arca* shell analysed with the AAR technique that allowed correlation of the fossil beach with Aminozone E, and hence, with MIS 5.5.

At Palermo, Fabiani (1941) described the presence of *S. bubonius* at an elevation of +10 m. On the coast NW of Palermo, Ruggieri et al. (1968) described a fossil deposit at +50 m elevation (site of Tommaso Natale) that correlated with MIS 5.5. Hearty (1986) dated using the AAR method some *Glycymeris* that correlated this deposit with the older MIS 9. However, we found *S. bubonius* in a fossil beach at +2 m and therefore can confirm the MIS 5.5 age of the deposit.

Between Terrasini and Castellamare (in the Gulf of Castellamare directly west of St. Vito—see Figs. 1 and 4), and at St. Vito itself, Mauz et al. (1997) studied palaeoecology and gave an age (using TL) on sand and for the presence of *S. bubonius)* of some deposits between +5 up to +18 m of MIS 5.5. A sand deposit at +37 m dated at 120 ka using TL (Mauz et al., 1997), was not included in this study because it does not contain marine fossils.

Extensive outcrops of Quaternary forms and deposits occur in the coastal plains of San Vito, Castelluzzo and Cornino, to Trapani. These deposits are represented by bioclastic calcarenites, conglomerates with sandy matrix associated with the lowermost marine terrace. They outcrop in lenses along the coastal tract of the Capo San Vito Promontory and Trapani, on Egadi islands. They are ascribed to the MIS 5.5 highstand on the basis of *S. bubonius* and other Senegalese taxa, and/or U/Th ages on speleothems sampled on marine notches (Abate et al., 1993, 1996; Antonioli et al., 1996; Mauz et al., 1997). On the basis of the present height along the W side of the Capo San Vito Promontory, previous authors pointed out a relative stability and a limited, differential, uplift for the area during the last 125 ka (Abate et al., 1996; Antonioli et al., 2002). The maximum elevation varies between 5 and 14 m (Fig. 4), well marked by the inner margin of a very continuous terrace and few tidal notches. Thus the area is quasi-stable, but there is much transcurrent tectonic activity post-MIS 5.5. In some locations during the Holocene, *Dendropoma* platforms developed (Antonioli et al., 1999a) but these are not uplifted. We interpret this to be a quasi-stable coast. Some movements of the north sector could be due to strike slip faults that were revealed as active after MIS 5.5 and reactivated during late Holocene time. An example is at St. Vito where some *Dendropoma* platform deposits are dated between 400 and 650 years, and are displaced by these active faults. West of Cornino the terraces continue westward to Trapani (based our unpublished observations) reaching 20 m of elevation well correlated with the terrace containing *S. bubonius* at St. Vito (Fig. 4).

The Egadi Islands were studied by Malatesta (1957). All islands display fossil beaches containing *S. bubonius* or Senegalese fauna between 2 and 6 m elevation. Abate et al. (1992, 1996) studied in detail both notch forms and deposits at Favignana, and recorded tidal deposits containing warm fauna up to 12 m, compared with a notch 5 m at Levanzo. Antonioli et al. (2002) measured at Marettimo some tidal notches between 5 and 8 m (Fig. 3E). These relationships between deposits and notches are very similar to those seen in the Bahamas (Neumann and Hearty, 1996).

In the coastline between Trapani and Marsala Ruggieri et al. (1968) and Ruggieri (1988) found beach deposits containing *S. bubonius* between 2 and 5 m.

Table 1
Summary of dated sites from this study

Site	Locality	Dating method	Elevation marker	Elevation (m)	Error (m)	Uplift rate mm/ka	Quality factor	References
1	Cefalù	Amino acid on *Glycymeris V.*	Beach deposit	29	±0.5	176	B	This paper
2	Capo Zafferano	Amino acid on *Arca s.p.*	Tidal notch	7	±0.5	0	A	1
3	Palermo town	*Strombus b.*	Beach deposit	10	±5	24	B	2
4	Palermo Capo Gallo	*Strombus b.*	Beach deposit	2	±5	−40	B	3
5	Castellamare-Terrasini	TL on marine sands	Inner edge	12–18	±3	88	A	4
6	Castellamare Cala Bianca	TL on marine sands	Beach deposit (infralitoral)	5	±3	−16	A	4
7	San Vito lo Capo NE side	*Strombus b.* and U/Th ages	Tidal notches	3–8	±0.5	8	A	5–9
8	San Vito lo Capo W side	*Strombus b.* and U/Th ages	Inner edge marine terrace	11–14	±1.5	56	A	5–9
9	M. Cofano-Trapani	Geomorphological corr.	Inner edge marine terrace	14–20	±1.5	104	B	This paper
10	Trapani tonnara S.Giuliano	*Strombus b.*	Beach deposit (infralitoral)	5	±5	−16	B	10
11	Trapani Birgi	*Strombus b.*	Beach deposit (infralitoral)	2	±5	−40	B	11
12	Levanzo	*Strombus b.*	Beach deposit and tidal notch	2–5	±5	−16	A	12
13	Marettimo	Senegalese fauna	Tidal notches	5.0–8.2	±0.5	8	A	8, 9,12,13
14	Favignana	*Strombus b.*	Inner edge marine terrace	3–11	±1.5	32	A	12, 14
15	Marsala, Torre Scibiliana-Mazzara del Vallo	*Strombus b.* and str. correl.	Inner edge marine terrace	35	±3	224	C	10, 15–17
Mean uplift rate Sector 1 (NW) 37.5 mm/ka								
16	Pachino	*Strombus b.* and str. Correl.	Beach deposit	15	±5	64	B	18
17	S. Lorenzo	Geomorphologic correlation	Beach deposit	4	±5	−24	B	This paper
18	Avola/L. Arenella	Geomorphologic correlation	Beach deposit	5	±5	−16	B	This paper
19	Coste di Gigia (Sr)	Geomorphologic correlation and older continental fauna	Beach deposit	34	±5	216	C	31
20	Contrada Fusco	ESR on mammal teeth	Inner edge marine terrace	32	±5	200	B	20, 21
21	Augusta Mt. Tauro	*Strombus b.*	Inner edge marine terrace	16	±1.5	72	A	This paper, 20, 21, 22
Mean uplift rate Sector 3 (SE) 85.3 mm/ka								
22	Catania (Leucatia)	Lava age 180 ka	Inner edge marine terrace	165	±5	1264	B	23

