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Bruno D'Argenio[1], Vittoria Ferreri[2] (1) and Instituto per l'Ambiente Marino Costiero, "Geomare Sud", National Research Council, Naples, Italy (2) Dipartimento di Scienze della Terra, Universita "Federico II", Naples, Italy

Sequence Cyclostratigraphy, a Methodology for Long-distance Correlation and Orbital Chronostratigraphy

Abstract

Cretaceous shallow-water carbonates of the Periadriatic Area show a hierarchical cyclic organization formed of elementary cycles, bundles and superbundles, superimposed in turn on lower-frequency Trangressive/Regressive Facies Trends. Composite palaeoceanographic-eustatic fluctuations, modulated by Earth's orbital forcing are at the origin of this hierarchy where elementary cycles are related to the precession and/or obliquity periodicities and bundles and superbundles to the short- and long-eccentricity, respectively. Also the Trangressive/Regressive Facies Trends may be related to eustatic changes, showing periodicities recording the Earth's eccentricity extended signal. Even if these deposits do not show evident progradational-retrogradational geometries, a sequence cyclostratigraphy approach can be used, whenever their litho-bio composition and stratal thickness may be considered as proxies of the sea-level changes. On this basis high-resolution, regional- to global-scale correlations may be attempted and orbital chronostratigraphy (quantifying the minimum time required for each succession to stack up) derived.

Introduction

The idea of high-frequency cyclicity dominated by conditions external to the depositional environments (***allocyclicity***) is nowadays widely accepted (***e.g.*** De Boer and Smith, 1994). It has been also shown in the last few years that high-resolution analysis (0,1-1,0 cm-scale data pick-up) of several Phanerozoic sequences, of shallow- and deep-water origin, has yielded a rich information about even minute modification in their depositional environment that, in turn, reveals systematic (cyclic) changes in the correspondent climatic-palaeoceanographic system, at a scale well beyond the resolution of the biostratigraphy (Strasser et al., 2001; D'Argenio et al., 2003).

In this paper we concisely report about our high-resolution studies on the shallow-water carbonates of the Mediterranean Cretaceous (sedimentology, but also stable isotopes and palaeomagnetism) that have resulted in a methodology aimed at understanding (a) the role of climatic and correspondent eustatic oscillations in the development of the above carbonates, as well as in their (b) hierarchical organization in elementary and composite facies-cycles, and (c) their genetic relationships with the Croll-Milankovic orbital periodicities, once the authocyclic (local) component of the sedimentary signal has been removed (Brescia et al., 1996). Moreover, being largely organogenic in nature, the carbonate deposits of the shallow (sub)tropical seas were produced at different rates and with changing mud/grains ratios, giving rise to variable sediment thickness per unit of time. At present, the above Cretaceous carbonates outstandingly outcrop in the Periadriatic Region as thick stratal successions that disclose a multiscale sequence-cyclostratigraphy configuration, well evident in the composite mode of their aggradational patterns, laterally consistent also at >100 km distance (D'Argenio et al., 1999; 2003; Amodio et al., this volume).

Cyclostratigraphy

Mesozoic-Paleogene carbonate platform sequences, widespread in the Mediterranean Region, developed for more than 200 my on both sides of the oceanic Tethys, forming large (up to 10^4 km^2) and thick (even >3-4 x 10^3m) sedimentary bodies, which are well stratified and characterized by high rate of sedimentation (from <30 up to >100 m/my). The carbonate platforms contain minor or no terrigenous admixtures and were highly sensitive to short-term climatic and oceanographic variations, as well as to high-frequency sea-level oscillations (Fig.1).

