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Sea Level Changes and Tectonic Mobility: Precise Measurements in Three Coastlines of Italy Considered Stable During the Last 125 ky

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Abstract Fast uplift or subsidence rates, related to intense tectonic-seismic activity, affect the Mediterranean coasts, especially in its eastern sector and Calabria, whereas other areas appear relatively stable. Along the southern Italian coast, the most widely distributed and therefore useful reference datum is the paleo sea level related to isotopic substage 5e (125 ky). In the present study, this marker (inner edge of marine terrace or notch) has been safely identified along three sectors of the Italian coast generally considered tectonically *stable*: eastern Sardinia, southern Latium and northwestern Sicily. In Latium the top of the Eutyrrhenian transgression was found to vary between -5 and +9.8 m a.s.l. along a 100 km long coast. A well carved Eutyrrhenian notch can be followed for ca. 35 km along the coast of Orosei in Sardinia, gradually varying in elevation between 7.7 and 10.5 m a.s.l., thus indicating a regional tilt. In Sicily, the inner edges of the Eutyrrhenian terrace and marine notches are at elevations between 8 and 13.9 m a.s.l.. In all these areas the stage 5e marker has shown a significant local mobility demonstrating its utility for detailing either areal or linear tectonic activity during the last 125 ky along the Tyrrhenian Sea coasts.

1 Introduction

Precise sea level indicators, mainly marine notches and terraces, demonstrate that many coastal sectors of the Mediterranean Sea have experienced differential rates of mobility during the Late Pleistocene-Holocene. Fast uplift or subsidence rates, even in very recent times, generally interpreted (or even observed in historical times) as the result of tectonic-seismic activity, are measured in the eastern sector of the Mediterranean and in Calabria (Miyauchi et al., 1994; Pirazzoli et al., 1996). Other areas appear relatively stable, mainly in the western and central Mediterranean Sea (e.g. Alessio et al., 1997; Antonioli and Ferranti, 1992). In addition to tectonic mobility, another factor of perturbation of the lateral continuity of eustatic sea level markers has been recently proposed: the glacio-hydro-isostatic movements due to the variable loading and unloading of ice and sea water masses on the mantle during glacial cycles. Although quantitative estimates have been attempted for several areas, also in the Mediterranean (Peltier, 1976a, 1976b; Lambeck and Johnston, 1995), results appear still speculative, due to the uncertainties in some parameters.

The recognition of a worldwide constant datum for the isotopic substage 5e highstand of the sea level (Eutyrrhenian, 125 ky) at + 7 m a.s.l. ± 1 m (Ku et al., 1974; Harmon et al., 1983) therefore provides an essential and precise marker on one side to characterize late Quaternary deformations of tectonic and/or isostatic origin and on the other side to identify stable areas where it should be possible to analyze the glacio-eustatic changes since then. For southern Italy a first synthesis of available data was carried out by Cosentino and Gliozzi (1988).

The Tyrrhenian Sea coast of Italy is characterized in many segments by relatively conservative physiographic features: high cliffs and terraces carved in Mesozoic limestone, with only few river deltas. This has allowed the good preservation of the Eutyrrhenian marker in many localities, either as marine notches and as terraces (with Senegalian fauna).

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The possibility to define as "stable" several coastal areas with respect to the 125 ky has justified some authors (Antonioli and Silenzi, 1998) to build up a curve of the latest Pleistocene-Holocene eustatic sea level changes with data derived from non contiguous sites spread around the Tyrrhenian sea. Aim of this work has been to analyze in great detail some of these coastal sectors considered tectonically stable (see for example Ambrosetti et al., 1983), either to underline the need for a careful check of the lateral homogeneity and evaluation of measuring errors, and to contribute to the concept of tectonic stability in the paleoeustatic reconstructions.

2 Data

The calcareous promontories and coastal plains of three sectors of the Tyrrhenian coast generally considered "stable": southern Latium, eastern Sardinia and northwestern Sicily, have been investigated to detail the occurrence of the Eutyrrhenian highstand.

Fig. 1. Example of marine notch along the coast of eastern Sardinia. The highest notch is referred to the Eutyrrhenian highstand of sea level (125 ky).