23	Acitrezza	Lava age 180 ka	Inner edge marine terrace	175	±5	1344	B	23
24	Taormina	ESR on littoral fossils	Inner edge marine terrace	**115**, 130, 185	±3	864	A	This paper, 24, 25
25	Capo d'Alì	Geomorphologic correlation	Inner edge marine terrace	**140**, 210	±3	1064	C	This paper, 25
26	Capo Peloro/Ganzirri	*Strombus b.* amino acid	Inner edge marine terrace	110	±3	704	A	25–28
27	Capo Rasocolmo	Geomorphologic	Inner edge marine terrace	110	±3	824	C	25
28	Milazzo	Amino acid and warm fauna	Marine Terrace	90	±10	664	B	This paper, 29
29	Tyndari	Geomorphologic correlation	Lithofaga holes band	85	±1.5	624	C	30
30	Naso	Geomorphologic correlation	Inner edge marine terrace	120	±10	904	C	29
31	Acquedolci	Geomorphologic correlation	Inner edge marine terrace	130	±3	984	C	31
Mean uplift rate Sector 4 (NE) 924 mm/ka								
32	Lipari	U/Th on *Cladocora C.*	Inner edge marine terrace	45	±3	304	B	29, 32, 33, 34
33	Salina	Geomorphologic correlation	Inner edge marine terrace	50	±3	344	C	32
34	Filicudi	Age of lava	Inner edge marine terrace	40–45	±3	304	C	32
35	Panarea	Geomorfologica./Amino acid	Inner edge marine terrace	**115**/50	±3	864	C	32,34
36	Ustica	U/Th on *Cladocora*, *Strombus*	Inner edge-beach deposit	30	±3	184	A	35, 36, 28
37	Lampedusa	*Strombus b.*	Fossil beach	4	±3	−24	B	37,38

References: (1) Antonioli et al. (1994); (2) Fabiani (1941); (3) Gignoux (1913); (4) Mauz et al. (1997); (5,6) Abate et al. (1991, 1993); (7) Antonioli et al. (1999b); (8) Antonioli et al. (2001); (9) Antonioli et al. (2002); (10) Ruggieri et al. (1968); (11) Ruggieri and Unti (1974); (12) Malatesta (1957); (13) Abate et al. (1996); (14) Abate et al. (1992); (15) Ruggieri et al. (1975); (16) Ruggieri and Unti (1988); (17) D'Angelo and Vernuccio (1996); (18) Malatesta (1985); (19) Rhodes (1996); (20) Bianca et al. (1999); (21) Di Grande and Scamarda (1973); (22) Di Grande and Neri (1988); (23) Monaco et al. (2000); (24) Bonfiglio (1981); (25) Catalano and De Guidi (2003); (26) Antonioli et al. (2004b); (27) Bonfiglio and Violanti (1983); (28) Hearty et al. (1986a, b); (29) Hearty (1986); (29) Catalano and Di Stefano (1997); (30) Gliozzi and Malatesta (1982); (31) Bonfiglio (1991); (32) Lucchi et al. (2004a); (33) Lucchi et al. (2004b); (34) Radtke (1986); (35) Ruggieri and Buccheri (1968); (36) de Vita et al. (1998); (37) Buccheri et al. (1999); (38) Segre (1960).

For location of the sites see Fig. 1. We calculated the uplift rate using for MIS 5.5 a eustatic sea level of 7 m. The formula to calculate the uplift rate is: elevation (m)−7/125. In the elevation column we report the published attribution at MIS 5.5 by different authors but the elevations that we used to calculate uplift rates (discussed in the text) are in **bold.**

Table 2
New AAR analyses details at Cefalù (Figs. 1 and 3D) showing MIS 5 age for the deposits

Sample	Meters b.s.l.	Amount	Ratio Aile/Ile	Mean values standard deviation	Age MIS
CEFALU' 1	6.9±0.5	g.7,1	0.32 0.29 0.34 0.31 0.28	0.31±0.02	5.1–5.3
CEFALU' 2	9.9±0.5	g.7	0.36 0.34 0.31 0.34	0.34±0.02	5.1–5.3

Fig. 3. Field photographs of key sites showing MIS 5.5 features. (A) Geomorphological expression of MIS 5.5 terrace surface at Taormina, at +110 m. (B) Modern Dendropoma reef at Capo St. Vito, showing a crak due to transcorrent fault. (C) And (D) MIS5.5 terrace at Taormina, showing terrace deposits with a dated fossil (**C**), and the morphological expression (arrow) of the terrace upon which Taormina town is built. (E) MIS5.5 tidal notch in Marettimo at 7.2 m demonstrating the stability of the coastline during the Late Quaternary in this area. (F) *Glycymeris* shells analysed using AAR analyses, correlated to Aminozone A/C at Cefalù. (G) a transgression of MIS 5.5 calcarenite containing S. Bubonius on the Rosso Ammonitico formation (Giurassic) containing fossil Ammonites, west coast of Favignana island (Egadi).