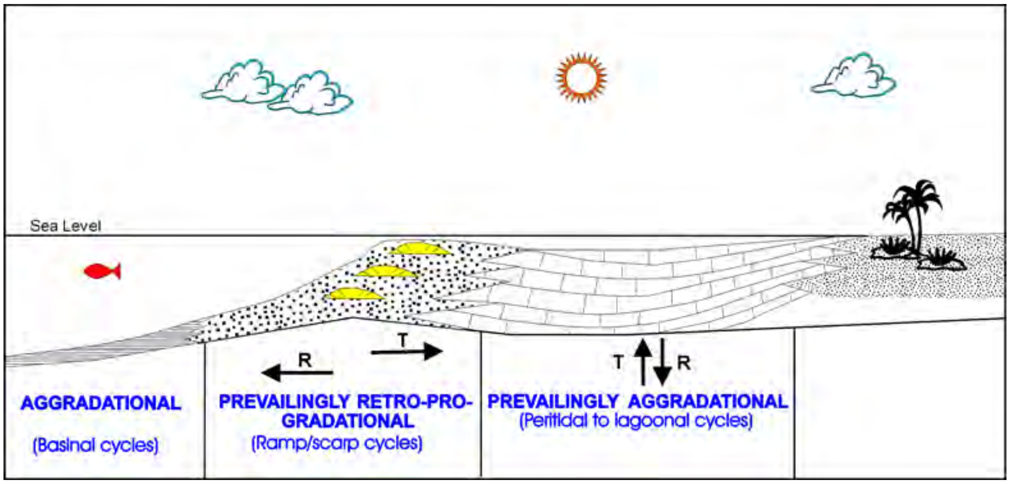

Fig.1. Cartoon showing carbonate platform interior deposits developing with a prevailing aggradational mode (right). Here lateral variations in bedding geometry, even if of km-extent, are very gradual and only the vertical strata organization carries evidence of eustatic oscillations (see also Fig.3) while typical retro-progradational geometries develop along the marginal sectors of the platform (centre) sloping into the aggradational basin settings (left).

In the last years we have measured and sedimentologically studied at centimeter scale a total of about 1500 m of Cretaceous carbonate platform strata from southern Italy and Montenegro (Dinarids). The study has been carried out on several wholly exposed sections or long bore cores, (D'Argenio et al., 1997; 1999; Buonocunto et al. 1999; 2002; Amodio et al., this volume). For each studied succession microstratigraphic analysis has shown a number of lithofacies organized in lithofacies associations suggesting, on the whole, inner settings of a large carbonate platform domain (from peritidal-supratidal to open platform and shallow ramp). The stacking pattern of depositional ad early diagenetic characteristics reveals a hierarchical organization composed of elementary cycles in turn grouped in bundles and superbundles. While the elementary cycles are related to the precession and/or the obliquity periodicities, bundles and superbundles record the short- and long-eccentricity Earth's orbital cycles, respectively. This interpretation has been confirmed by mathematical treatment of the sedimentary data (lithofacies and related early meteoric fabric thickness) carried out at cm-scale on numerous Cretaceous carbonate platform successions of southern Italy (Longo et al., 1994; Brescia et al., 1996; Tagliaferri et al., 2001), as well as by the analysis of the magnetostratigraphic parameters (remanent inclination and declination) measured in the Hauterivian-Barremian of southern Apennines (Iorio et al., 1996). The above high frequency cycles are superimposed on lower frequency Transgressive/Regressive Facies Trends (T/RFTs, Fig.2) whose time duration (1200-2000 ky) suggests a likely relationship with extended eccentricity periods (Fischer, 1991; D'Argenio et al., 2003).

Sequence Cyclostratigraphy and Long-Distance Correlation

Aggradational sequence-stratigraphy. The above well ordered aggradational sequence-cyclostratigraphic configuration enables the stratal (cycle) composition and thickness of the shallow-water carbonates to be considered as proxies of (a) the progradational (thinning)-retrogradational (thickening) mode and geometries of the stratal successions, as well as of (b) the relatable climatic conditions and eustatic ranges (D'Argenio et al., 1999; 2003).

On the basis of the notions and approaches here outlined, series of strata, unique in their organization and tied to the Croll-Milankovic orbital signals, may be constrained in terms of sequence-cyclostratigraphy, considering the superbundles as depositional sequences and their upper limits, normally marked by downwards penetrating early meteoric diagenesis, as Sequence Boundaries (SB); within each superbundle the most open marine lithofacies indicates the related maximum flooding surface (mfs). The choise of the superbundles (about 400-ky cycles) as depositional sequence equivalents was suggested by their high probability to be represented in the stratigraphic record, even if lacking some of their elementary cycles (and/or bundles), more likely to be missing because of lower

