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Field Trip Guide Book - P56

32nd INTERNATIONAL
GEOLOGICAL CONGRESS

MILANKOVITCH CYCLES AS A GEOCHRONOMETRIC TOOL TO CONSTRUCT GEOLOGICAL TIME SCALES

Leader: F. Hilgen

Post-Congress **P56**

Florence - Italy
August 20-28, 2004

The scientific content of this guide is under the total responsibility of the Authors

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Series Editors:
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English Desk-copy Editors:
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Front Cover:
Astronomically controlled quadripartite color cycles of the
Trubi Formation at Punta di Maiata

Leader: F. Hilgen

Introduction

Astronomical tuning is rapidly becoming a widely accepted method of absolute dating as an alternative to radioisotopic dating and has already been used to construct time scales as far back in time as 30 Ma. The method is based on correlating ("tuning") sedimentary (or Milankovitch) cycles and other cyclic variations in paleoclimatic records to curves, which describe the past variations in the Earth's orbital parameters (precession, obliquity and eccentricity) or insolation. These curves have been computed with the help of an astronomical solution for the Solar System. In this respect the fieldtrip is of great scientific interest as it will primarily serve as a vehicle to demonstrate the principles of this novel approach for constructing geological time scales with an unprecedented resolution and accuracy to a broader audience in the field. This goal will be achieved by visiting the by now classical marine sections of Miocene and Pliocene age on Sicily. All these sections played a crucial role in developing the astronomical (polarity) time scale for the Mediterranean Neogene, which already underlies the standard geological time scale for the Pliocene. These sections are all the more important because all Pliocene stage boundaries are defined in these sections and, as a consequence, are incorporated in the standard time scale by means of first-order calibrations. In addition, the application of the new time scale in paleoclimatic studies directed at the understanding of the astronomical influences on the climate will be briefly outlined, a topic which is of prime scientific interest as well.

Geologic setting and stratigraphy

The prime focus of the excursion are the Neogene sediments which are exposed along the south coast of Sicily. These mainly open marine sediments were deposited in the Caltanissetta Basin. This basin became part of the Apenninic-Maghrebian foredeep that developed external to the evolving orogen, but was affected by African-verging thrusting in late Neogene times. The so-called Argille Scagliose ("Scaly Clays") repeatedly acted as a lubricant for décollement. The African foreland is represented by the nearby Ragusa platform on southeastern Sicily.

The succession starts with deep marine hemi-pelagic sediments of Miocene age, which usually overly intensily deformed multi-colored clays of the "Argille Scagliose". These sediments belong to the Licata Formation and consist of a cyclic alternation of homogeneous marls and brownish often-laminated beds enriched in organic carbon termed sapropels. The marls of the Licata Fm are followed by diatomites of the Tripoli Fm (the pre-evaporitic Messinian) and capped by the evaporitic limestones of the Calcare di Base and evaporites (gypsum, salts) of the Gessoso-Solfifera Fm (Fig. 1). The latter, which reflect the sedimentary expression of the so-called Messinian Salinity Crisis (MSC) in the Mediterranean, are abruptly overlain by deep marine marls of the Pliocene Trubi Fm. The evaporites in turn can be subdivided into two units, the Lower Evaporites and the Upper Evaporites, which are separated by an erosional and sometimes even angular unconformity (Fig. 1).

On a large scale the lithostratigraphic succession tells the story of the dynamic evolution of the connection between the Mediterranean and Atlantic Ocean. This connection was severely interrupted during the late Miocene resulting in the MSC and the deposition of vast amounts of evaporites (up to two km in the deep basins of the Mediterranean).

On a smaller scale the succession is of a cyclic nature. All the sediments, including the evaporites, show a distinct cyclic bedding that is driven by orbitally-controlled variations in regional Mediterranean climate. Clearly the Mediterranean as a whole is very sensitive to astronomically-induced climate changes due to its paleolatitudinal position and semi-enclosed character. The patterns of the sedimentary cycles, as will be convincingly demonstrated in the field, reflect the influence of all the three orbital parameters, namely precession, obliquity and eccentricity.

Earth's orbital parameters

The climate changes inferred by Milutin Milankovitch as producing Pleistocene ice ages are caused by variations in solar insolation received by the Earth, which in turn results from periodic changes in the shape of the Earth's orbit and in the position of its rotational axis (Fig. 2). Such changes are caused by the gravitational interactions of our planet with the Sun, the Moon and the other planets of the Solar System. These interactions give rise to quasi-periodic variations in the eccentricity of the Earth's orbit (the eccentricity cycle) with main periods of 100,000 and 400,000 years, and in the tilt (obliquity cycle) and precession (precession cycle) of the Earth's axis, with main periods of 41,000 and

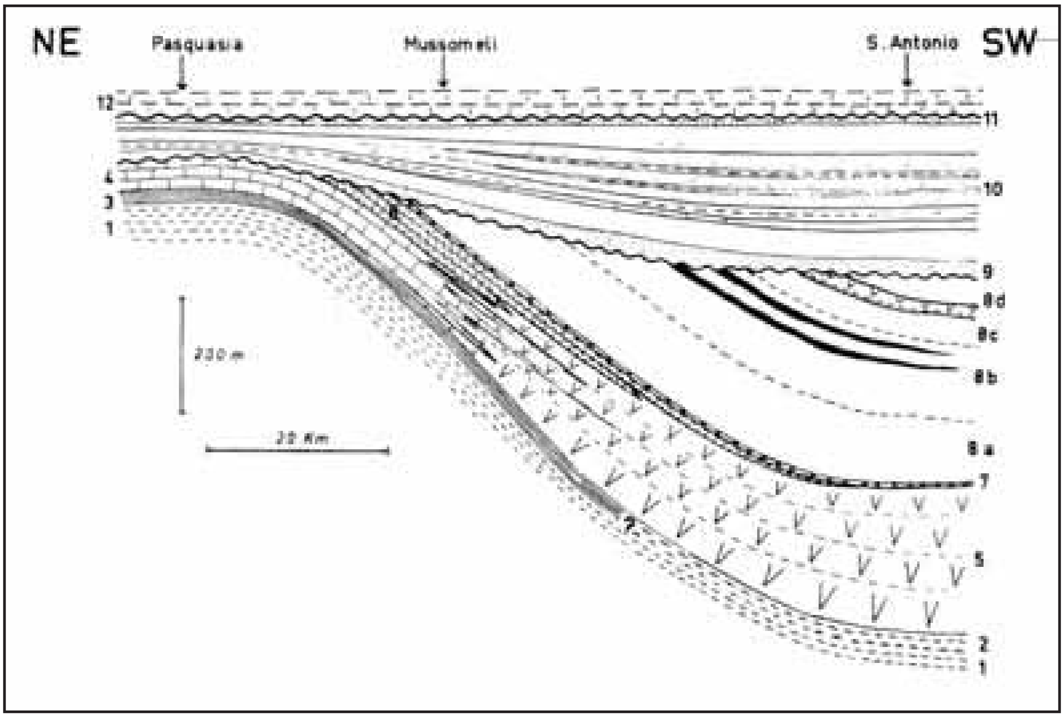


Figure 1 - Schematic NE-SW cross-section through the Caltanissetta Basin. 1. Licata Fm; 2 and 3. Tripoli Fm; 4. Calcare di Base; 5-8. Gypsum and salts of the Lower Evaporites; 9 and 10. Upper Evaporites; 11. Arenazzolo, and 12. Trubi marl Fm (after Decima and Wezel, 1973).

21,000 years, respectively (Figs. 2 and 3). These perturbations in the Earth's orbit and rotation axis are climatically important because they affect the global, seasonal and latitudinal distribution of the incoming solar insolation. Astronomers have been able to calculate these changes back in time with the aid of astronomical solutions for the Solar System (Fig. 3).

Eccentricity cycle: The shape of the Earth's orbit is seldom a perfect circle, but it is usually elliptical with the Sun positioned in one of the two foci. This implies that the Earth is located closer to the Sun during part of the year, receiving a higher-than-average insolation, and that it is located farther away from the Sun during the remainder of the year. The Earth receives slightly more solar energy (insolation) when on an elliptical orbit, but the difference between the amount of energy that is received on a circular orbit is very small. The cycle of **eccentricity** portrays the changes in the shape of the Earth's orbit from circular to elliptical, with main periods of 100,000 and 400,000 years (Figs. 2 and 3). Eccentricity is in particular important because it modulates the amplitude of the precession cycle (see below).