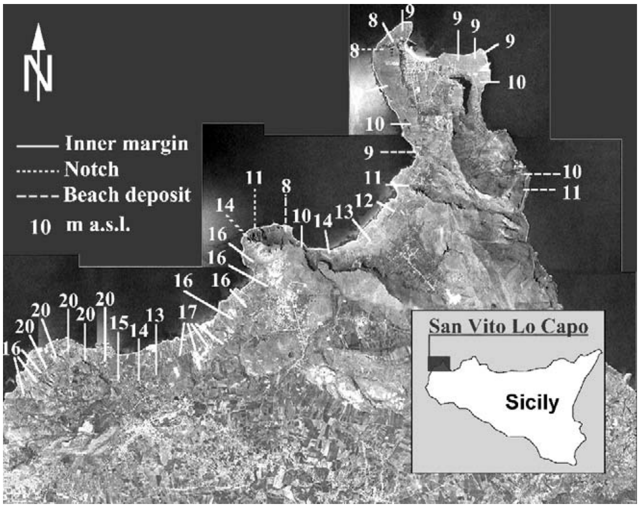

Fig. 4. Enlarged view of the data in the St. Vito Promontory area, showing the location of deposits and features of MIS 5.5 in that area, which is a stable location.

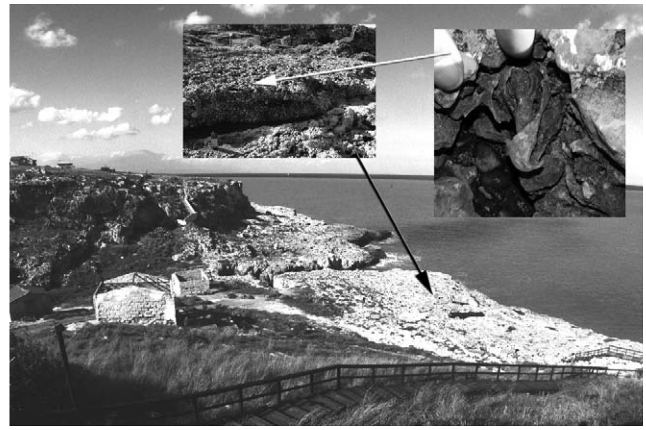

Fig. 5. MIS 5.5 terrace at Augusta, SE Sicily. Main photo is an oblique downward view of the terrace surface, upon which is deposited a coarse conglomerate (left inset photo), containing well-preserved examples of *Strombus bubonius* (right inset photo).

Southeast, between Marsala and Mazzara del Vallo, Ruggieri et al. (1975) published a geomorphological map containing a first-order terrace, the so-called Grande Terrazzo Superiore (GTS) with an inner margin that reaches 150 m and an enormous areal coverage; this terrace cuts the Calcareniti di Marsala (Lower Pleistocene, Siciliano; Ruggieri et al., 1968). Below an intermediate terrace of Middle Pleistocene age, the Tyrrhenian terrace is identified by the presence of *S. bubonius* at 2–3 m elevation. This deposit is on a large terrace extending to the coast with an inner margin at +34 m.

3.2. Sector 2

In contrast to Sector 1, between Capo Granitola and Capo Passero, careful search in all coastal sites with outcrop (Tre Fontane, Porto Palo, Sciacca Agrigento, Castello di Falconara, Marina di Ragusa, Pozzallo, Pantano Longarini, Fig. 2) did not reveal any evidence of marine Tyrrhenian deposits. Instead, in these coastal zones we found well-cemented sandy sediments of considerable thickness and containing fossils indicating they were Mio-Pliocene in age.

3.3. Sector 3

Malatesta (1985) found at Pachino a fossil beach containing *S. bubonius* at +15 m. We found at +4 m at Marzamemi a beach containing *Cardium* and *Cerastoderma* covered by aeolian deposits. To the north at Avola and Lido Arenella we found between +3 and +6 m a well-cemented fossil beach containing a non-Senegalese fauna.

Near Augusta on the Monte Tauro, Di Grande and Scamarda (1973) and Di Grande and Neri (1988) published the finding of terraces on which are more than one *S. bubonius*. We visited the sites and also found the fossil beach containing *S. bubonius*. Fossils lie on a conglomerate 1 m thick that covers the terrace over a horizontal distance of about 70 m wide (Fig. 5), and higher at +16 m is a band of *Lithophaga* holes. For geomorphological correlation with Pachino and Augusta we correlate the fossil beach of Marzamemi and Avola with MIS 5.5. Bonfiglio (1991) reports the presence of marine deposits up to 34 m at the site of Coste di Gigia (Fig. 2). The correlation with MIS 5.5 is on the basis of mammalian fauna.

