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STRATIGRAPHIC FRAMEWORK AND SEDIMENTARY FEATURES OF THE LOWER APTIAN "LIVELLO SELLI" IN THE LOMBARDY BASIN (SOUTHERN ALPS, NORTHERN ITALY)

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Riassunto. Nella successione aptiana del Bacino Lombardo è presente un livello di età Aptiano inferiore, potente circa 3 metri, che costituisce un equivalente del Livello Selli del Bacino Umbro-Marchigiano. Tale unità (Livello Selli Equivalente: LSE) è costituita dall'associazione di calcilutiti pelagiche bioturbate, marne laminate mediamente ricche in carbonio organico, *black shales* e rare torbiditi pelagiche calcaree, fini.

Il LSE non è presente con continuità nel Bacino Lombardo, in quanto manca in tutte le successioni incomplete che si sviluppano in prossimità di aree di alto strutturale ed in alcuni settori di bacino. Il confronto con le unità equivalenti appenniniche e sudalpine indica inoltre che la successione comprendente LSE non è mai completa, a causa della presenza di discontinuità stratigrafiche nell'intervallo Barremiano sommitale-Aptiano. Queste caratterizzano il brusco cambiamento da sedimentazione a dominante carbonatica a sedimentazione esclusivamente terrigena fine.

Nell'ambito della successione cretacica inferiore del Bacino Lombardo, LSE occupa la parte centrale di un'unità stratigrafica, della durata di circa 5 MA, delimitata localmente da discontinuità a letto e tetto. Tale unità viene interpretata come un ciclo trasgressivo/regressivo di secondo ordine (Barremiano superiore - Aptiano superiore), espresso in ambiente bacinale, in cui l'orizzonte ricco in *black shales* del LSE, rappresenta il massimo di trasgressione.

Le caratteristiche sedimentarie del ciclo Barremiano superiore - Aptiano superiore consentono di integrare i confronti con le successioni coeve, anche se sostanzialmente differenti, tipiche di altri bacini.

Abstract. A stratigraphic unit, Early Aptian in age, equivalent to the Lower Aptian Livello Selli of the Umbria-Marche Basin, has been recognized in the Lombardy Basin (Southern Alps) and is here described. The unit is up to 3 m thick, and consists of alternating pelagic calcilutites, marlstones, black shales and rare pelagic turbidites. Due to the uneven basin morphology, with intrabasinal structural highs, the Livello Selli Equivalent unit (LSE) is often lacking.

The LSE is located in the central part of a stratigraphic unit, locally bounded by discontinuities, that is here interpreted as a complete transgressive/regressive (T/R) cycle of latest Barremian to Late Aptian age. The sedimentary features of this cycle, can be used to support comparisons between the lombardian succession and those from other basins.

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Introduction.

The "Livello Selli" has been identified in the pelagic succession of the Umbria-Marche Basin of the northern Apennines where it has been defined as a shaly and ichthyolithic layer, with organic carbon-rich intervals and siliceous beds, Early Aptian in age (Coccioni et al., 1987). Equivalent units are well known from other tethyan as well as boreal regions (e.g.: Goguel layer of the Vocontian Basin, Bréhéret, 1988; Fischschiefer of the Lower Saxony Basin, Thurow & Mutterlose, 1993; unnamed layers in the Belluno Basin of the venetian Southern Alps, Weissert, 1989). In the apenninic sections, the Livello Selli has been attributed to the upper part of the *C. litterarius* Zone (calcareous nannofossil), and to the *G. blowi* Zone (planktonic foraminifera), i.e. well above the Barremian/Aptian boundary (Coccioni et al., 1992). In the apenninic and southalpine successions, where a magnetostratigraphic calibration is available, the Livello Selli and equivalent units occur at the base of the Cretaceous Long Normal interval (Gorgo a Cerbara and Cismon sections, respectively; Channell et al., 1979; Weissert, 1989; Herbert, 1992; Coccioni et al., 1992).

The Livello Selli and equivalent black shales are thought to document an Aptian Oceanic Anoxic Event (OAE1a) (Arthur et al., 1990). Their deposition has been attributed to a worldwide climatic change that forced production and storage of organic matter, and resulted in a pronounced shift towards positive values of the carbon isotope curve (Weissert et al., 1985; Weissert, 1989; Weissert & Lini, 1991). This is combined with an increased amount of terrigenous sediments (Weissert, 1990). A dramatic turnover is also recorded during this time by the planktic and benthic communities (Coccioni et al., 1992; Erba, 1993).

The aim of this paper is to document a stratigraphic unit equivalent to the "Livello Selli" in the Lombardy Basin (Livello Selli Equivalent unit, LSE), and to describe its sedimentary features. An attempt to relate the development of the LSE to a framework of transgressive/regressive cycles, as interpreted on the basis of the pelagic record in the basinal setting, is also provided; it will serve to support comparisons with coeval successions from different regions.