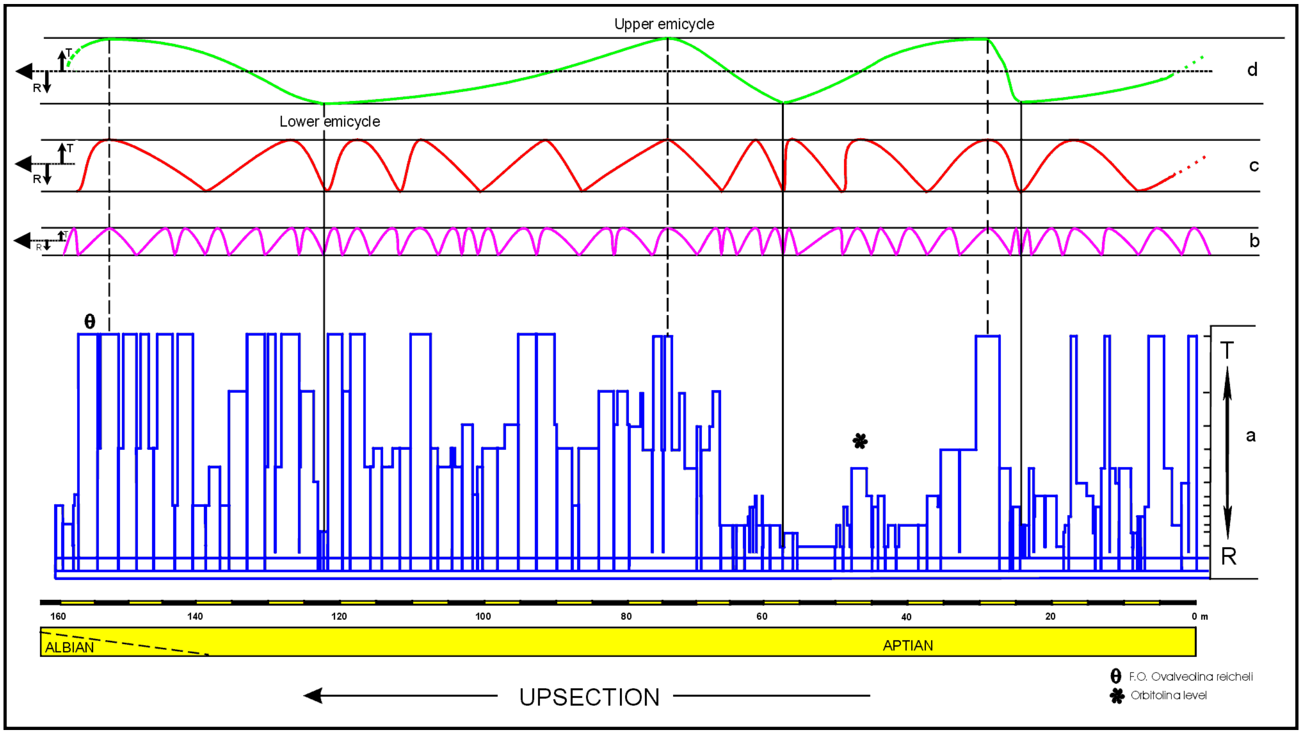

Fig.2. Example of hierarchical cycle organization and of environmental changes primarily produced by climatic and eustatic response to Earth's orbital cyclicity at Serra Sbregavitelli (Campania Apennines). (a) Elementary cycles (about 20-40 ky cycles); to the right T indicates transgressive trends and R its regressive trends; em: the horizontal line separates the marine interval (above) from the emersion-related cap topping the cycles (below); (b) bundles (about 100-ky cycles); (c) superbundles (about 400-ky cycles); (d) T/RFTs, Transgressive/Regressive Facies Trends (about 1.2-2 my each). Here two climatic and eustatic conditions are suggested by the organisation of the elementary cycles: a first condition of wider eustatic range (Upper Hemicycle), where the subtidal domains prevail , a second of smaller eustatic range (Lower Hemicycle), where peritidal domains dominate.

accommodation. Accordingly, based on the stacking pattern of the superbundles, also the Transgressive/Regressive Facies Trends (third order cycles, *sensu* Vail et al., 1991) may be interpreted in terms of depositional sequences.

Regional correlation. On this basis and using appropriate biostratigraphic markers, high resolution physical correlations (precision $\leq$100 ky) at regional scale may be delineated among Lower Cretaceous coeval sections (D'Argenio et al., 1999; 2003; Amodio et al., this volume). These correlations (present-day distance from each other up to >500 km) allow to restore the lateral thickness variations of discrete (even <10 m) stratal intervals that change according to the environment (Fig.3).