Bianca et al. (1999) recognized numerous terraces from the coast up to an elevation of +450 m in the area of Augusta and Siracusa (including Monte Tauro). Those authors based their chronological interpretation of the terraces on mammals' teeth collected from continental deposits containing remnants of *Hippopotamus pentlandi and Elephas mnaidrensis.* Samples of teeth have been dated with ESR geochronological techniques (Rhodes, 1996). These deposits are covered by marine deposits the inner margin of which reaches +32 m. Using younger ESR ages (74.9–84.5 ka), Bianca et al. (1999) attributed the continental deposits containing *Elephas* and *Hippopotamus* to MIS 5.2, but attributed the subsequent marine deposits to MIS 5.1. The 4° slope of the terrace (MIS 5.5 for Bianca et al., 1999) in the study area is tilted towards SE with elevations decreasing from north (Augusta) to south (near Avola) (see Fig. 2 for the sites) varing from +105 to +75 m.

3.4. Sector 4

In eastern Sicily, correlations of MIS 5.5 highstands are based on *S. bubonius* discovered at 86 m (Bonfiglio and

Violanti, 1983) at Capo Peloro (site 26 of Fig. 1) and correlated with the inner margin terrace at +110 m. In the Catania/Etna volcano area, Monaco et al. (2000) mapped and dated the MIS 5.5 inner margin of terrace at elevations between 175 m (Aci Trezza) and 165 m at Catania, based on geomorphological correlation of the inner margin of the terraces and the age of underlying lava. The terrace, correlated with MIS 5.5, incised 180 ka-old lava.

In the Taormina area, Bonfiglio (1981) described a cave at +130 m containing a marine notch and Serpulids. We discovered a fossiliferous marine conglomerate deposit on a terrace with an inner margin at 115 m, in an area where undated terrace morphology and elevation data have been published (Catalano and De Guidi, 2003) at an elevation of 200 m. Palaeontological analysis (*Patella coerulea, Vermetids, Conus mediterraneus, Bolma rugosa, Osilinus Turbinatus, Venerupide*) indicates that the sea was few metres deep, but do not establish an age (no Senegalese fauna). Based on ESR methodology applied to a *Patella* and venerupid shells (sample nos. K-4343 and K-4244, University of Koln) collected at +105 m, we obtained ages of 76.4 ± 7.2 and 103.3 ± 12.5 ka. If the age is calculated using a constant Uranium-uptake model, the value is 124.5 ± 15.0 ka. We attribute these terraces to MIS 5, probably MIS 5.5 (Figs. 3C, D and 6). This age allows us to constrain the date of one point in a very long coastline that is otherwise undated.

Further north, at Capo St. Alessio and Capo d'Alì, we measured a terrace geomorphologically correlated with the Capo Peloro one that shows an inner margin at 140 m. The deposits are marine conglomerate without any possibility of age determination using a fossil assemblage. The depositional terrace of Capo Peloro, which contained *S. bubonius* (Bonfiglio and Violanti 1983; Hearty et al., 1986a, b), was recently mapped at 110 m by Antonioli et al. (2004b) and at 125 m by

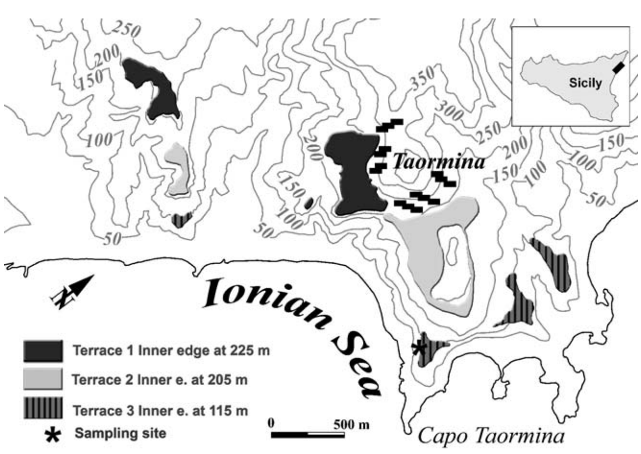

Fig. 6. Marine terraces at Taormina. Terrace 1 inner margin (i.m.) is at 225 m; terrace 2 i.m. is at 205 m; terrace 3 i.m. is at 115 m. A sample from Terrace 3 (location highlighted on the diagram, has revealed an age consistent with MIS5.5; see text for discussion.

Catalano and De Guidi (2003). Catalano et al. (2003) identified a terrace at Capo Rasolcomo at +125 m, and geomorphologically correlated it with MIS 5.5.

On the Milazzo promontory the MIS 5.5 terrace is well exposed up to +70 and +85 m (Fig. 7A). The terrace was dated by Hearty (1986) with AAR on *Arca* and *Glycymeris,* giving a clear result of Aminozone E. According to Catalano and Cinque (1995), the inner margin of this terrace occurs south of the Milazzo promontory on the mountain of Sicily at +120 m.