The study area is located between Lake Como and Brescia (Fig. 1), and is representative for the major part of the Lombardy Basin, where the investigated units are best exposed.

Regional geology and stratigraphy.

The Jurassic and Cretaceous successions of Lombardy, represent the infillings of Jurassic rift-related half grabens, and of an Upper Cretaceous synorogenic basin, the latter located in the back-side of the pre-collisional alpine belt (Gaetani, 1975; Castellarin, 1976; Winterer & Bosellini, 1981; Doglioni & Bosellini, 1987; Bersezio & Fornaciari, 1987). The two different successions are separated by post-rift sequences that predate the onset of syntectonic turbidite sedimentation. The change between the op-

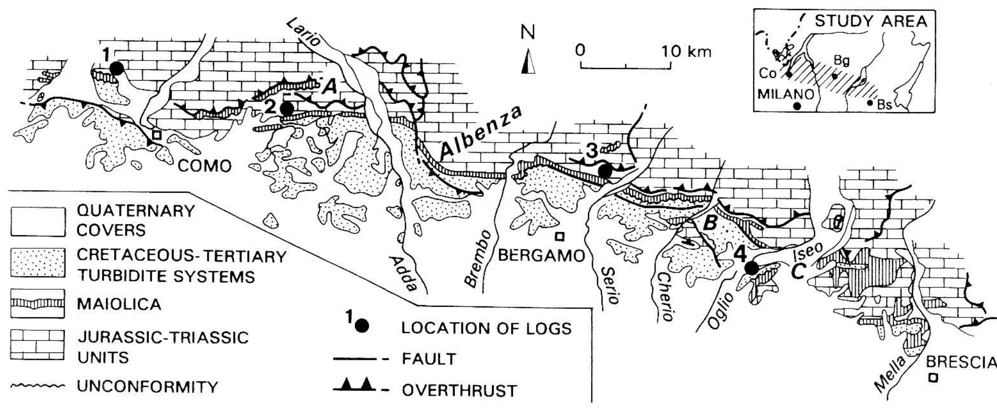


Fig. 1 - Location of stratigraphic logs reported in Fig. 2 and 3, within the study area: 1) Breggia; 2) Cesana/Suello composite section; 3) Bruntino; 4) Capriolo; A) Corni di Canzo; B) Zandobbio; C) Piè del Dosso.

posite geodynamic regimes is recorded by the Lower Cretaceous stratigraphic units. They consist mainly of pelagic carbonates, often affected by synsedimentary slumping.

The transition from carbonate to terrigenous sedimentation occurred during the Aptian, and was marked by the deposition of the LSE. As a result, this layer separates the pelagic calcilutites of the uppermost Tithonian-lowermost Aptian Maiolica (Arthur & Premoli Silva, 1982) and the pelagic to turbiditic marlstones and shales of the Scaglia Variegata and equivalent units (Marne di Bruntino, Lower Aptian-Upper Albian; Passeri, 1969; Sass de la Luna, uppermost Albian; Venzo, 1954; Arthur & Premoli Silva, 1982).

The Barremian-Albian succession.

The litho- and biostratigraphy of the Barremian-Albian succession of the Lombardy Basin have been described in previous works (Barberis et al., 1992; Bersezio, 1992, 1993). Biostratigraphic data are provided also by literature (Arthur & Premoli Silva, 1982, for the Breggia area; Erba & Quadrio, 1987, for the Piè del Dosso area) and by courtesy of E. Erba (calcareous nannofossil biostratigraphy of the Cesana quarry section; unpublished data). Only a brief summary of the main features of this succession will be reported here, starting from the Barremian interval of the Maiolica Formation (Fig. 2).

Maiolica. The Barremian-Aptian part of Maiolica (Mc) consists of two lithozones. The Barremian lithozone, is represented by cyclically arranged couplets and bundles of pelagic calcilutite beds, with black cherts, and dark grey to black shaly interbeds (Weissert et al., 1979; Herbert, 1992). At the top of this unit, a sharp and paraconformable boundary can be present (hiatus encompasses the uppermost Bar-