Obliquity cycle: The seasons are not only controlled by the eccentricity of the Earth's orbit but also by the tilt of the rotational axis relative to the orbital plane. Furthermore, this tilt, or **obliquity,** is not constant, and the angle between the Earth's axis and a line perpendicular to the orbital plane varies between 22° and 25° with a main period of 41,000 years (Figs. 2 and 3). This small difference in tilt has a noticeable effect on the contrast between the seasons: seasonal contrast is enhanced during those times when the tilt angle is at a maximum. The effect of obliquity is noticeable in particular at higher latitudes and it is the same for both hemispheres.

Precession cycle: Apart from changes in tilt, the rotation axis goes through another motion which is called the astronomical cycle of **precession** with a period of 26,000 years. This movement can best be compared with that of a rapidly and obliquely spinning top: its tip remains stationary while the spin-axis rotates slowly and the far end describes full

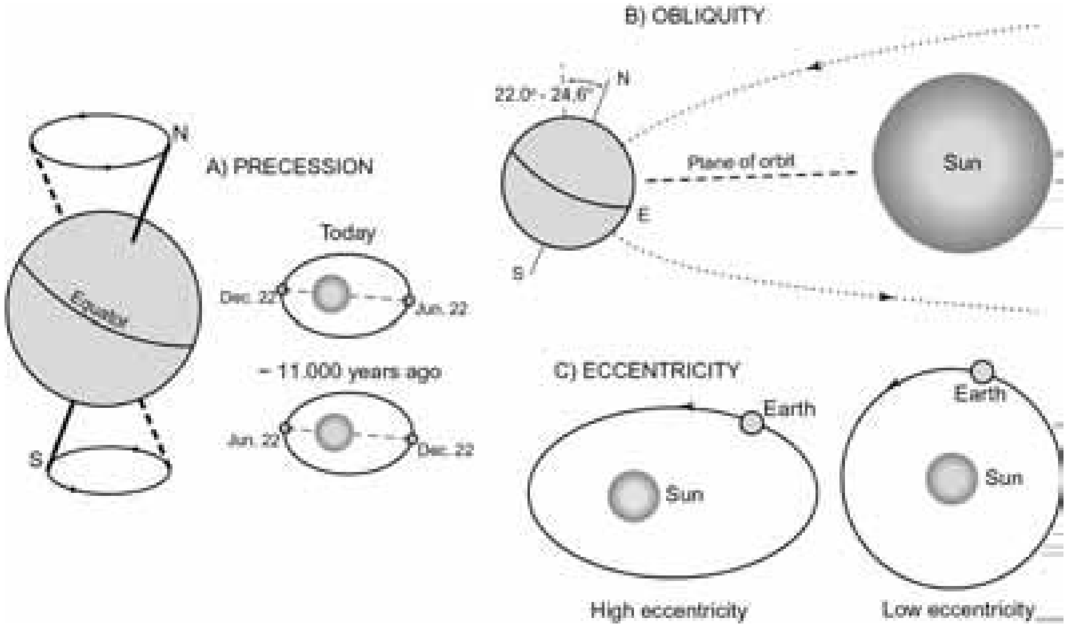


Figure 2 - Earth's orbital cycles of precession, obliquity and eccentricity.

circles. The rotation axis of the Earth makes a similar movement with the Earth's centre as its hinge point. The precession cycle that actually influences climate (**"climatic precession"**) has a shorter period, with an average of 21,000 years, than the astronomical precession cycle because of the opposite motion of the eccentric orbit with respect to the Earth's direction of movement around the Sun (Figs. 2 and 3).

The precession cycle only affects climate in case of an elliptical orbit. At present, the Earth's orbit is elliptical and the Earth is positioned closest to the Sun (i.e., in perihelion) during boreal (= Northern Hemisphere) winter and farthest away (in aphelion) during boreal summer. This implies that we (i.e., the Northern Hemisphere) experience mild winters and cool summers. This is different for the Southern Hemisphere which experiences colder winters and warmer summers, resulting in an enhanced seasonal contrast. Due to the precessional movement, the situation was opposite 11,000 years ago. In other words, the precession cycle causes an alternation of maxima and minima in seasonal contrast between the Northern and Southern Hemisphere over a period of 21,000 years.

It is evident that the effect of precession on seasonal contrast is amplified when the Earth's orbit is strongly elliptical. Because it modulates the amplitude of the precession signal, it is not surprising that the eccentricity parameter is part of the precession formula. Finally, the precession cycle has a stronger effect on lower latitudes, i.e. in contrast to the obliquity cycle.

Field itinerary

DAY 1

Eraclea Minoa - Capo Rossello

In the morning we will visit the geological section of Eraclea Minoa, which includes the GSSP of the Miocene-Pliocene boundary. We will walk along the coast (partly through water) to Capo Bianco (White Cape). In the afternoon we will visit the classical area of Capo Rossello some 25 km further to the east. In the evening there is the possibility of visiting the famous "Valle dei Templi" near Agrigento.

Stop 1.1:

Eraclea Minoa – Capo Bianco

Eraclea Minoa was part of Magna Graecia during classical times and the archeological remains of the town built on top of the cliffs can still be seen and visited. The Eraclea Minoa section contains the lower part of the Trubi marl Formation, including its

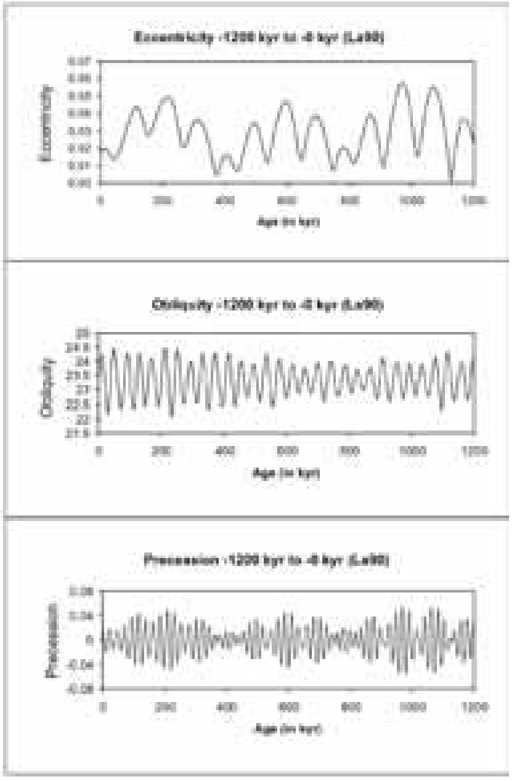


Figure 3 - Changes in precession, obliquity and eccentricity over the last 1,200,000 years.

base, while the middle and upper parts of the Trubi are exposed at nearby Capo Bianco (Figs. 4 and A). Underlying the Trubi marls, the gypsum cycles of the Upper Evaporites and the Arenazzolo sandstone are well exposed at Eraclea Minoa. These older Neogene sediments are overlain with an angular unconformity by Pleistocene terrace deposits.

A. Capo Bianco

Upper Evaporites

The gypsum was exploited by the ancient Greeks to build the city walls and watch towers of ancient Eraclea Minoa. The Upper Evaporites at Eraclea Minoa consist of 7-8 sedimentary cycles that each show a facies evolution from marls to laminated gypsum and, finally, selenitic swallow-tail gypsum at the top, reflecting an increase in salinity. Ostracode assemblages with Paratethyan affinities are found in the marls, indicating that this unit belongs to the terminal Lago-Mare (“Lake Sea”) phase of the MSC. This phase is characterised by oligo-mesohaline environments throughout the Mediterranean, which at that time consisted of isolated brackish shallow water basins with environmental conditions similar to those that existed in the Paratethyan domain during the Neogene.

Arenazzolo sandstone

Sedimentary structures in the sandy Arenazzolo unit overlying the evaporites of the Upper Evaporites include flaser bedding indicative of higher energy conditions. They suggest a littoral setting at the edge of the lake, or a delta lobe. The Arenazzolo sandstone, which seems to be limited to the Caltanissetta Basin, most likely represents a limited amount of time only, in the order of several thousands of years. The unit has previously been misinterpreted as a transgressive unit separating the Messinian evaporites from the overlying deep marine marls of the Trubi Fm.