On the coast west of Capo Milazzo, Gliozzi and Malatesta (1982) studied fossil Megacerine bones and a skull in a cave at Capo Tindari. The cave shows a band of *Lithophaga* holes at 85 m which the authors attributed to MIS 5.5. There is no possibility of determining a precise age at this level. Dating of *Cervus* bones using AAR indicated MIS 6. The Naso promontory (C. D'Orlando, site 30 of Fig. 1) presents a series of terraces at different elevations up to 650 m. Some Middle Pleistocene terraces have been dated (Catalano and Di Stefano, 1997) on the basis of the micropalaeontological fauna. The MIS 5.5 terrace occurs at +130 m. Finally, at Acquedolci (site 31 of Fig. 2), Bonfiglio (1991) attributed a terrace at +131 m to MIS 5.5.

3.5. Islands

Apart from the Egadi Islands described in Section 3.1 (Fig. 2, sites 12–14), other islands close to Sicily contain some MIS 5.5 data, which is reported here. However, the islands lie in different places with different geological and structural places and it is not possible compare the uplift rates.

For the Aeolian islands (Fig. 1, sites 32–35), two recent publications (Lucchi et al., 2004a, b) present findings where age and elevation of the terraces are correlated with MIS 5.5 for Lipari, Salina, Panarea, and Filicudi. The correlations are based on the age of the lavas into which the terraces were carved.

For Ustica (Fig. 1, site 36) there are numerous studies of the terraces and deposits using AAR and U/Th ages (Hearty 1986; de Vita et al., 1998). An U/Th age of 119 ± 6 ka was obtained for a *Cladocora caespitosa* coral, where the terrace is at an elevation of 30 m. This attribution is fully confirmed by Ruggieri and Buccheri (1968) who also found *S. bubonius*.

At Lampedusa (Fig. 2, site 37) Segre (1960) described deposits containing *S. bubonius*. Buccheri et al. (1999) provided palaeontological analyses on a fossil beach, the maximum elevation of which reaches 4 m.

4. Comparison with Holocene uplift

Because sea level fell between MIS 5.5 and modern times, there is no record of the intervening MIS times.

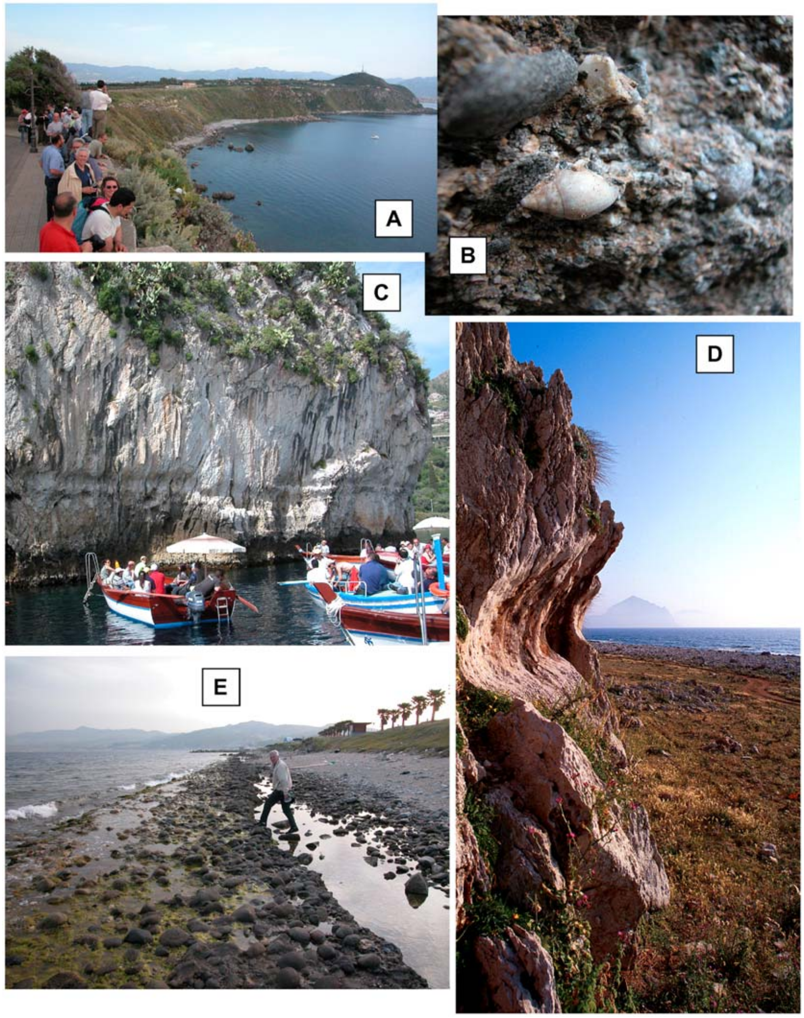

Fig. 7. (A) Marine terraces at Milazzo. (B) An Holocene fossil marine gastropod, uplifted at 2 m at Milazzo. (C) A late Holocene marine notch uplifted at 5 m, at Taormina. (D) St. Vito tidal notch. (E) Ganzirri the Holocene conglomerate hosting marine gastropods uplifted at 0.7 m.

Therefore the Holocene deposits and geomorphology can be compared with MIS 5.5 evidence to determine any changes in tectonic activity during the time since the last interglacial. New published data (Stewart et al., 1997; Rust and Kershaw, 2000; Antonioli et al., 2003, 2004b; Gringeri et al., 2004) have extended the tectonic record into the Holocene by using cores and uplifted and laterally extensive marine notches (with radiocarbon-dated biological sea level markers) allowing comparison of uplift rates using as reference sea-level curves the relative sea level local curves published by Lambeck et al. (2004) for Sicily.