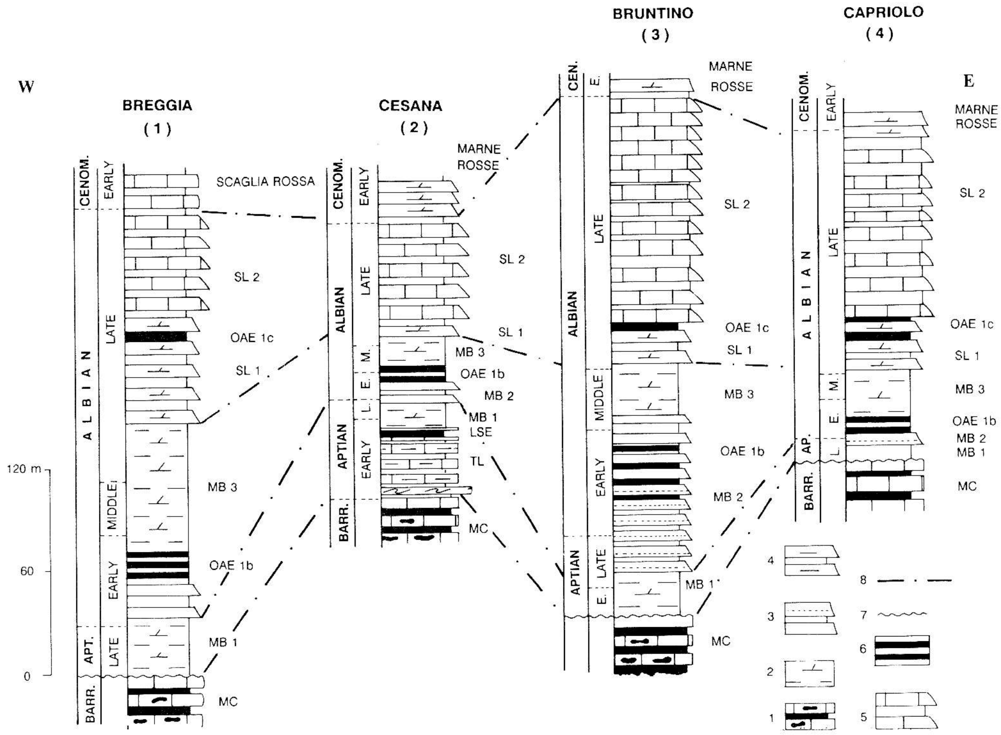


Fig. 2 - Simplified Barremian-Albian stratigraphy of the Lombardy Basin. Mc) Maiolica; TL) Maiolica/Scaglia Variegata-Marne di Bruntino transitional lithozone; LSE) Livello Selli Equivalent unit; MB1) Marne di Bruntino lower pelagic lithozone; MB2) Marne di Bruntino intermediate turbiditic lithozone; MB3) Marne di Bruntino upper hemipelagic lithozone; SL1) Sass de la Luna lower lithozone; SL2) Sass de la Luna upper lithozone (main body of pelagic turbidites). OAE1a, OAE1b, OAE1c) Oceanic Anoxic sub-Events.
Legend: 1) pelagic calcilutites with black cherts and interbedded black shales; 2) grey, green, and red, marlstones and shales; 3) fine-grained siliciclastic turbidites; 4) marly "hemipelagic" turbidites; 5) pelagic calcareous turbidites and interbedded marlstones; 6) black shales; 7) discontinuity; 8) boundaries of the proposed 2nd order stratigraphic units. Location of stratigraphic logs is reported in Fig. 1.

remian to Lower Albian) (Arthur & Premoli Silva, 1982). Otherwise the gradational boundary with the overlying Scaglia Variegata, is represented by an uppermost Barremian-Lower Aptian transitional lithozone (TL) (Fig. 2 and 3). The latter unit consists of pelagic calcilutites, with rare grey cherts, marlstones, fine grained pelagic turbidites and dark shales (Barberis et al., 1992).

Livello Selli Equivalent unit (LSE). The LSE is present at the top of the transitional lithozone, but is absent in areas where the Maiolica/Scaglia Variegata (Mc/SV) boundary is unconformable to paraconformable. The unit consists of marly calcilutites and dark gray shales, with a maximum thickness of about 3 m (Cesana-Suello area; Fig. 2 and 3). A more detailed description of the LSE is reported further on.