The morphological and depositional markers used in this study are marine notches (Fig. 1), inner edges (landward margins) of marine terraces containing typical Senegalian fauna, and lagoon deposits with *Cerastoderma* sp.. In general, marine notches have been attributed to substage 5e because directly linked to dated deposits. No doubts exist about the possible confusion with substages 5a or 5c, because of the stratigraphic and altimetric continuity with the Senegalian fauna deposits, dated via aminoacids racemization, and because it is not reasonable to believe that a notch of comparable morphology in adjoining areas has not developed during the same substage.

The error associated with the measurement of marine notches is estimated in the range ± 50 cm (Carobene and Pasini, 1982; Pirazzoli, 1986). The measurement of the landward margin of marine terraces is in general much more uncertain. Here, the reference datum for the sea level is a well-defined *Vermetid* reef. Living exactly at the mean tide, *vermetids* provide a very accurate datum for the present-day mean sea level. This fact and the use of a total station has allowed to reduce the error to less than 20 cm, mainly related to the uncertainty in the assessment of the correct inner edge, because of some local erosional reshaping.

Cerastoderma edulis cannot survive at depth larger than 1 meter, hence, the maximum estimated error is ca. 1.5 meters, including the uncertainty in the determination of the present-day sea level.

Parts of the data presented in this study are the result of original measurements, while some have been taken from appropriate references. All sources are listed in the Tables.

2.1 Southern Latium

The coastal segment considered here, ca 100 km long, includes two main plains (Pontina plain and Fondi plain), a main promontory (Circeo), and sectors of high coast, interrupted by minor promontories (Terracina, Sperlonga and Gaeta), corresponding to the western flank of the calcareous Aurunci mountains. The good exposures of high cliffs show that the Eutyrrhenian notch and the associated strips of *lithophaga* holes are the only paleo-shoreline preserved in the geological record. The data presented here are listed in Table 1 together with the source references.

The elevation a.s.l. of the markers (marine notches and *Cerastoderma* deposits) vary from 9.8 m near Minturno to ca. 5 m at Gaeta, 7 m at Sperlonga and -5 m in the Fondi plain (*Cerastoderma* deposits), corresponding to a difference of 14.8 m in nearly contiguous sectors (Figs. 2 and 3, Table1). In the western sector, notches in the Terracina and Circeo promontories indicate the Eutyrrhenian paleo-shoreline at 7.3 and 9.0-9.6 m respectively, whereas lagoon deposits with *Cerastoderma* outcrop at elevations between +5.3 to -1.8 m a.s.l. Active subsidence in the Pontina and Fondi plain due to the compaction of clay and peat deposits is evident (e.g. Brunamonte and Serva, 1990), thus affecting the elevation of Eutyrrhenian deposits, to which the effects of tectonic movements active since the Middle Pleistocene should be added (Antonioli et al., 1990). In the lowest elevation areas the Eutyrrhenian lagoon deposits are covered by a similar facies related to the Holocene transgression (radiocarbon dating on *Cerastoderma sp.* shells indicates that a mesohaline environment established ca. 8 ky BP). The age attribution to the Eutyrrhenian of the deposits connected to the Sperlonga and Gaeta notches has been based on the aminoacids racemization of *Glycimeris* shells. The obtained values pertain to the aminozone E, which corresponds in the Mediterranean Sea to the isotopic substage 5e (Villani, unpublished master thesis, 1997). The Circeo notch hosts a deposit with *Strombus bubonius*.

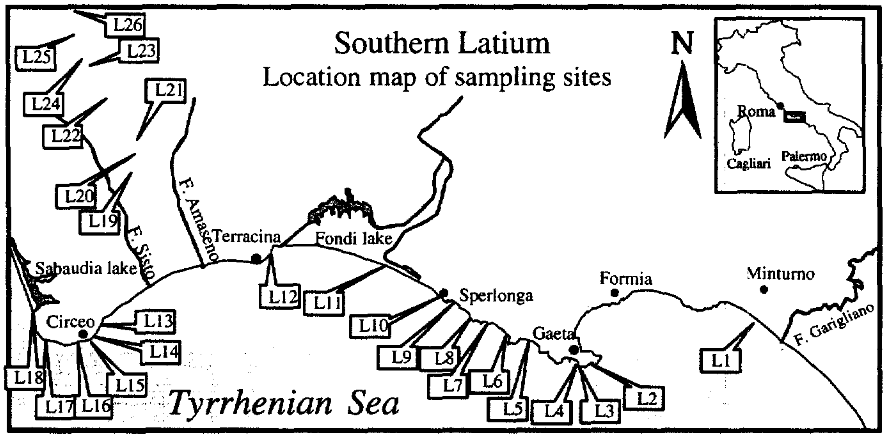

Fig. 2. Location of measurement sites of the Eutyrrhenian datum in southern Latium.