The western sector remains a quasi-stable coastline during Late Holocene. On the eastern sector it is possible compare some sites of late Holocene uplift with the MIS 5.5 and in all sites the uplift rates are always higher (between 1.6 and 2.4 mm/yr in eastern coast), such that the uplift rate has increased, with an acceleration between 97% up to about 154% (Table 3 and Fig. 7). The Catania Plain yields Holocene uplift rates (Monaco et al., 2004) of about 0.5 mm/yr. However, due to scanty MIS 5.5 data, comparisons of rates are not possible.

5. Discussion

In many sites around Sicily the elevation of MIS 5.5 appears to be well defined and with good age control provided by the presence of *S. bubonius.* Dating using U/Th, AAR or TL methods (Fig. 8) has helped to clarify some uncertain sections. However, there are some sites where assignment to a chronological position is based only on geomorphological correlation. In response to these variables we adopt a quality rating in order to highlight where data are excellent (A), scarce (C) or intermediate (B). Some sites where there is disagreement over the chronological interpretation of the terraces, and sites 20, 24, 25, 26 (Table 1) are discussed below.

Table 3
Comparison between MIS 5.5 and late Holocene uplift rates in Sicily

Sites	Late Holocene uplift (mm/ka)	Holocene reference	MIS 5.5 elevation	MIS 5.5 uplift (mm/ka)	MIS 5.5 Reference	Acceleration MIS 5.5/late Holocene
St. Vito Lo Capo	≈0	1	8–14	8–56	7	—
Milazzo (southern)	1.700	2	90	664	8	154
Ganzirri	1.400	3	110	710	9	97
St. Alessio	2.400	4	140	1.070	This paper	123
Taormina	1.900	5	115	870	This paper	118
Simeto Plain	560	6	—	—	—	—

The acceleration has been computed according to: $A = \left((O - T)/T\right) \times 100$, where O is the Holocene uplift and T is the MIS 5.5 uplift.
References: (1) Antonioli et al. (1999b); (2) Gringeri et al. (2004); (3) Antonioli et al. (2004b); (4) Stewart et al. (1997); (5) Antonioli et al. (2003); (6) Monaco et al. (2004); (6) Monaco et al. (2004); (7) Antonioli et al. (2002); (8) Hearty (1986) and Catalano and Cinque (1995); (9) Miyauchi et al. (1994).

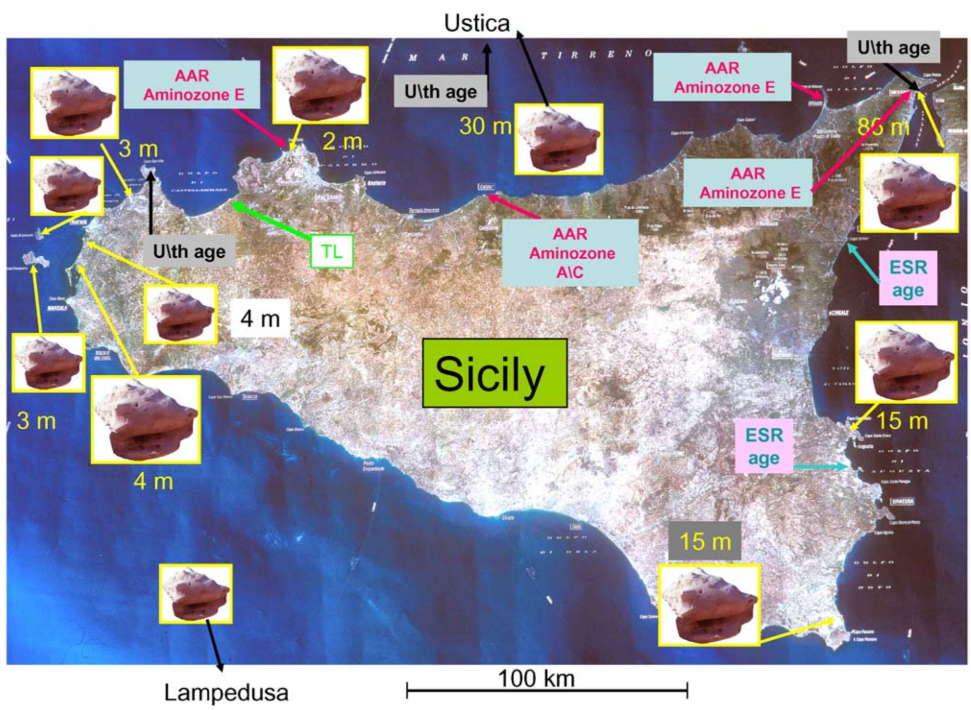

Fig. 8. Location of occurrences of *Strombus bubonius* and different dating methods provided for the Sicily coastline.