Global-scale correlation. Global correlations have also been proposed between our Transgressive/Regressive Facies Trends (D'Argenio et al., 2003; Ferreri et al., 2003; Amodio et al., this volume) and the third order sequences of Hardenbol et al. (1998), concurrently anchoring the studied sequences (on biostratigraphic, isotopic and/or paleomagnetic bases) to the standard time scales. This allows an eccentricity precision ($\leq$ 400 ky) to be also attained in long-distance correlation ($\geq$ 500 km present-day separation) among successions laid down under the same or different sedimentary regimes, like carbonate platforms and pelagic basins (e.g. D'Argenio et al., 2003).

Here the tie-points used as stratigraphic markers in global correlations are (1) the Valanginian/Hauterivian boundary individuated in the Sferracavallo (Palermo Mountains, north-western Sicily) and in the San Lorenzello (Matese Mountains, Campania Apennines) successions, (2) the Barremian/Aptian boundaries individuated in the Monte Raggeto succession (Monte Maggiore Mountains, Campania Apennines) and in an industrial bore core from central Apennines,

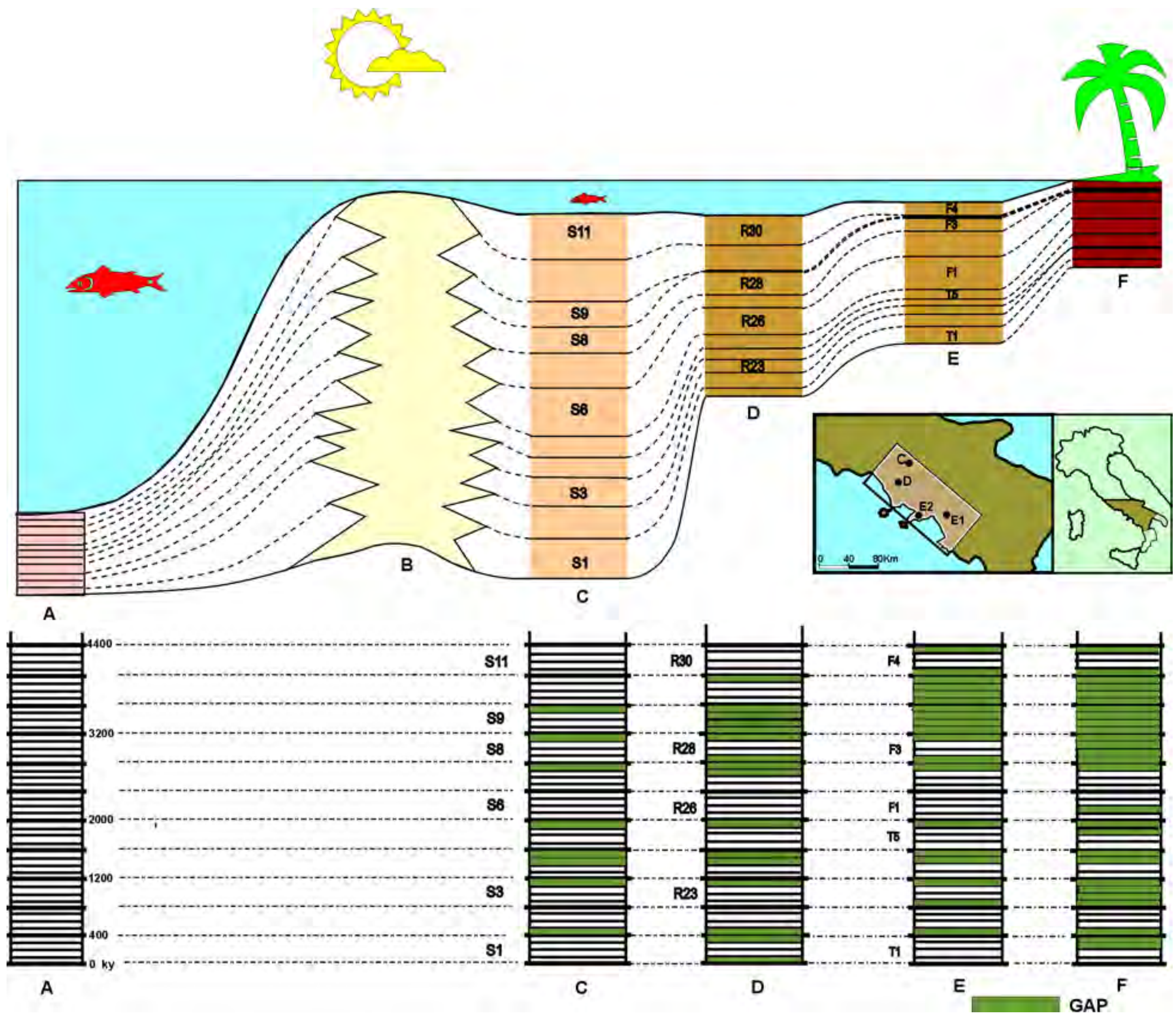

Fig 3. Cycle stacking patterns and regional organization of some Cretaceous sections studied at cm-scale or added to restore an ideal section across the southern Apennines. Sections C, D, E1 and E2 are real (and their superbundles are represented and numbered according to D'Argenio et al., 2003), while sections A, B and F are ideally placed on their sides. In the upper row the sections are reported at the same horizontal scale. Note their different thickness according to the position in an ideal carbonate platform, where the thicker and more continuous sedimentation develops in the open lagoonal areas (column C) decreasing in thickness and increasing in omissions towards the more restricted lagoon sectors (columns D and E1+E2). In the lower row the correspondent chronostratigraphy is represented. Inset: C Serra Sbregavitelli section; D Monte Raggeto section; E composite section (E1: T1-T5, Monte Tobenna section; E2: F1-F4, Monte Faito section); A, B and F: ideal sections.

(3) the Aptian/Albian boundary individuated at Monte Raggeto as well as at Serra Sbregavitelli (Matese Mountains) and at Monte Faito (Picentini Mountains, Campania Apennines). In particular, in the Aptian-Lower Albian of Serra Sbregavitelli, M. Raggeto and M. Faito such correlation has been corroborated by high-resolution carbon-isotope stratigraphy. From the integrated cyclostratigraphic-isotopic approach (D'Argenio et al., 2003) a good correspondence emerges (a) from carbon-isotope longer trends between the pelagic and the carbonate platform domains as well as (b) between the Transgressive/Regressive Facies Trends singled out in the Periadriatic Region and the third order eustatic cycles already known for the corresponding Cretaceous time.