Miocene-Pliocene boundary

The transition between the non-marine Arenazzolo sandstones of latest Messinian age and the deep marine pelagic Trubi marls by definition marks the Miocene/Pliocene boundary, now dated astronomically at 5.33 Ma. Initially, Cita (1975) proposed defining the boundary at Lido Rossello (stop 1.2) but, due to the much better preserved primary paleomagnetic signal (Hilgen and Langereis, 1993), it is now formally defined at Eraclea Minoa at the base of the first sedimentary cycle of the Trubi marls (Van Couvering et al., 2000). The abruptness of the lithological transition has long been discussed, but is now assumed to mark the catastrophic flooding of the Mediterranean following the restoration of the marine connection with the Atlantic Ocean at the end of the MSC.

Trubi marls

The Eraclea Minoa section is the lowest segment of the Rossello Composite Section (RCS), which

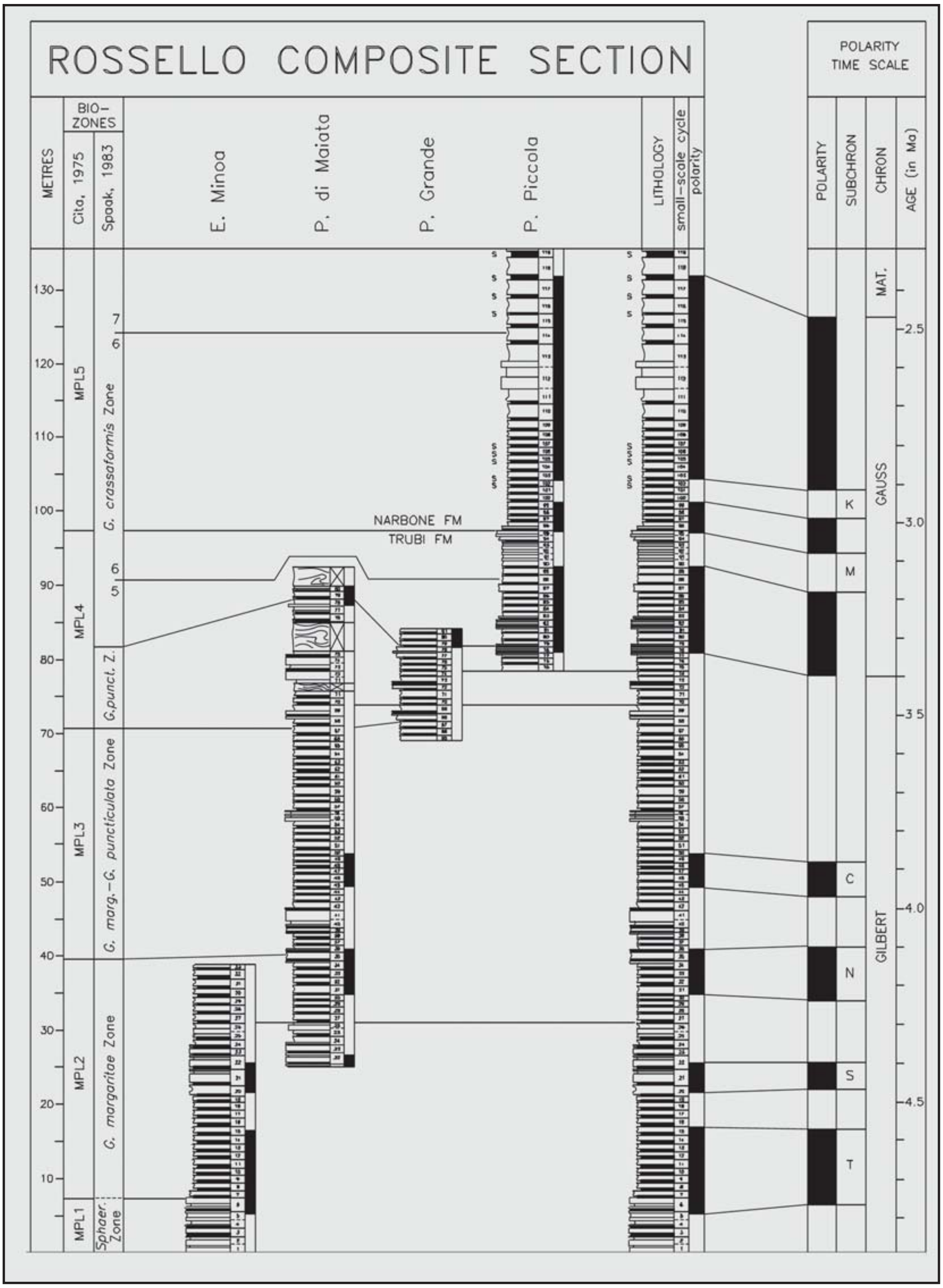


Figure 4 - Integrated stratigraphy of the Rossello Composite Section and calibration to the Geomagnetic Polarity Time Scale (after Langereis and Hilgen, 1991).

B. Punta di Maiata – panoramic view

contains the entire Trubi marl Formation and the lower part of the overlying Narbone clays (Fig. 4).

Stop 1.2:

Lido Rossello

This beautiful natural cliff section was initially selected as a reference section for the Trubi marls and, hence, as neostratotype of the Zanclean Stage by Cita and Gartner (1973). In addition the section was proposed as stratotype for the Miocene-Pliocene boundary (Cita, 1975). The transition from the Messinian evaporites and Arenazzolo sandstone to the deep marine Trubi marls is exposed in several small outcrops along the beach. The presence of an hiatus, the poor paleomagnetic signal and the less distinct sedimentary cyclicity eventually made the section be replaced by other sections (Eraclea Minoa, stop **1.1**; Punta di Maiata, stop **1.3**, and; Punta Piccola, stop **1.4**) as the standard reference for the Trubi (Langereis and Hilgen, 1991).

A very peculiar feature of Lido Rossello are the 6 diatomaceous beds, which are locally intercalated in the Trubi marls in an interval marked by a distinct reddish color. The same beds are already absent in the same stratigraphic interval at Punta di Maiata, approximately 1 km to the east. The detailed study of geochemical parameters may shed important new lights on possible diagenetic effects on proxies that are often used for paleo-climate and -oceanographic reconstructions.

Stop 1.3:

Punta di Maiata

The Punta di Maiata section forms yet another impressive natural cliff exposure of the Trubi marls (Fig. B). The other name for this section is Scala dei Turci, which translates to Turkish staircase. Most likely, this refers to Turkish raiding parties who used the natural steps built by weathering of the sedimentary cycles to swiftly climb the cliffs and raid the villages on top.

The Punta di Maiata forms the middle segment of the Rossello Composite Section (Fig. 4). The basic precession-related sedimentary cycles of the Trubi are beautifully exposed here showing a distinct grey-white-beige-white colour alternation (Fig. C). The influence of obliquity can easily be recognised by marked alternations in the distinctness of especially the beige layers in successive basic cycles. Finally, larger-scale eccentricity related cycles are clearly visible in the weathering-profile of the cape. The most prominent expression of these cycles is the so-called motorcyclist bed. Several slumps are intercalated in the top part of the section, indicating increased slope instability probably related to thrusting in the subsurface.

Stop 1.4:

Punta Piccola

The Punta Piccola section represents the upper segment of the Rossello composite (Fig. 4). The section contains the boundary between the Trubi and Narbone formations and the GSSP (Global Stratotype Section and Point) of the Piacenzian (base Piacenzian = Zanclean/Piacenzian stage boundary). The GSSP is defined within sedimentary cycle no. 77 of the Trubi, close to the Gilbert/Gauss reversal boundary (Castradori et al., 1998). The Gelasian GSSP is defined at the top of the uppermost sapropel at Punta Piccola but in another section (Monte San Nicola, stop 2.2). In the Punta Piccola section the quadripartite carbonate cycles of the Trubi with their grey-white-beige-white colours change gradually into the sapropel-marl cycles typical of the Narbone Fm (Fig. D). Evidently the sapropels correspond to the grey carbonate-poor

C. Punta di Maiata - detail

layers of the carbonate cycles as can be observed in the field. The basic sedimentary cycles show an upward increase in thickness reflecting an increase in sedimentation rate. This stepwise increase is at least partly controlled by the onset of major Northern Hemisphere glaciations and the associated glacio-eustatic sealevel lowerings (Zachariasse et al., 1990; Hilgen, 1991).