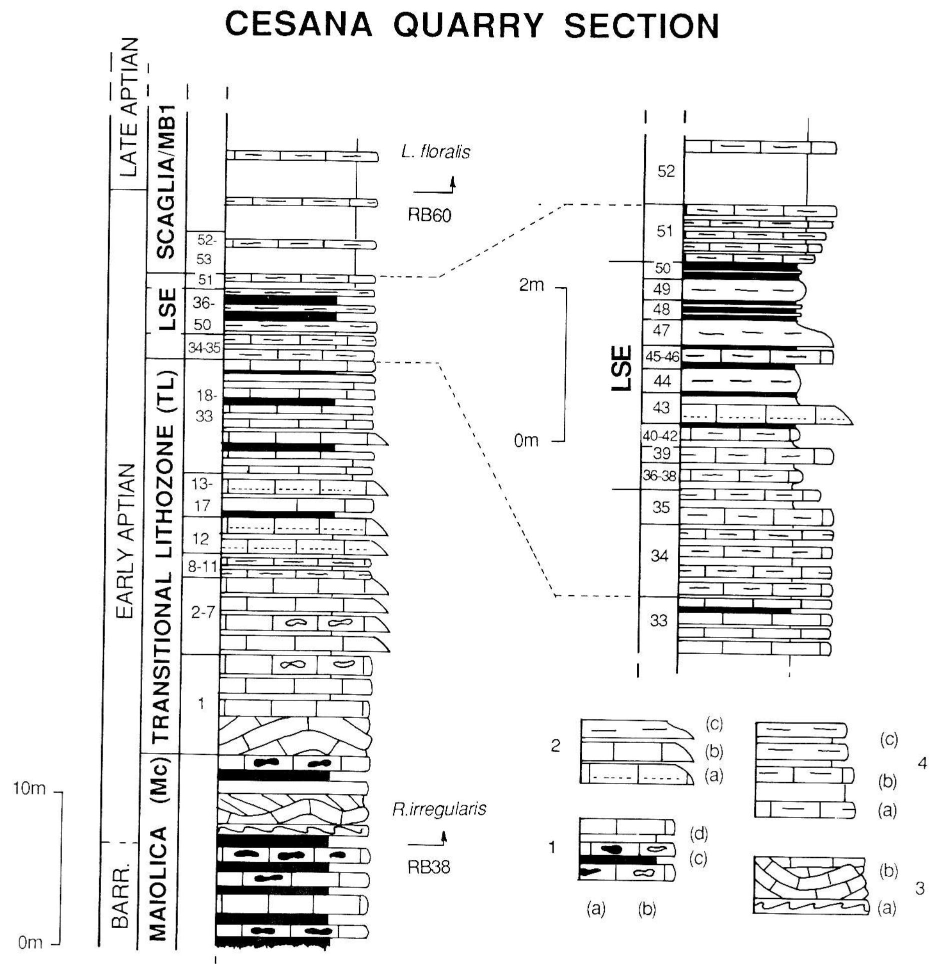


Fig. 3 - Sedimentary features of the LSE in the Cesana quarry section (location in Fig.1; description in Appendix 1).
Legend: 1) pelagic calcilutites with (a) black or (b) grey/mellow cherts, and interbedded black (c) or grey/olive green (d) shales; 2) pelagic turbidites: (a) calcisiltites, (b) calcilutites, (c) marlstones; 3) slumps (a) and disturbed beds (b); 4) pelagic/hemipelagic marly calcilutites (a) and interbedded grey/olive green marlstones (b), and marlstone-shale alternances (c). 1 - 53 numbers are referred to measured intervals in Appendix 1. Intervals 34-35 and 51 could respectively correspond to the lower and upper critical intervals of the Gorgo a Cerbara section (Coccioni et al., 1992). The first occurrence of *R. irregularis* and *L. floralis* has been reported with the number of the corresponding samples.

Scaglia Variegata-Marne di Bruntino (SV-MB). The Lower Aptian-Upper Albian units of the westernmost and easternmost Lombardy Basin (respectively near lakes Como and Iseo) are called Scaglia Variegata (Arthur & Premoli Silva, 1982, and references therein), while the equivalent formation in the central part of the basin (Bergamo Prealps) is called Marne di Bruntino (Passeri, 1969). The latter unit, up to 150 m thick, consists of three main lithozones (Fig. 2). In ascending order, these are represented by a lower unit of pelagic-hemipelagic marlstones and shales (MB1), an intermediate body of fine-grained, turbiditic, quartz-arenites and siltstones with black shales (MB2), and an upper unit of hemipelagic marlstones with rare pelagic turbidites (MB3). The base of the intermediate arenitic lithozone (latest Aptian to Early Albian in age) is correlative to a minor, intraformational, discontinuity marked by lenticular conglomerates (Bersezio, 1992). The siliciclastic turbidites of MB2 lithozone are very rare or absent in the distal basinal and marginal sectors, where the "Scaglia"-like facies are prevalent.

Sass de la Luna (SL). The uppermost Albian Sass de la Luna represents a more than 300 m thick unit of foraminiferal-intraclastic, pelagic turbidites and hemipelagic marlstones, widespread in the central part of the Lombardy Basin (Bergamo Prealps). It is subdivided in two lithozones (Fig. 2). The upper lithozone represents the main turbidite body (SL2), while the lower one (SL1) marks the lower transitional boundary (Bersezio, 1992) and contains black shale layers of Late Albian age (Arthur & Premoli Silva, 1982). The Scaglia Bianca equivalent formation in western and eastern Lombardy (Gelati et al., 1981; Arthur & Premoli Silva, 1982, and references therein) is much thinner (20-120 m) due to the lower thickness and frequency (or absence) of the pelagic turbidites.

The Livello Selli Equivalent unit (LSE).

The LSE is present in the complete and conformable successions (Cesana-Suello, Pusiano, Albenza, east Iseo areas; Fig. 1). It is obviously absent in the truncated successions located above the uplifted edges of tilted blocks ("structural highs": Corni di Canzo, Zandobbio; Fig. 1) or at their flanks (Breggia, Bruntino; Fig. 1 and 2) (Barberis et al., 1992). It is also missing in some basinal locations, where the Mc/SV boundary is paraconformable (Capriolo; Fig. 1 and 2). Due to the Tertiary tectonic decoupling of the Lower and Upper Cretaceous successions, the LSE can also not be found in some basinal sectors where it had been probably deposited (part of the Albenza and west Serio-Oglio areas; Fig. 1). Moreover, in the easternmost area (Iseo-Brescia), some uncertainty affects the identification of the LSE, due to poor exposure and lithological peculiarities (e.g., Piè del Dosso section, north of Brescia, Fig. 1; Erba & Quadrio, 1987).