Orbital Chronostratigraphy

The superbundles can be used to assemble chronostratigraphic diagrams that are based on the following assumptions: (a) superbundles in cyclostratigraphy are equivalents of depositional sequences in sequence stratigraphy, (b) maximum flooding surfaces of the time-equivalent superbundles are isochronous at the scale of the bundles (100-ky cycles and even of the elementary cycles in those bundles without elementary cycle omissions); (c) bundles are used as chronostratigraphic units, (d) the highest probability of omission in the stratigraphic record (as non depositional or erosional gaps) occurs at the boundaries of the T/RFTs, where the sedimentary record suggests the lowest accommodation space. Orbital chronostratigraphy (Fig.3) allows (a) to locate the missing cycles (bundles) throughout the studied successions, (b) to calculate for each superbundle, as well as for each succession, its average accumulation rate regardless of gaps occurring in the sedimentary record and (c) to estimate the minimum time required for each succession to accumulate (D'Argenio et al.,1997; 1999; 2003). For example, a time span of 2.9 my has been estimated for the Valanginian-Hauterivian interval of the S. Lorenzello succession (Ferreri et al., 2003) whilst a time duration of 8.0 my has been evaluated for the whole Aptian stage of M. Raggeto (Amodio et al., this volume).

Final Remarks

Changes in facies and thickness recorded in Cretaceous carbonate platform strata of the Periadriatic Region are mainly allocyclic in nature and controlled by variable eustatic oscillations modulated by the climatic system, via Earth's orbital cyclicity.

Based on their cyclic stacking patterns, shallow-water carbonates (Fig.1) are interpreted in terms of sequence stratigraphy (***sequence cyclostratigraphy***). This allows high-precision ($\leq$ 100 ky) correlations to be traced, and a 3D carbonate platform lithostratigraphy to be restored, at regional scale (Fig.3). Once such a high-precision correlation is fitting two or more distant sequences, a graphic and/or numerical expression of the acquired data may be derived and the following results obtained (Figs.2, 3): (a) recognition of subtle gaps, otherwise hidden (at least in their real extent) by lack of adequate biostratigraphic evidences; (b) quantitative measurement of the geologic time expressed by the whole sequence, regardless from gaps truly punctuating it (orbital chronostratigraphy); (c) projection of these data on the standard sea-level oscillation curves (Haq et al., 1987; Hardenbol et al., 1998), contributing often to increase their precision or, sometimes, to their emendation (Amodio et al., this volume).

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