D. Punta Piccola

Astronomical tuning and time scales

The Rossello Composite Section (RCS) was astronomically tuned by correlating the sedimentary cycle patterns to astronomical target curves. But before a tuning can be established the phase relations between the sedimentary cycles and the orbital parameters have to be exactly known. The phase relations were established by comparing the independent chronology developed for upper Pleistocene sapropels with the astronomical curves for past variations in precession, obliquity and eccentricity (Fig. 5). This comparison revealed that individual sapropels correspond to precession minima and hence to boreal summer insolation maxima and that sapropel clusters correspond to eccentricity

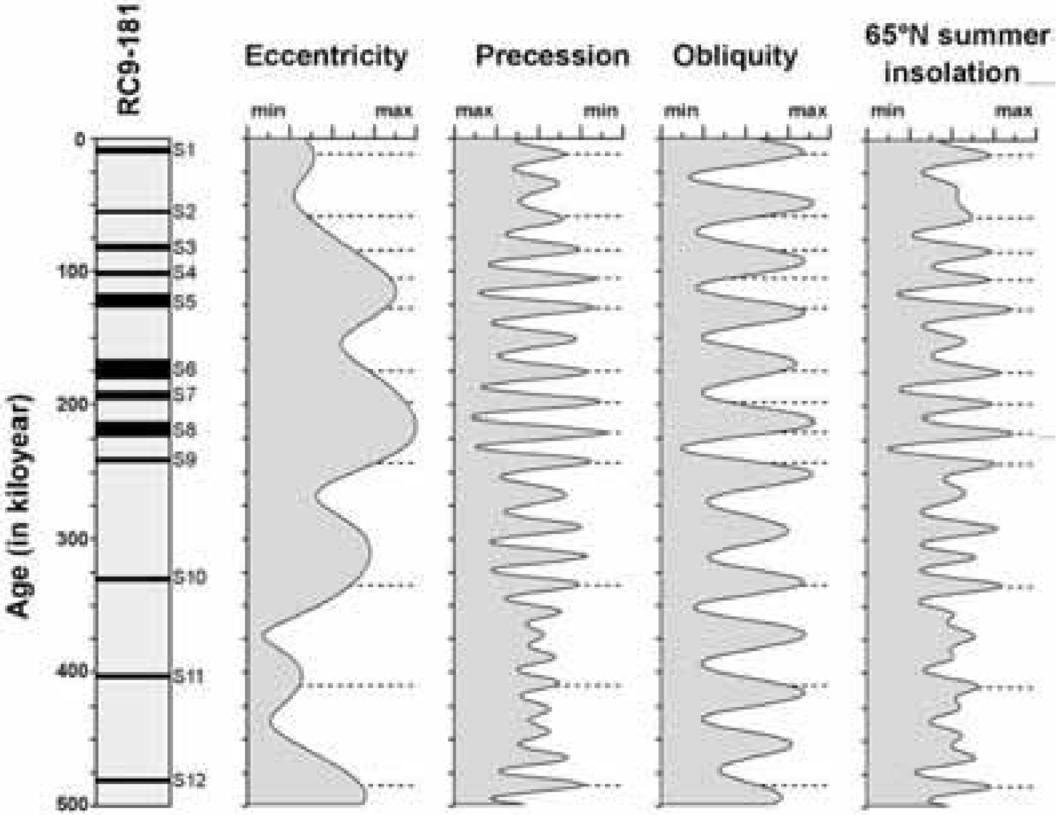


Figure 5 - Comparison of the sapropel chronology of the last 500,000 years with variations in the Earth's orbital parameters and insolation used to establish the phase relations between sapropel cycles and astronomical cycles.

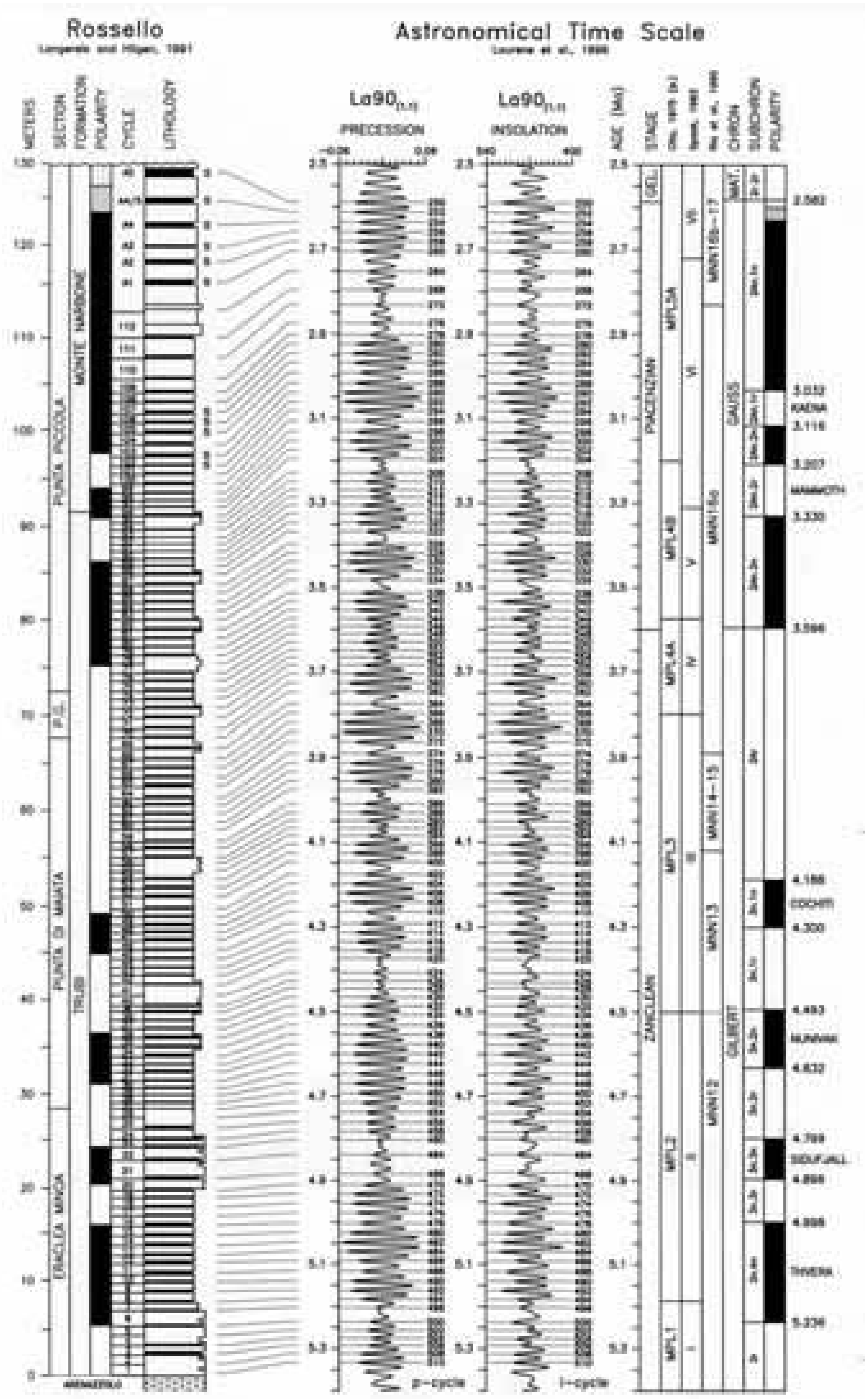


Figure 6 - Astronomical tuning of the Rossello Composite Section to the precession and insolation time series of the La93$_{(1,1)}$ solution (after Lourens et al., 1996).