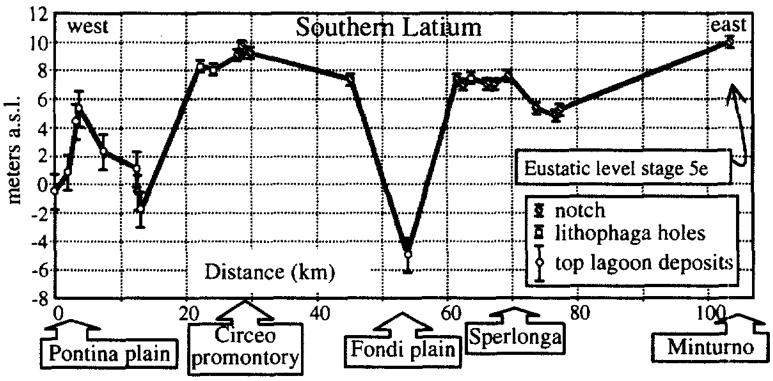

Fig. 3. Plot of Eutyrrhenian elevation vs. distance for southern Latium data.

2.2 Sardinia

In eastern Sardinia we have reinterpreted data in a sector ca. 30 km long in the Orosei Gulf, between the Biddiriscottai marine cave and Pedra Longa (Fig. 4), collected by Carobene and Pasini (1981) in the northern part, and Antonioli and Ferranti (1992) in the southern part. Age attributions came from the recognition of "warm" Senegalian fauna and some dating based on the racemization of aminoacids. The elevation of the Eutyrrhenian marker was referred to the present-day mean tide by Carobene and Pasini (1982) and to the *Vermetid* reefs by Antonioli and Ferranti (1992).

The elevation a.s.l. gradually decreases from north to south from 10.5 m down to 7.7 m (Fig. 5 and Table 2), corresponding to ca. 2.8 m in 30 km (9.3 cm/km). The coast shows a homogeneous morphology, with high linear cliffs and a few promontories cut in Jurassic compact limestone rocks. Only modest rivers interrupt the continuity of the high coast. The marine notch is well preserved and continuous over ca. half of the cliff length, without any abrupt change of elevation. Faults inland have been active concurrently with the Pliocene-Early Pleistocene basaltic volcanism and do not show any evidence of movement since then (Cherchi et al., 1980). Instead, faults parallel and orthogonal to the north-south-trending coast are mapped offshore with probable Pleistocene activity (Ambrosetti et al., 1983).

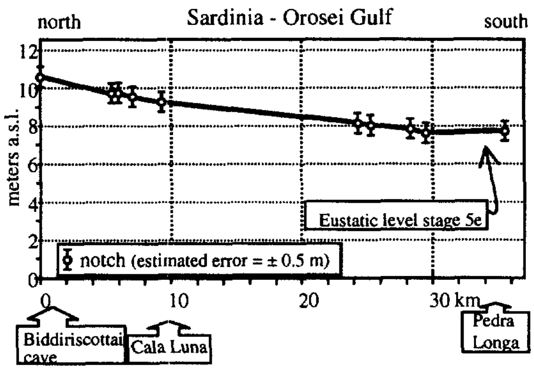

Fig. 5. Plot of Eutyrrhenian elevation vs. distance for eastern Sardinia data.