Calcareous plankton biostratigraphy (Arthur & Premoli Silva, 1982; Erba & Quadrio, 1987; Barberis et al., 1992; Channell & Erba, 1992) indicates that the LSE is younger than the first occurrence of *R. irregularis* and belongs to the upper part of the *C. litterarius* nannofossil Zone, and to the upper part of the *G. blowi* foraminiferal Zone.

Magnetostratigraphic calibration is available for the Piè del Dosso section only (Erba & Quadrio, 1987; Channell & Erba, 1992), and indicates that the most plausible

LSE in the Lake Iseo area, developed above the magnetic chron CM0, that means in the lowermost part of the Cretaceous Long Normal interval.

Sedimentary features.

The best exposures of the Mc/SV transition, and of the LSE can be observed in the area near Lecco (Pusiano-Cesana-Suello zone; Fig. 1), that represents a reference area for this unit. The sedimentary features and the range of thicknesses of the described intervals, including the LSE, are thus reported for this area. A more detailed description of the Cesana quarry section (Merone Cement Factory), that has been sampled in 1993 for magnetostratigraphy by J.E.T. Channell, for which a complete biostratigraphy based on calcareous nannofossils is available (E. Erba), and ammonite biostratigraphy is in progress (F. Cecca & G. Landra), is reported in Appendix 1.

In the considered region the LSE gradually developes from the TL (Fig. 3). At the top of the LSE, the change to grey-green clayey marlstones of the SV-MB1 sharply occurs. The exposed successions show the following stratigraphy (Fig. 3 and 4a):

1) *Maiolica*, represented by grey to cream parallel bedded calcilutites with black shale interbeds and some thick bedded slump. Black chert nodules and layers are frequent;

2) *Maiolica/Scaglia Variegata transitional lithozone* (TL), represented by an alternation of 5-30 cm thick strata, consisting of laminated calcisiltites-calcilutites, grading up to marlstones, parallel-laminated marlstone layers and black shales. Black cherts are absent, and light grey to mellow chert nodules and layers are very rare. Their frequency decreases upwards, until they disappear a few meters below unit 3. A prominent black shale (about 25 cm thick) is present in the upper part of TL. In the reference area the total thickness changes from 15 up to 25 m;

- transitional boundary;

3) thin to medium and parallel bedded, grey/olive green, marly limestones, intensively burrowed, with dark grey, shaly marlstone interbeds. The more calcareous beds show parallel laminations in the upper part and gradational transitions to the shaly interbeds. Some thin to medium bedded, calcisiltite grading to calcilutite layers, are present in the upper part of this interval. Radiolarian-rich marlstone interbeds are sometimes rich of woody fragments and contain glauconite particles. Thickness never exceeds 1.5 m;