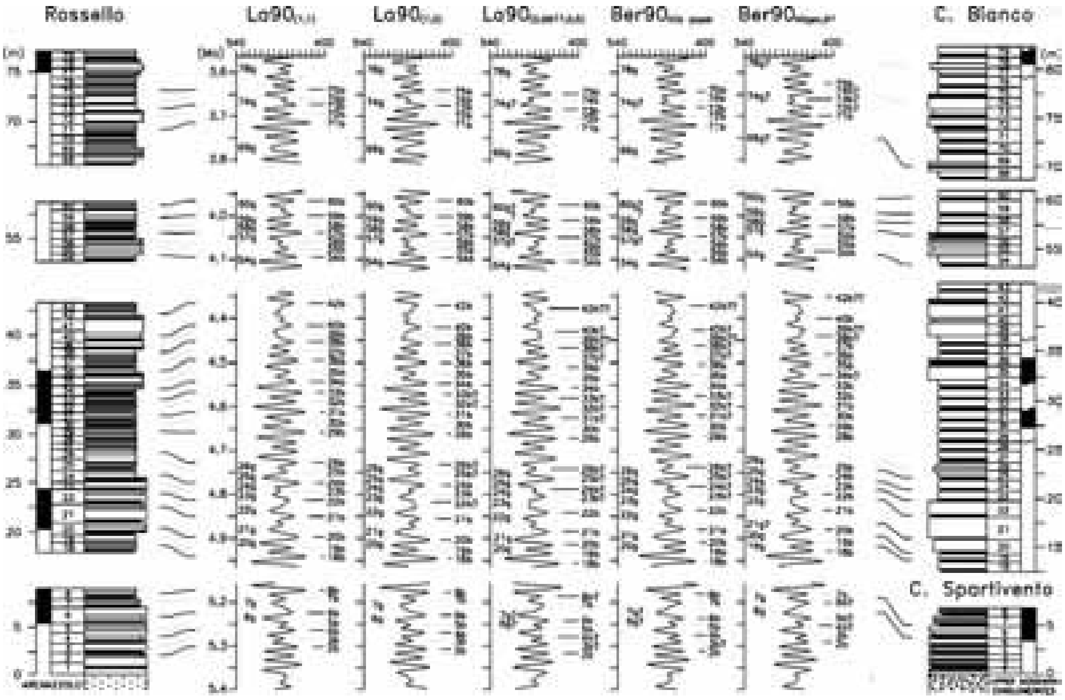
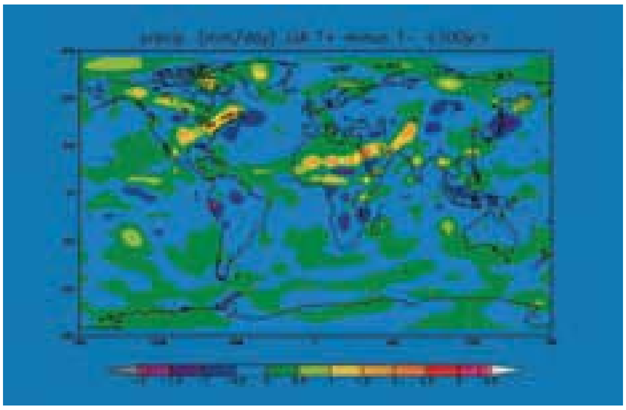


Figure 7 - Comparison of cyclostratigraphic details, in particular as related to precession-obliquity interference, and the insolation target curve according to different astronomical solutions (after Lourens et al., 1996).

maxima of both the 100 and 400 kyr cycle. The influence of obliquity is reflected in changes in the thickness of successive sapropels with thicker sapropels corresponding to obliquity maxima.

The tuning started with the calibration of the RCS magnetostratigraphy to the geomagnetic polarity time scale. This initial step was followed by tuning the larger-scale sedimentary cycles to the eccentricity; tuning of the successive small-scale cycles to precession and insolation then ensued (Fig. 6). This tuning provides very accurate astronomical ages for all the basic sedimentary cycles in the RCS, as well as for the paleomagnetic reversal boundaries and calcareous plankton bioevents. Moreover, it underlies the absolute age calibration of the early Pliocene part of the standard geological time scale (Berggren et al., 1995). This is a very important aspect because all Pliocene stage boundaries are defined in the RSC and, as a consequence, are directly tied to the standard time scale by means of a first-order calibration. Both the RCS as well as the Miocene sections to be visited during the second day of the excursion, are used to age calibrate the Astronomically Tuned Neogene Time Scale (ATNTS) 2004 to be presented during the 32nd International Geological Congress to be held in Florence (Lourens et al., 2004). Finally, sedimentary cycle patterns, in particular those that result from precession/obliquity interference, have been used to



F. Obliquity control on monsoonal precipitation

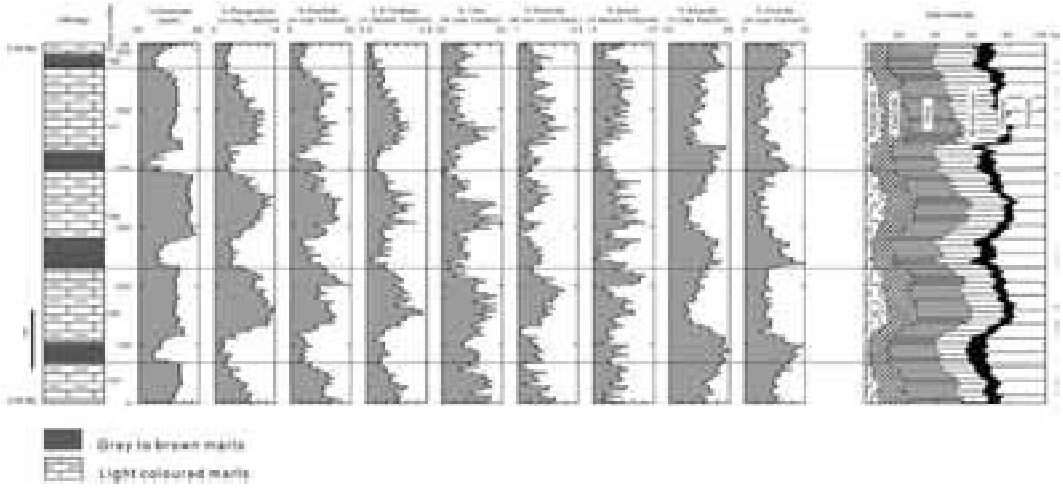


Figure 8 - Variations in clay mineral content in a number of selected precession-related basic cycles in the Punta Piccola section (after Foucault and Melières, 2000).

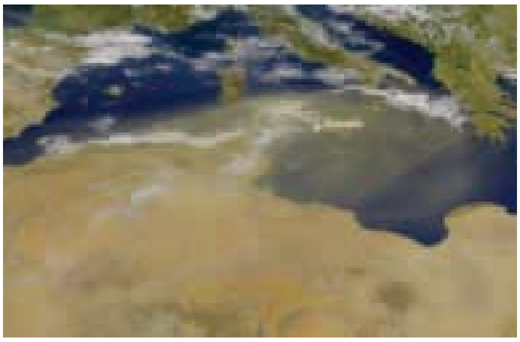
test which astronomical solution is the best from a geological point of view (Fig. 7; Lourens et al., 1996). The newly-developed astronomical time scale is of fundamental importance for paleoclimatic studies directed at the understanding of the orbital influences on climate.

Paleoclimatic significance of the sedimentary cycles

The sedimentary cycles in the Rossello Composite Section and in the Punta Piccola section in particular have been subject to detailed multidisciplinary studies to unravel their paleoclimatic significance. The basic sedimentary cycles of the Trubi marls are precession controlled and quadripartite showing a grey-white-beige-white colour alternation and two carbonate minima per cycle (grey and beige). Grey marls and the corresponding sapropels are characterized by minima in planktonic _^{18}O and the Ti/Al ratio of the terrigenous fraction (Van Os et al., 1994), by abundance maxima in the clay minerals smectite and chlorite (Fig. 8; Foucault and Melières, 2000) and by peak abundances in the oligotrophic planktonic foraminiferal group *Globigerinoides* spp. (Sprovieri, 1993), while the lighter coloured white and beige marls are marked by abundance maxima in kaolinite and palygorskite (Fig. 8).

Maxima in Ti/Al and palygorskite/kaolinite in the lighter coloured marls are crucial for the paleoclimatic interpretation of the cycles because of their origin as eolian dust from North African sources (Figs. 9, E). The rate of dust flux and accumulation around the African continent is positively correlated with the degree of aridity of source areas. Hence these proxy signals are interpreted as reflecting the dry arid phase of the climate cycle associated with precession maxima.