For Contrada Fusco (site 20 of Fig. 1 and Table 1) Bianca et al. (1999) wrote: "Geochronological data of mammals' teeth collected from continental deposits cropping out along the northern border of the Floridia basin are good constraints for the age of the Akradina terrace. The Akradina biocalcarenites lie above continental deposits containing remnants of *Hippopotamus pentlandi and Elephas mnaidrensis,* whose teeth have been dated with ESR (electron spin resonance) geochronological techniques (Rhodes, 1996). The ages of the youngest samples collected at this level produce dates with mean values ranging from 74.9±22.2 to 84.5±24.7 ka, strongly suggesting that the continental deposits were developed during the sea-level lowstand corresponding to MIS stage 5.2. This implies an age of about 80 ka (stage 5.1), the subsequent marine highstand, for the Akradina terrace". Notwithstanding the above interpretation by Bianca et al. (1999), for the following reasons, we propose to use only the data from the nearby Augusta site. Firstly, the continental layers containing mammal fossils at Contrada Fusco occur between marine sediments dated as late Sicilian (890 ka) and fossiliferous marine sands referred to the middle Pleistocene (Carbone et al., 1982) or Tyrrhenian (Di Grande and Neri, 1988). Secondly, Rhodes (1996, Table 2, p. 43), on the basis of EU ages (between 56.1±3.4 and 125.0±9 ka with a mean of 88.2±19.5 ka and LU[1]

[1]Two models of uranium uptake are generally considered in order to calculate an ESR age. In the early uptake (EU) model, it is assumed

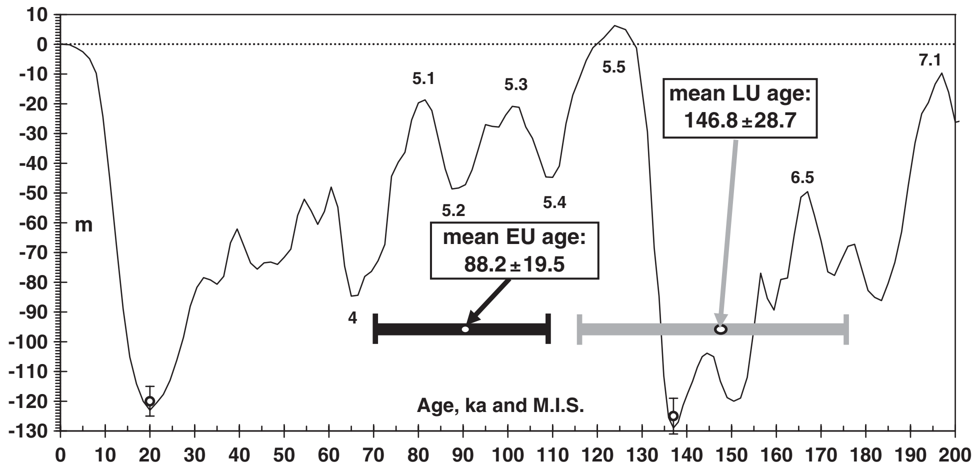

Fig. 9. Waelbroeck et al. (2002) sea level curve with the ESR data and error bars.

dating (between 92.1 ± 5 and 180.2 ± 10.8 ka concluded: "the age variations observed between different teeth is not consistent with their stratigraphic ordering within the site. The most likely date for the samples is between the EU and LU model ages, from late oxygen isotope stage 6 to early oxygen isotope stage 4". However, if we consider not only the "youngest" age of the continental samples, but all the EU and LU ages published by Rhodes (1996), and if we compare these data with a global sea level curve (Fig. 9, Waelbroeck et al., 2002), the Rhodes ages (including error bars) do not appear to allow a precise interpretation of the age of the terraces. Thirdly, we disagree with the Bianca et al. (1999) interpretation that the ESR data strongly suggests that the Akradina terrace and deposits should be correlated to the MIS 5.1 highstand. We are concerned that ESR dating produces ages with an uncertainty range of the order of ±20 or 30 ka. This dating technique should be used only when other methods are ruled out. This is not the case for the coast at Augusta (10 km from Contrada Fusco); Di Grande and Scamarda (1973) and Di Grande and Neri (1988) found more than one *S. bubonius* in situ in a normal fossil beach containing many circalittoral fossils, this deposit occurs on a well-defined terrace with a inner band of lithophaga borings that reaches +16 m. In this same coastal site Bianca et al. (1999) put the MIS 5.5 terrace at 60 m, apparently ignoring the terrace containing *S. bubonius*, the well-known Mediterranean marker of this marine highstand. In view of the above points we prefer not to use the datum of Contrada Fusco, so therefore the inner margin at 32 m is correlated to MIS 5.5. We use the elevation of the MIS 5.5 terrace at Augusta–Monte Tauro that occurs at an elevation of 16 m, well controlled by the *Lithophaga* band.

For the sites at Taormina (24), Capo d'Alì (25) and Capo Peloro (26) we consider elevations of, respectively, 115, 140, and 110 m to be correct for the inner margins of these "Tyrrhenian" terraces. This disagrees with the Catalano and De Guidi (2003) and de Guidi et al. (2003) estimates for the elevations of the same places that employ a different geomorphological interpretation to arrive at inner margin elevations of 180, 210 and 140 m for MIS 5.5. We base our interpretation on field surveys of the inner margins in the Taormina area (Figs. 5 and 3C, D) study of 1:10.000 aerial photographs, and the ESR age of the fossils sampled at 105 m on the 3° order terrace (Fig. 4). We also visited the cave described by Bonfiglio (1981) and found inside the cave at 140 m the Vermetid (*Dendropoma*) reef described in the Bonfiglio's paper. This deposit, however, is not associated with any terraces. For sites 25 and 26 we studied aerial photographs and, on geomorphological grounds, made a correlation with the terrace at Capo Peloro that contains *S. bubonius* and preserves the inner margin at 110 m.