Table 1. Eutyrrhenian datum for southern Latium

Site	Id.	Elevation (m a.s.l.)	Marker	Error (m)	References
Minturno	L1	9.8	notch	±0.5	10
Gaeta	L2	5.2	notch	±0.5	1
Gaeta	L3	4.8	notch	±0.5	1
Gaeta	L4	5.3	notch+*Glyc.*	±0.5	1
Arenauta	L5	7.5	notch	±0.5	10
S. Agostino	L6	7.0	notch	±0.5	1
S. Agostino	L7	7.0	notch	±0.5	1
Torre Capovento	L8	7.4	lith. holes+ *Glycimeris*	±0.5	10
Grotta di Tiberio	L9	6.9	notch+*Glyc.*	±0.5	2
Sperlonga	L10	7.3	notch	±0.5	10
Fondi	L11	-5.0	lagoon dep.	±1.5	2
Terracina	L12	7.3	notch	±0.5	2, 11
Guattari cave	L13	9.2	notch	±0.5	5, 9, 10, 12
Torre del Fico	L14	9.2	notch	±0.5	6
Capre cave	L15	9.6	notch	±0.5	5, 6, 7, 10
Fossellone cave	L16	9.0	notch	±0.5	4, 8
La Batteria	L17	8.0	Lith. holes	±0.5	6
Breuil cave	L18	8.3	Lith. holes	±0.5	3
Borgo Vodice	L19	-1.8	lagoon dep.	±1.5	13
Borgo Vodice	L20	-0.6	lagoon dep.	±1.5	13
Borgo Vodice	L21	1.0	lagoon dep.	±1.5	13
Pontinia	L22	-0.5	lagoon dep.	±1.5	13
Pontinia	L23	0.8	lagoon dep.	±1.5	13
Pontinia	L24	2.3	lagoon dep.	±1.5	13
Pontinia	L25	4.4	lagoon dep.	±1.5	13
Pontinia	L26	5.3	lagoon dep.	±1.5	13

1 Antonioli (1991); 2 Antonioli et al. (1988); 3 Bietti et al. (1990); 4 Blanc (1938); 5 Blanc and Segre (1953); 6 Dai Pra and Ozer (1985); 7 Durante and Settepassi (1974); 8 Durante (1975); 9 Durante and Settepassi (1977); 10 Ozer et al. (1987); 11 Remiddi (1911); 12 Segre (1991); 13 Villani (1997).

Table 2. Eutyrrhenian datum for eastern Sardinia (Orosei Gulf)

Site	Id.	Elevation (m a.s.l.)	Marker	Error (m)	References
Biddiriscottai c.	Sr1	10.49	notch	±0.5	14
Cala Fuili	Sr2	9.65	notch	±0.5	14
Cala Fuili	Sr3	9.70	notch	±0.5	14
Bue Marino	Sr4	9.53	notch + *Strombus b.*	±0.5	14
Cala Luna	Sr5	9.23	notch	±0.5	14
Punta Caroddi	Sr6	8.11	notch	±0.5	15
Punta Caroddi	Sr7	8.00	notch	±0.5	15
Punta Quao	Sr8	7.80	notch	±0.5	15
Capo M. Santu	Sr9	7.60	notch	±0.5	15
Pedra Longa	Sr10	7.70	notch	±0.5	15