During the subsequent wet phase, the renewed vegetation cover greatly reduces wind erosion and the transport of eolian palygorskite, kaolinite and related minerals out of Africa. This humid phase is also reflected by the shift to lighter values in planktonic _^{18}O, which reflects reduced surface water salinities due to enhanced river outflow. The outflow is also responsible for an enhanced terrigenous contribution from northern, European sources characterized by chlorite and smectite, due to stronger fluvial erosion. Also, the Nile will have contributed to smectite enrichment because of the intensified monsoonal activity during precession minima (as a consequence of the enhanced Northern Hemisphere summer insolation, see Tuenter et al., 2003). Climate



E. African dust storm over Sicily

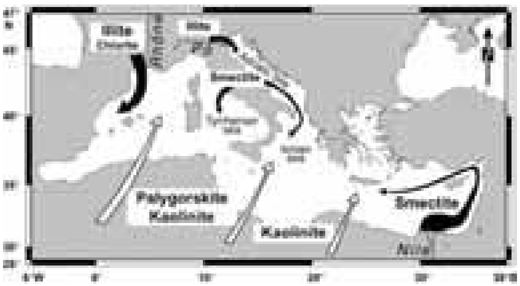


Figure 9 - Source areas for different clay minerals in the basic sedimentary cycles at Punta Piccola (after Foucault and Melières, 2000).

modelling experiments in additional reveal an obliquity control on African monsoonal intensity (Fig. F), providing a possible explanation for the influence of obliquity on the sedimentary cycle patterns in the Mediterranean. The link between the grey layers / sapropels and precession minima is collaborated by the peak abundances in *Globigerinoïdes* spp., which indicate stronger summer conditions as a consequence of enhanced insolation during this part of the year. In addition, the rate of deepwater formation diminished at times of precession minima due to increased precipitation and, hence, increased density stratification of the watercolumn resulting in suboxic or even anoxic bottom water conditions and the deposition of sapropels. Detailed studies have convincingly shown that the dominantly precession-controlled oscillatory climate system has been operative over at least the last 14 million years.

Also the evaporite cycles in the Gessoso-Solfifera Fm reflect orbitally-induced climate change. The total number of cycles in the Lower and Upper Evaporite Units indicate that they are primarily related to precessional-controlled variations in regional Mediterranean climate (and hence net evaporation) rather than to glacio-eustatic sealevel oscillations, which at that time were obliquity controlled. Gypsum beds in the cycles of the Lower Evaporites were deposited at times of raised salinities, but detailed studies indicate that relatively normal marine conditions prevailed in between. In contrast to the Upper Evaporites, strontium isotope values of primary gypsum in the Lower Evaporites plot on the open ocean strontium curve pointing to a relatively open marine connection with the adjacent Atlantic during this early stage of the salinity crisis.

Paleomagnetic signal: magnetostratigraphy and rotational and reversal histories

Paleomagnetic analysis of the samples from the Rossello Composite clearly revealed a primary magnetic signal carried by magnetite. This signal produced an excellent magnetostratigraphy that could be calibrated straightforwardly to the geomagnetic polarity time scale. The declination of the primary component further revealed that the Trubi marls underwent a 30-35˚ clockwise rotation. The deviation is slightly less in the upper part of the Rossello Composite indicating that a 5-10˚ rotation occurred at around the boundary between the Trubi and Narbone formations (Scheepers and Langereis, 1993). Following initial magnetostratigraphic studies reversals were sampled in great detail to unravel their mechanism of recording and to detect their underlying cause. The complex behaviour of these transitional records with sometimes rapid multiple excursions around the reversal proved to be diagenetically controlled rather than to reflect processes related to the actual behaviour of the Earth's magnetic field during a reversal (van Hoof et al., 1993; see also below).

Notwithstanding the very good to excellent magnetostratigraphy, a complex multistage history is needed to explain the extended paleomagnetic data, including an early syndiagenetic and a late epidiagenetic stage. The first stage followed the formation of primary magnetite and resulted in the magnetic excursions around reversal boundaries mentioned above; this behaviour is explained by the migration of ferrous iron soon after burial, while subsequent oxidation produces the "secondary magnetite" that records the post-transitional polarity (van Hoof et al., 1993). The second late stage is probably related to fluid flow during uplift and thus to epidiagenesis (Dinarès-Turell and Dekkers, 1999). This stage involves an anoxic event, which is necessary to cause dissolution of the magnetite and precipitation of iron sulphides (pyrrhotite). This event may be linked to a phase of fluid flow associated with thrust emplacement during late Pliocene or Pleistocene times.

Extra stop.

In Agrigento it will be possible to visit the archeological area of the famous "Valle dei Templi". Located on a plateau overlooking Sicily's southern coast, Agrigento was founded around 582 BC by a group of colonists who were the immediate descendants of Greeks from Rhodes and Crete.

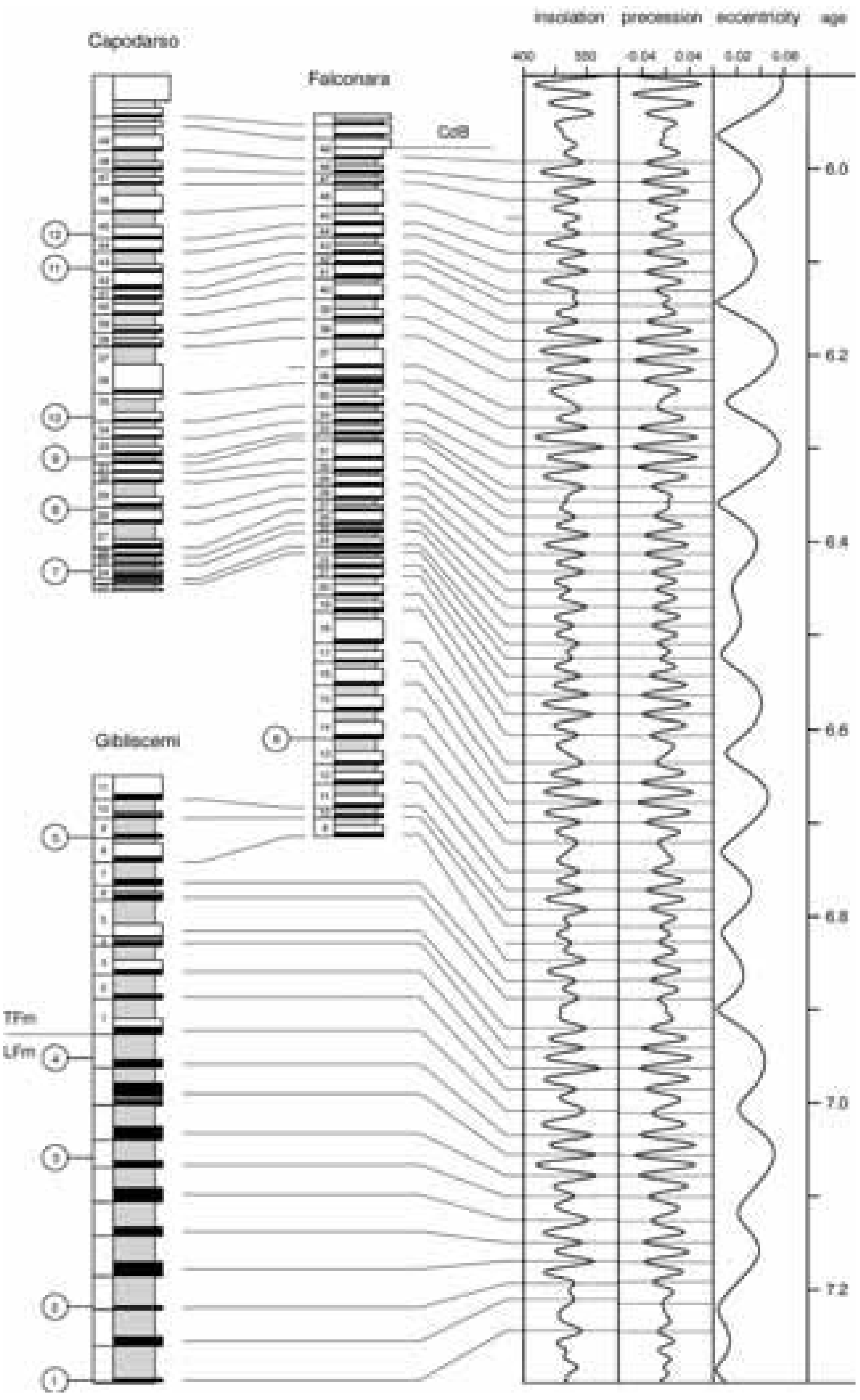


Figure 10 - Astronomical tuning for small-scale diatomite-bearing cycles of the Tripoli Fm in sections on Sicily (after Hilgen and Krijgsman, 1999).