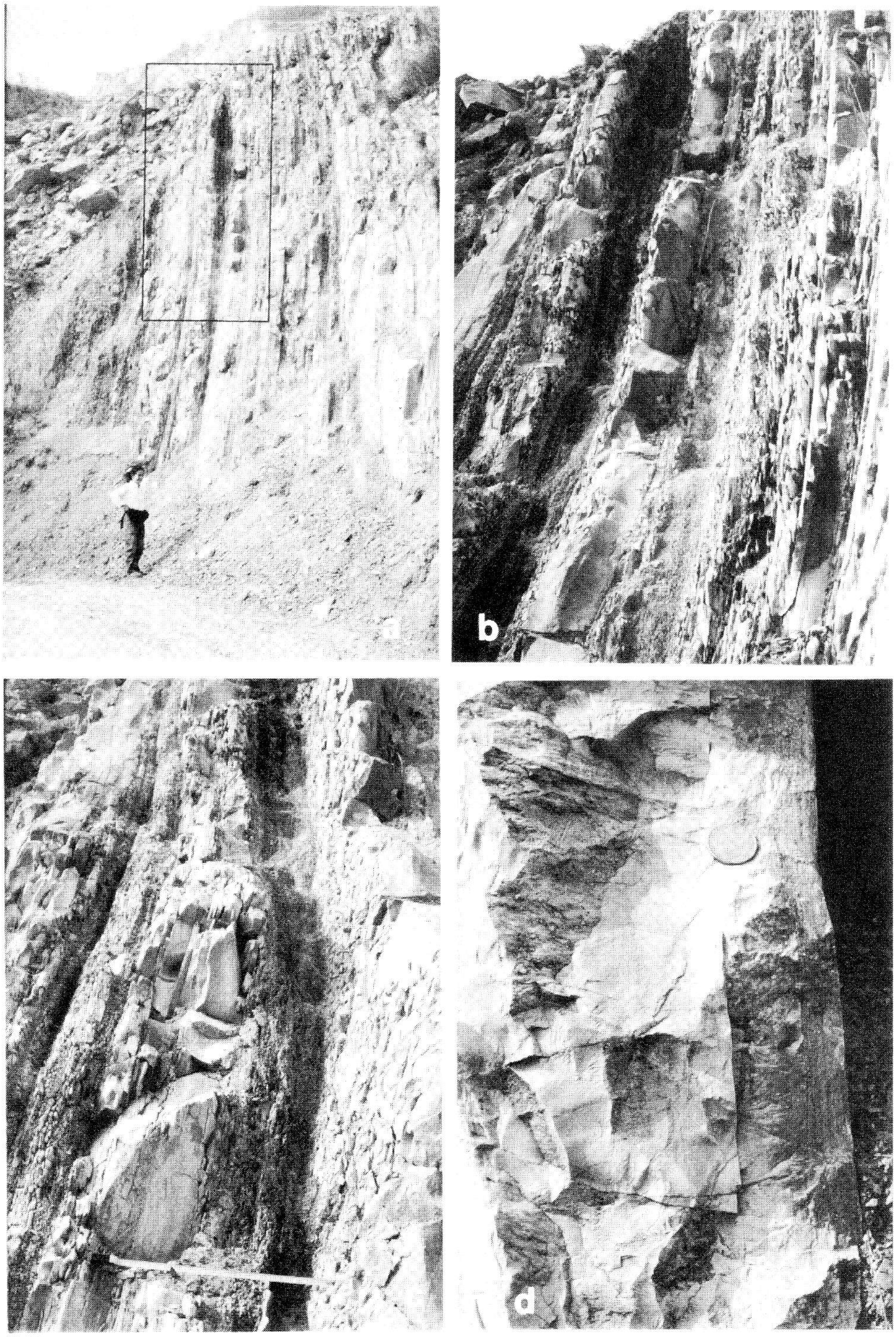
4) *Livello Selli Equivalent unit*: the lower part of this unit consists of thin to medium bedded, grey marlstones, in association with thin to very thin, clayey marlstone and shale interbeds, dark grey to olive green in color. The upper half of the LSE consists of thin-bedded, homogeneous to parallel-laminated marlstones, dark grey to olive-green colored, gradually passing to dark grey and black, clayey marlstones and shales (Fig.4b-c). The latter are parallel-laminated and radiolarian-rich beds, in which the light-colored laminae have a more calcareous composition. Silt-sized quartz, glauconite particles and woody fragments are common. Some graded-laminated beds, up to 44 cm thick, consisting of light grey to cream, calcisiltites-calcilutites, with a sharp lower boundary, and gradually passing upwards to marly burrowed limestones, are interbedded as a minor lithology (Fig. 4d). Their thickness and frequency determines the total thickness variations of this interval (2.5-3 m);

5) thin to medium bedded, marly limestones, dark grey in color, burrowed to parallel-laminated; they alternate with very thin, laminated, grey marlstones. Intraclasts, silty quartz, radiolarians and woody fragments are common. Thickness is about 0.7 m;

- sharp boundary;

6) *Scaglia Variegata-MB1*: olive-green and grey, siliceous marlstones with dark grey argillites and black, laminated shales (less than 10 m discontinuously exposed).

The first occurrence of *R. irregularis*, corresponding to sample RB38 in the Cesana section (Fig. 3, Appendix 1), is located approximately 5 m below the base of the TL, marked by the disappearance of black chert nodules in the calcilutites. The first


a
b
d

occurrence of *L. floralis*, corresponding to sample RB60 in the same section, is located within the SV-MB1, about 5 m above the base of interval 6 (Fig. 3).

The Barremian part of Maiolica (interval 1), mostly consists of pelagic/hemipelagic facies, rhythmically interbedded with black shales, in association with rare slumped beds. The sharp-based, graded and laminated calcisiltite-marlstone strata typical of the TL unit (interval 2), can be interpreted like fine grained, pelagic turbidites (see analogous examples in Stow et al., 1984). The TL is therefore a turbidite-dominated interval, with associated pelagites and recurrent black shales. The LSE (interval 4) mostly consists of pelagic-hemipelagic marlstones and shales in association with some fine grained pelagic turbidites. In the pelagites, carbonate content varies from less than 5% to more than 75%, and burrowing is less intense in the shaly than in the marly layers. Intervals 3 and 5, embedding the LSE, are represented by pelagic marly calcilutites, with dark grey hemipelagic intercalations. The overlaying SV-MB1 lithozone (interval 6) mostly consists of hemipelagites, with rare dark grey, organic-poor shales and silicified calcarenites.