14 Carobene and Pasini (1982); 15 Antonioli and Ferranti (1992).

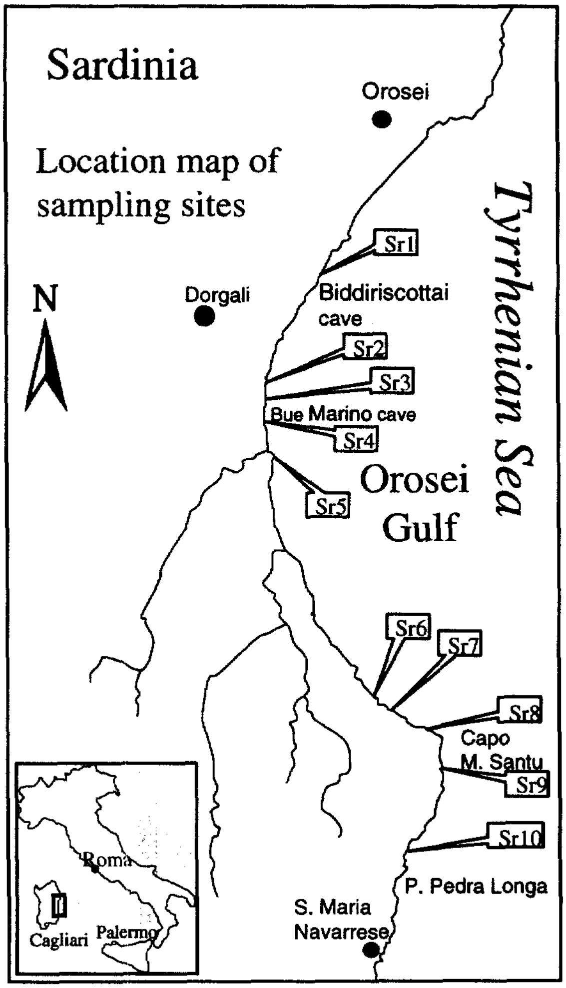

Fig. 4. Location of measurement sites of the Eutyrrhenian datum in eastern Sardinia (see Table 2 for data details).

2.3 Northwestern Sicily

In the area comprised between San Vito Lo Capo and Mt. Cofano (Fig. 6) the morphotectonic setting of the widely outcropping Mesozoic shelf limestone has determined the deposition of coastal facies calcarenites during the Lower Pleistocene (Abate et al., 1991, 1993).

Successively, a suite of five main marine terraces has formed. The age attribution to the isotopic substage 5e of the lowest, best preserved and continuous of these terraces is based again on *Strombus bubonius*, which is abundant in the deposits mantling the terrace. The higher terraces are attributable to Middle Pleistocene sea highstands based on U/Th dating (see Antonioli et al., this volume).

The Eutyrrhenian datum is marked by marine notches carved in the Mesozoic limestone cliffs at Mt. Cofano (11.5 m a.s.l.) and Cala Mancina (8 m), ca. 15 km far from each other (Figs. 6 and 7, Tab. 3) (Antonioli et al., 1997). Moreover, the occurrence of the Eutyrrhenian terrace in the Castelluzzo plain has allowed a detailed measurement of the landward margin by means of a Total Station. We have measured, as common practice, the intersection between the upper terrace scarp and the Eutyrrhenian surface. We have referred our data to the present-day sea level as determined by the well-developed *Vermetid* reefs common in the area. Terrace elevations range between 10.7 and 13.9 m a.s.l. within a distance of less than 5 km.

Table 3. Eutyrrhenian datum for northwestern Sicily

Site	Id.	Elevation (m a.s.l.)	Marker	Error (m)	References
Cala Mancina	S 0	8.00	notch + *Strombus b.*	±0.5	16
Castelluzzo plain	S 1	11.13	inner edge	±0.2	this work
Castelluzzo plain	S 2	11.12	inner edge	±0.2	this work
Castelluzzo plain	S 3	10.71	inner edge	±0.2	this work
Castelluzzo plain	S 4	11.80	inner edge	±0.2	this work
Castelluzzo plain	S 5	12.03	inner edge	±0.2	this work
Castelluzzo plain	S 6	13.90	inner edge	±0.2	this work
Castelluzzo plain	S 7	12.00	inner edge	±0.2	this work
Castelluzzo plain	S 8	12.10	inner edge+ *Strombus b.*	±0.2	this work-16
Saraceno plain	S 9	11.50	notch	±0.5	this work

16 Antonioli et al. (1997).

3 Discussion and conclusions

The evidence of the Eutyrrhenian (125 ky) highstand of sea level provides an essential marker to analyze the tectonic mobility, or stability, of coastal areas where erosional-depositional conditions have allowed its conservation, as it is the case along central and southern Italy. A sample study in three different sectors, where the 125 ky marker is well documented, has shown diversified styles of deformations.

In southern Latium we have observed the marker (Fig. 3) very low inside the coastal plains, down to - 1.8 m a.s.l. in the Pontina plain and -5 m a.s.l. in the Fondi plain (Table 1). At least, part of the subsidence is due to the compaction of soft sediments (peat and clay deposits), especially in the Pontina plain (Brunamonte et al., 1990; Villani, 1997).

However, in the Fondi plain active normal faulting is clearly evident: the same Middle Pleistocene deposit is at 60 m a.s.l. on the western flank of the plain and at –50 m a.s.l. inside the plain (Antonioli et al., 1990). Also, the different elevations of the Eutyrrhenian marker in the calcareous promontories can only support a tectonic explanation, possibly linked to block faulting, although the activity of normal faults is not evident in the field and in the seismicity of the area. (Carrara, 1995). The Sperlonga and Terracina promontories appear as the only "stable" sectors. The easternmost site, Marina di Minturno, might be affected by isostatic/volcanotectonic movements related to the now quiescent Roccamonfina volcano located nearby.