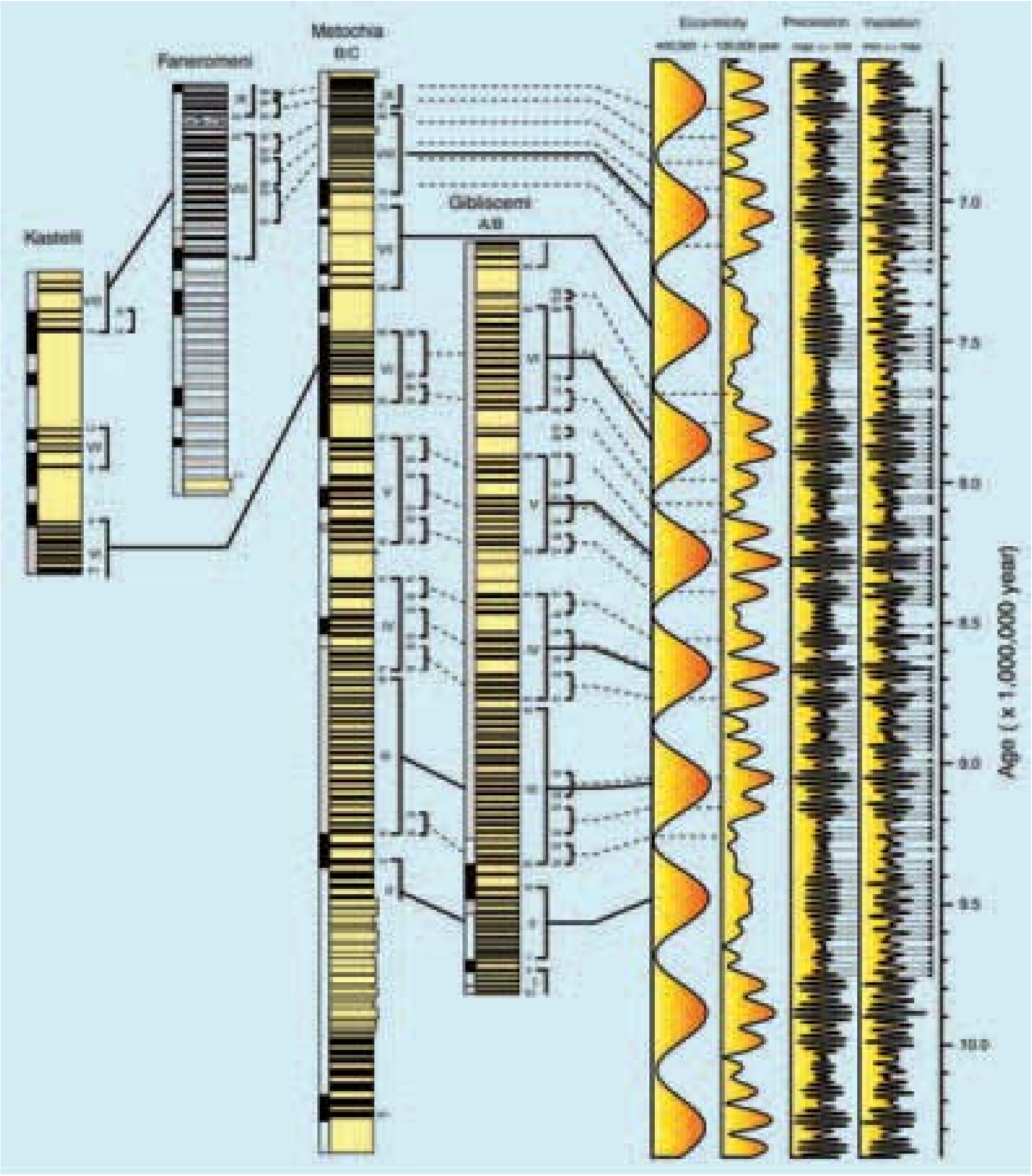


Figure 11 - Astronomical tuning of the younger part of the Gibliscemi section.

DAY 2

Falconara-San Nicola-Gibliscemi

In the morning we will visit the Falconara section with its beautiful exposures of the pre-evaporitic diatomites of the Tripoli Formation and the San Nicola section with its impressive outcrops of the Trubi marls and sapropel bearing clays of the overlying Narbone Formation. In the afternoon we will visit the Gibliscemi section which was used to extend the astronomical time scale back in time into the Miocene. This section very convincingly portrays the sedimentary expression of all the Earth's orbital parameters in the field.

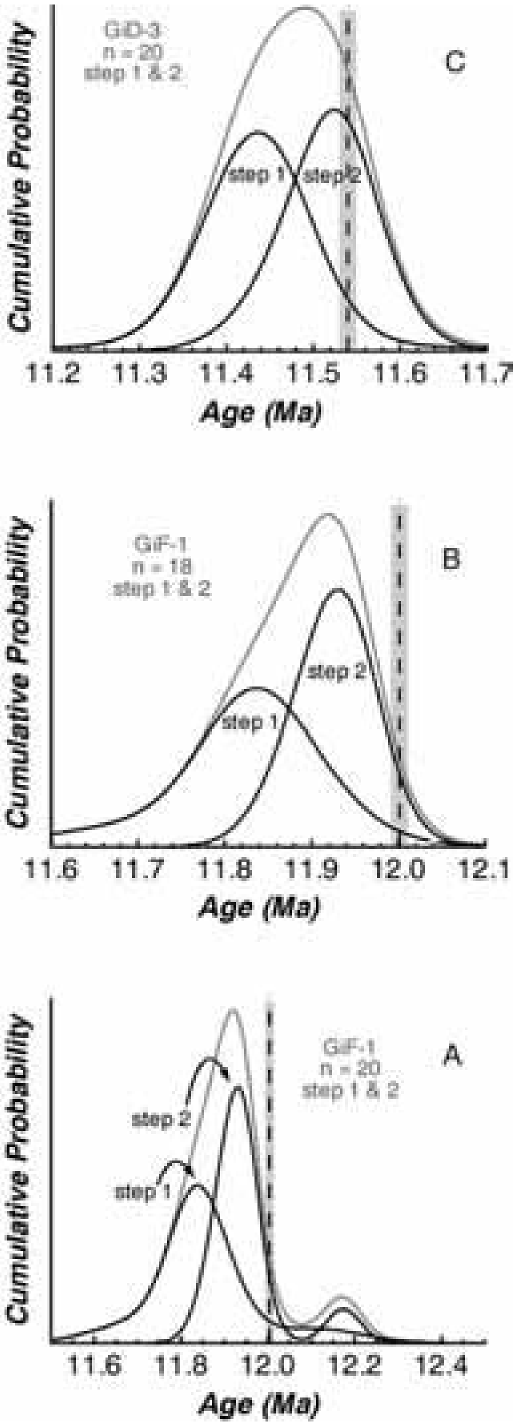


Figure 12 - Age probability distributions of Ar/Ar ages for ash layers in the Gibliscemi section and comparison with astronomical ages for the same layers (Kuiper, 2003).

H. Monte Gibliscemi

Stop 2.1:

Falconara

On Sicily, cyclically bedded diatomites of the Tripoli Formation of middle Messinian age stratigraphically underlie limestones and evaporites of the Gessoso-Solfifera Formation. An integrated stratigraphic framework was developed for the Tripoli by investigating three key-sections, namely Falconara, Gibliscemi and Capodarso (Hilgen and Krijgsman, 1999). The sections were selected because they occupied a relatively distal basinal position where tectonic deformation is moderate as compared with other Tripoli sections. The Falconara section is located 3.5 km NW of Falconara castle, between Licata and Gela, and was proposed as the Tortonian/Messinian boundary stratotype by Colalongo and others (1979). Capodarso represents the neostratotype section for the Messinian stage as designated by Selli in 1960. This section, which is located on central Sicily along the NW flank of Monte Capodarso, 45 km north of Falconara, will not be visited during this excursion. The Gibliscemi section is located 25 km east of Falconara and will be visited during stop 2.3.

The Tripoli diatomites are extremely well exposed in

G. Monte San Nicola

the Falconara section (Hilgen and Krijgsman, 1999). The basic sedimentary cycle of the Tripoli unit is tripartite and consists of a homogeneous greenish coloured marl followed by a reddish-brown laminite (sapropel) and capped by a white laminite (diatomite). Field observations reveal how the tripartite cycles of the Tripoli unit evolve from the bipartite sapropel cycles of the Licata Fm., which consist of homogeneous marl-sapropel alternations. Sapropels in the upper part of the Licata Fm. attain already a whitish diatomaceous top. This diatomaceous top is then replaced by diatomites in the Tripoli unit.