Clay minerals in the shales and clayey marlstones of the LSE are illite, smectite, illite/smectite mixed layers and chlorite (Bersezio, 1992). This mineralogical association does not substantially differ from that of the underlaying shale beds of the Barremian Maiolica and of the TL. On the contrary chlorite is not present in the overlaying SV-MB1, whose clay mineral association is more smectite-rich than that of the LSE. Moreover, the LSE clay mineralogy has resulted very similar to that of the black shales interbedded in the upper part of the turbiditic unit of the uppermost Aptian-Lower Albian MB2 (OAE1b) (Bersezio, 1992) (Fig. 2).

Organic matter composition of six black shales sampled in the LSE (2 in the Cesana quarry section, 2 in the Pusiano area and 2 in the Piè del Dosso section near Brescia), is dominated by continental woody and herbaceous fragments, with amorphous aggregates and a minor proportion of marine phytoplankton. The total organic carbon content is never higher than 1.5% weight in the darker shaly layers, showing a more mixed (continental-marine) composition.

Comparisons with the Livello Selli.

The stratigraphic framework indicates that the LSE of the Lombardy Basin is coeval with the Livello Selli of the Apennines and of the Belluno Basin. It documents

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Fig. 4 - a) The LSE in the Cesana quarry section. Younging is from right to left. The woman for scale marks the base of the SV-MB1. b) Detail of Fig. 4a (framed area): organic-rich beds in the LSE 3 interval. c) Detail of Fig. 4a (left part of the framed area): marlstone-shale alternance, with transitional boundaries between dark grey, laminated marlstones/shales and grey, partly burrowed marlstones. d) Pelagic turbidite, consisting of parallel-laminated, radiolarian-rich calcisiltites (Td), passing upwards to burrowed, light grey calcilutites (Te). The overlying pelagite (non visible) is a dark grey clayey marlstone.

the transition from a pure calcareous to a more shaly depositional environment.

The LSE is embedded between two more calcareous intervals (respectively intervals 3) and 5) in the described stratigraphy of the Cesana-Suello area) (Fig. 3 and 4). The lower one (up to 1.5 m thick), in which marlstone and shale interbeddings get more abundant upwards, could correspond to the "lower critical interval" of the Gorgo a Cerbara section (Apennines; Coccioni et al., 1992). The identification of a true "upper critical interval", corresponding to the one described in the Gorgo a Cerbara section, is not obvious. It could be represented by interval 5), which is considerably thinner than interval 3) and is sharply overlaid by the Scaglia mudstones. The latter facts support the identification of a minor discontinuity between the possible "upper critical interval" and the base of the SV-MB1.

Differences in thickness between the LSE, the Livello Selli in the Apennines and in the Belluno Basin (Fig. 5) are controlled by the presence of unconformities, the deposition of pelagic turbidite beds and changes in sedimentation rate from site to site. In Lombardy the Mc/SV-MB1 discontinuity is in fact a regional feature, that is present not only in the successions located on intrabasinal structural highs or at their margins,

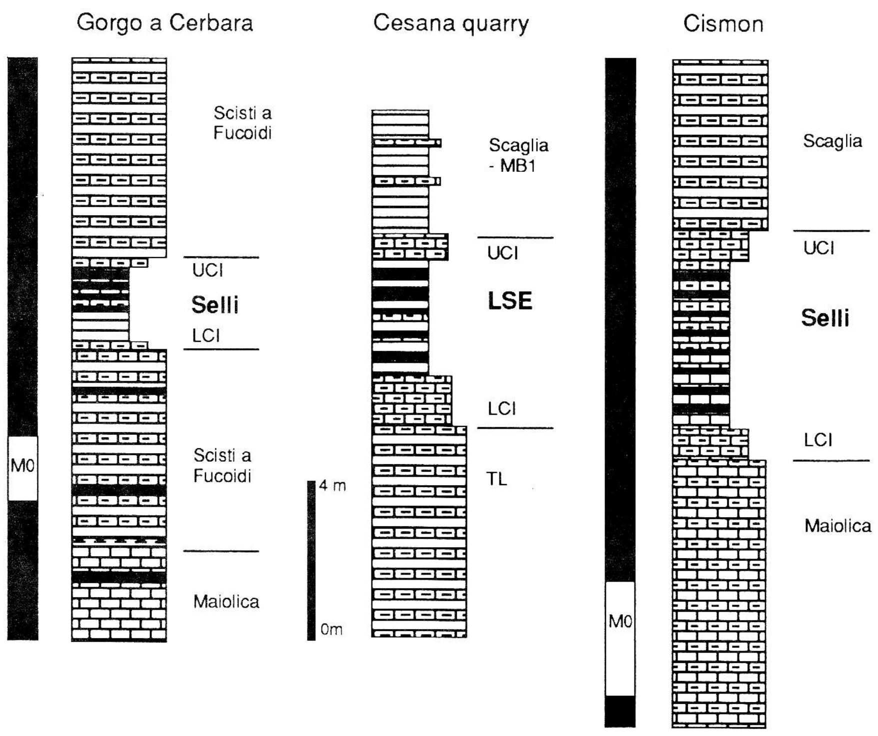

Fig. 5 - Comparison of the LSE in the Cesana quarry section, with the Livello Selli of the Gorgo a Cerbara section (redrawn after Coccioni et al., 1992), and of the Cismon section (redrawn after Channell et al., 1979 and Herbert, 1992). LCI: Lower critical interval; UCI: Upper critical interval.