In eastern Sardinia, where the marker slopes down from 10.5 m a.s.l. in the north to 7.7 m a.s.l. in the south within a distance of ca. 35 km, there is no evidence for faulting, but for a tilt of the analyzed coastal sector (Fig. 5). Comparison with other other coastal sectors of Sardinia shows that this tilt, which should have a geodynamic explanation, does not extend to the northwest (Capo Caccia – Alghero area) and to the south (Cagliari). Unfortunately, conservative conditions are rare outside the study area and a comprehensive picture is still missing. Anyway, the differential behaviour observed in the cited areas makes unlikely an explanation for the tiltingbased on the effect of glacio-hydro-isostasy (Lambeck and Johnston, 1995).

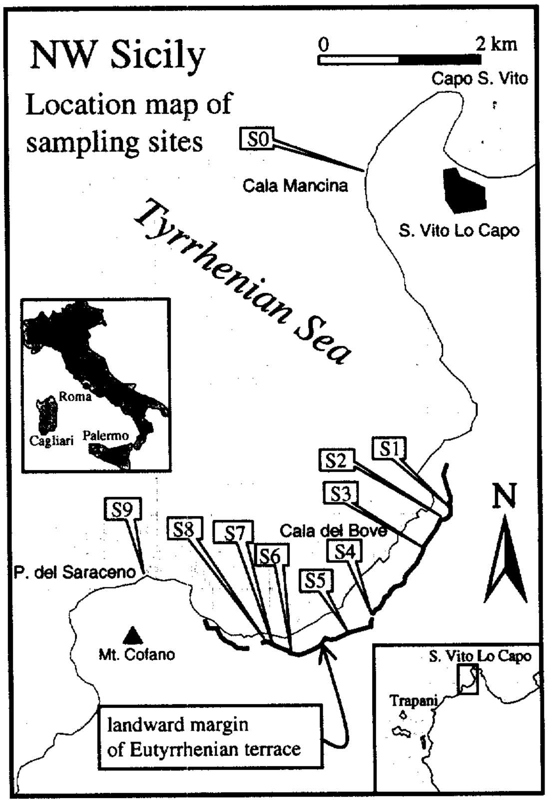

Fig. 6. Location of measurement sites of the Eutyrrhenian datum in northwestern Sicily (see Table 3 for data details).

In northwestern Sicily the 125 ky shoreline only approaches the world datum at Cala Mancina, being elsewhere generally well above 8 m a.s.l.. The abrupt shift in elevation between the nearby sampling sites S5 and S6 (almost 2 m, Fig. 7) is likely due to one of the strike-slip faults affecting Tyrrhenian and even younger sediments along this sector of the Sicilian coast and Egadi islands.

The three cases described in this study demonstrate that a significant spatial variability affects the 125 ky marker even where a tectonic stability is generally postulated during the Late Quaternary, or even over a much longer time span, such as in Sardinia. A careful verification is therefore

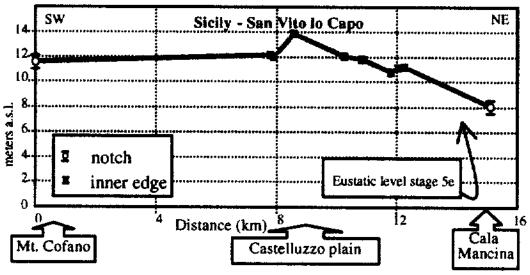

Fig. 7. Plot of Eutyrrhenian elevation vs. distance for NE Sicily data.

needed before assuming any lateral continuity, even in short distance extrapolations. In general, the post-125 ky mobility in the investigated areas is interpretable essentially as the effect of local tectonics; there is not clear evidence of the generalized loading and unloading processes in the Tyrrhenian Sea predicted by glacio-hydro-isostasy models, possibly because equilibrium has been now re-established after the last glacial cycle or because local mobility is able to mask such larger scale variations. An accurate and critical review of the Tyrrhenian datum in Italy, based on precise measurements is therefore necessary in order to better constrain the tectonic and isostatic adjustments during the last 125 Ky.

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