Results of the integrated stratigraphic study allowed the sections to be cyclostratigraphically correlated in detail and the diatomite-bearing cycles to be calibrated to astronomical target curves (Fig. 10; Hilgen and Krijgsman, 1999). The high-resolution correlations show that the beginning of diatomite formation is diachronous in the Mediterranean, while the onset of the actual salinity crisis occurred remarkably synchronously (Krijgsman et al., 1999) even though it was preceeded by a long and stepwise history of increasing basin restriction. The timing reveals that the onset is not related to a glacio-eustatic sealevel lowering but reflects the tectonically controlled geodynamic evolution of the Atlantic-Mediterranean gateways with a superimposed effect of the 400-kyr eccentricity cycle on top (Krijgsman et al., 1999).

Origin of diatomites

The origin of the cyclic bedding of the diatomites long remained controversial despite intensive study (e.g., Blanc-Valleron et al., 2002). Partly opposing scenarios to explain the cyclic diatomite formation include intensification of Atlantic inflow (due to glacio-eustatic sea-level lowering), periodic upwelling, surface water warming, enhanced continental run-off, global sealevel rise in combination with enhanced upwelling and pulsating tectonics. However, the astronomical link outlined above has farther-reaching implications for models trying to explain Tripoli diatomite formation. For instance, glacio-eustatic sealevel variations are not primarily involved because glacial cyclicity was dominantly obliquity-controlled during the Messinian, whereas Tripoli diatomite cycles are dominantly precession controlled. The dominance of precession in controlling the cyclicity points instead to a regional climate mechanism similar to that proposed for sapropels. The observation that thin/thick alternations in diatomite beds follow precession-obliquity interference patterns in insolation maxima suggests that deposition of Tripoli diatomites is indeed causally related to sapropel formation. A possible scenario includes nutrient storage at times of sapropel formation followed by nutrient release when the density stratification of the water column becomes seasonally interrupted (Sierro et al., 1999). Such a mechanism is consistent with the relationship between sapropels and diatomites observed in the field.

Stop 2.2:

Monte San Nicola

The San Nicola section is located 5 km northwest of Gela. The section starts with rhythmically bedded marls of the Trubi Fm. overlying the multicoloured clays of the Argille Scagliose, but note that the basal part of the formation is missing. The Trubi marls are followed by the sapropel-bearing clays of the Narbone Fm, which in turn are overlain by shallow marine sandstones of Pleistocene age (Fig. G).

The San Nicola section contains the Gelasian GSSP (Rio et al., 1998). The Gelasian was introduced in 1994 as a standard stage for the Upper Pliocene to fill in the gap between the Middle Pliocene of the Piacenzian and the Pleistocene (Rio et al., 1998). The Piacenzian/Gelasian boundary is formally designated at the top of sapropel A6 in marine isotope stage (MIS) 103 and in close correspondence with the Gauss/Matuyama reversal boundary astronomically dated at 2.588 Ma. The sapropel pattern higher up in the succession can easily be correlated to the Monte Singa and Vrica sections in Calabria. The two thick and distinct sapropels in the top part of the section (photo) correlate with sapropels c and e at Vrica, with the Plio-Pleistocene boundary being formally defined at the top of the latter sapropel.

The San Nicola section is also extraordinary because it brings to light sedimentary cycles that are not related to precession-induced oscillations in regional climate but instead reflect glacial cycles that at that time were obliquity controlled. In particular, the prominent glacial MIS 100, 98 and 96 can easily be distinguished as dark beds in the succession (Fig. G). Under good light conditions it is possible to see high-frequency lithologic changes in the glacial stages that are within the sub-Milankovitch frequency band of the spectrum. Detailed multiproxy studies clearly revealed the validity of these changes, which are of a cyclic nature and have periods in the order of 5-8 kyr. They can be correlated throughout the Mediterranean and into the adjacent Atlantic Ocean and are most likely similar (in origin) to the well-known Heinrich events of the late Pleistocene. A major question is whether these variations are related as harmonics or combination tones to the primary orbital (Milankovitch) cycles.

Stop 2.3:

Gibliscemi

The Gibliscemi section is named after Monte Gibliscemi and is located 10 km southwest of the well-studied section of Giammoia and 25 km east of Falconara. The section is well known for its extra-ordinary succession of deep marine sapropel-bearing marls of the Licata Formation ("Argille di Licata"), which have been employed to extend the astronomical time scale into the Middle Miocene. The cyclically bedded succession of the Licata Fm overlies intensely deformed multi-coloured clays of the "Argille Scagliose" and is followed by diatomites of the Tripoli Formation, and capped by Calcare di Base limestones of the Gessoso-Solfifera Formation. The pre-evaporite part of the sedimentary succession is well exposed in the two main gully complexes along the southern slopes of Monte Gibliscemi.

The succession was incorporated in the African-verging thrust wedge during the Plio-Pleistocene, the "Argille Scagliose" acting as a lubricant for décollement and the African foreland being represented by the nearby Ragusa platform of southeastern Sicily. Despite the close proximity to the foreland, deformation in the Gibliscemi sections is extensional only and, especially in the lower parts, consists of low angle shearplanes, which tectonically reduce the stratigraphy.

The younger part of the Gibliscemi section

Sapropels in the younger part of the Gibliscemi section are not distributed evenly throughout the succession, but instead reveal distinct patterns with both small-scale and large-scale sapropel clusters, in addition to individual sapropels. These patterns reflect the influence of all three orbital parameters and are similar to the patterns found in the Late Pleistocene used to establish the phase relations between the sedimentary and astronomical cycles.

Miocene sections in the Mediterranean were astronomically tuned following the calibration of the magnetostratigraphy to the GPTS for initial age control (Krijgsman et al., 1995). This tuning was established using the Late Pleistocene phase relations shown in Figure 5 and started from the longest period (400-kyr) of the eccentricity cycle, which corresponds to the large-scale sapropel clusters. The final calibration was achieved by tuning individual sapropels to precession and insolation (Fig. 11). The tuning resulted in an excellent fit between characteristic details in the astronomical and sedimentary cycle patterns back to 9.5 Ma, which resulted from precession-obliquity interference (Hilgen et al., 1995).

The older part of the Gibliscemi section

The tuning was subsequently extended to the intensely deformed older part of the Gibliscemi section (Hilgen et al., 2000). Most of the sedimentary cycles in this part of the section consist of a whitish-coloured homogeneous marl and a dark, grey-coloured marl (or marly clay). The darker coloured marls are replaced by sapropels in the top and bottom part of the section so that the cycles become identical to those in the upper part of the section. Reddish colour bands are occasionally present either as distinct thin bands above the darker grey marls or as more diffuse and thicker bands below them and reflect paleoredox fronts along which iron-oxides precipitated during early diagenesis. Four distinct fine-grained ash layers are found in the lower part of the section.

Because of the intense deformation, no continuous succession could be logged and sampled along a single trajectory and the construction of a reliable composite was not an easy task. The older cycles in this part of the Gibliscemi section were calibrated to the astronomical record based on the tuning of the youngest sapropels and using a very similar pattern matching procedure.

Intercalibration of astronomical and ^{40}Ar/^{39}Ar time

Sanidine from the ash layers intercalated in the lowermost part of the section has been dated using the ^{40}Ar/^{39}Ar single fusion laser technique. The study formed part of an elaborate and rigorous attempt to intercalibrate the ^{40}Ar/^{39}Ar and astronomical dating methods and to introduce an astronomically dated standard in ^{40}Ar/^{39}Ar dating (Kuiper, 2003). Such an introduction would strongly reduce the error in ^{40}Ar/^{39}Ar dating by eliminating errors that result from uncertainties in decay constants and in the age of the secondary dating standard while the uncertainty in the age of the primary standard is reduced as well. The astronomical ages for the Gibliscemi ash layers are slightly older than single fusion ^{40}Ar/^{39}Ar ages for the same ash layers if an age of 28.02 Ma is used for the secondary FCT sanidine standard (Fig. 12). But in this case xenocrystic contamination by older sanidine grains cannot be excluded.

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