The explanation of why the South coast does not preserve evidence of uplift remains uncertain, although there are at least two different interpretations: (1) the relatively weak bedrock is easily eroded and possible terrace features and recent sediments have not been preserved, (2) there is tectonic subsidence. We believe the second of these possibilities could be correct: the Grande Terrazzo Superiore (GTS) studied by Ruggieri and Unti (1974) is a very wide terrace (probably polygenic in origin) well developed on W and SW coasts of Sicily (Fig. 1). On the basis of the micro- and macropalaeontological content of the deposits that overlie this terrace, and on the lithologies into which the terrace is cut, Ruggieri et al (1975) considered it to be younger than the Calcarenite di Marsala (of Sicilian age, about 930 ka) and older than the first Middle

(*footnote continued*)
that all uranium in the tooth was adsorbed early in the burial history, whereas in the linear uptake (LU) model it is assumed that the uptake was continuous and constant throughout the burial history.

Pleistocene terraces that are visible in the Marsala area above the MIS 5.5 terrace occurring at 34 m.

The inner margin of the GTS is found at an elevation of 200 m in the Marsala coastal area and at about 400 m on the southern coast (Fig. 2). Notably, in the Marsala area the younger terraces are cut into and below the outer edge of the GTS, while in the south the GTS surface appears to descend beneath the sea. It may be that a Tyrrhenian terrace was formed in this area (between Trifontane and Agrigento, Fig. 2) but has since been drowned. Such subsidence could be linked, at least in part to tectonic loading beneath the Gela frontal thrust system. This suggestion is consistent with the Quaternary depression of the Gela–Catania foredeep farther east, while the emergence of the Hyblean Plateau, unrepresented along the southern coast, may be primarily related to the presence of major lower plate structures such as the Malta Escarpment and the Scicli fault zone (Fig. 2). Such speculations also appear consistent with the appreciable Tyrrhenian uplift along the Monte Tauro–Augusta coast closest to the Malta Escarpment and with the Lampedusa data indicating essentially no uplift southwards away from the thrust belt.

The highest uplift rates occur north of the thrust front on Mt. Etna near Catania and at Taormina, places also adjacent to major coast-bounding structures (Malta Escarpment and Messina fault system; Fig. 2). This region is affected by north–south compression and east–west extension as well as possibly being influenced by slab rollback and detachment and thermal inputs from asthenopheric upwelling (Lanzafame and Bousquet, 1997; Gvirtzman and Nur, 1999).

Finally, the overall main displacements in the Tyrrhenian coastal areas can be viewed as controlled by overlapping mechanisms that can be summarized as follows: large-scale regional uplift, subsidence and transcurrent processes, triggered by the evolution of the Tyrrhenian basin. Localized uplift and subsidence are responsible for fault-bounded headlands and associated coastal plains.

6. Conclusions

In addition to compiling and evaluating all published Tyrrhenian shoreline data for the Sicily region, we have discovered and dated two important new Tyrrhenian sections: a terrace outcrop at Taormina (with an ESR age) and shoreline deposits at Cefalù (with an AAR age). A new continuous survey of the Tyrrhenian inner margin has also been carried out over a distance of about 85 km between E S. Vito and Trapani, involving re-measuring elevations and establishing error bars at many sites. Overall, these data lead us to divide the Sicilian coastline into four sectors, each characterized by different MIS 5.5 heights and uplift rates:

Sector 1: NW Sicily: here we calculate a mean uplift rate of 37 mm/ka, with a maximum of 224 and a minimum of −40 mm/ka, leading us to regard this as a quasi-stable area. Nevertheless, some dislocations in this sector probably result from recently identified post MIS 5.5 strike-slip faulting that in some places continues into the late Holocene, for example at St. Vito where *Dendropoma* platforms dated at only 650–400 years are displaced (Fig. 3B).

Sector 2: S Sicily: along this coastline, some 350 km in length, there appear to be no MIS 5.5 outcrops. The inferred subsidence may be due to tectonic loading at the Gela frontal thrust system.

Sector 3: SE Sicily: in this area, dominated by the Hyblean Plateau, we estimate a mean uplift rate of 85 mm/ka, with a maximum of 216 and a minimum of −24 mm/ka. As with the NW sector we accordingly regard this as a quasi-stable coast, based on the low elevations of MIS 5.5 deposits, although affected by the proximity of the Malta Escarpment offshore. Adjacent to this structure the MIS 5.5 terrace reaches its maximum elevation of about +32 m. Farther south along the coast near Siracusa, another terrace at 105 m has also been proposed as MIS 5.5 (Bianca et al., 1999) although, in our view, this interpretation is not well supported by the available evidence.

Sector 4: NE Sicily: here we estimate a mean uplift rate of 924 mm/ka, with a maximum of 1344 (corresponding to the eastern flank of Etna in close proximity to the coast-bounding Malta Escarpment) and a minimum of 704 mm/ka. Regional north–south compression results in east–west extension and rifting, possibly coupled with slab rollback and detachment with associated isostatic uplift and asthenospheric upwelling. Within this framework, comparisons between MIS 5.5 and Holocene uplift indicators suggest a mean acceleration in uplift of about 100%.

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