but also in some basinal settings. Also the minor discontinuity at the top of the possible upper critical interval is recorded in the basinal settings. These features suggest that a fully complete Aptian succession is not present in the Lombardy Basin, because the upper critical interval, overlaying the LSE, could be incomplete at the top. Where present, the LSE itself is thinner than the organic carbon-rich layer representing the Livello Selli in the Belluno Basin (Cismon section, thickness of about 4 m, after Weissert, 1989, and about 5 m, after Herbert, 1992); on the contrary it is a little thicker than, but comparable with, the Livello Selli of the Apennines (about 2 m in the Gorgo a Cerbara section; Coccioni et al., 1992).

From the lithological point of view, the LSE is characterized by more frequent calcareous layers (pelagic and turbiditic) than the apenninic Livello Selli, chert nodules are absent and silicified beds are rare, the total organic carbon content in black shales is lower. On the contrary the LSE is more similar to the Livello Selli of the Belluno Basin, the latter showing more abundant marlstones.

The facies association of the LSE includes pelagic turbidites, that are absent in the other cases, and shows a rhythmic, but in some way irregular, alternance of calcilutite-marlstone couplets with dark shales, that only partly resembles the bundling described by Herbert (1992) in the Cismon section. A comparison based on the number of bundles involved is therefore impossible.

The significance of the LSE within the Barremian-Albian stratigraphic framework.

The uppermost Barremian to Albian succession of the Lombardy Basin can be subdivided into three sedimentary units, bounded either by discontinuities or by the base of turbidite bodies (Fig. 2). From bottom to top they are:

- *the uppermost Barremian-Upper Aptian unit*, that consists of the Mc/SV transitional lithozone (TL), the LSE and the pelagic lithozone of the SV-MB1, and spans about 5 MA (compare with the time scale adopted by Haq et al., 1988). The lower boundary of this unit is represented by the Mc/SV-MB1 unconformity, in the incomplete successions, and by the base of the TL pelagic turbidite interval in the conformable ones;

- *the uppermost Aptian-Upper Albian unit*, delimited at the base by the lower boundary of the MB2 turbidite body and the correlative unconformity. The unit comprises the turbiditic and hemipelagic lithozones of the Marne di Bruntino (MB2, MB3) and spans about 9 MA;

- *the Upper Albian unit* is open by the onset of pelagic turbidite deposition; the top boundary is the Lower-Middle Cenomanian unconformity (Bersezio & Fornaciari, 1987). This unit consists of the Sass de la Luna lithozones (SL1, SL2), mostly represented by pelagic turbidites in the central part of the Lombardy Basin, and spans about 3 MA.

Within each of these units, an organic-rich interval coeval with an Oceanic Anoxic (sub)-Event is present. As it has been previously introduced, these intervals are represented by the LSE, in the middle part of the uppermost Barremian-Upper Aptian unit, the black shales interbedded with siliciclastic turbidites in the Lower Albian part of MB2 (uppermost Aptian-Upper Albian unit), and the organic-rich marlstones at the top of the Upper Albian SL1 (Upper Albian unit) (Arthur & Premoli Silva, 1982; Bersezio, 1992) (Fig. 2). The LSE is coeval with the OAE1a; the Lower Albian organic-rich horizon probably corresponds to the OAE1b and the Upper Albian one to the OAE1c (Robaszynski, 1989; Arthur et al., 1990).

In order to interpret the significance of the LSE within this stratigraphic framework, the following topics will be briefly discussed.

Boundary conditions to the Barremian-Aptian Lombardy Basin.

The important variations of sedimentary regime that occurred through the Lombardy Basin from Barremian to Aptian time, have been controlled by the regional evolution, that induced substantial changes of subsidence patterns and accomodation. The pre-Aptian configuration, still reflecting the geometries inherited from the Jurassic rifting (Weissert, 1981; Winterer & Bosellini, 1981) was replaced by a new, elongated, basin shape, with minor influences of the old intrabasinal structural highs (Errico et al., 1979; Gelati et al., 1981; Barberis et al., 1992; Bersezio, 1992). Whether the gravitational instabilities, that led to deposition of slumps and turbidites in the upper part of the Maiolica Fm. and the overlaying TL during the time of this change, were due to synsedimentary tectonism (Bersezio, 1993), or to the uneven morphology of the basin floor, connected with differential compaction of the underlaying Jurassic sediments (Deconinck & Bernoulli, 1991), is not established. In both the alternatives, the control exerted by the local evolution is obvious.

Sediment supply.

During the Barremian-Aptian interval, sediment supply to the basin switched from a calcareous regime, controlled by carbonate productivity and redeposition, to a very fine grained, siliciclastic regime. In the more complete successions this transition is represented by the increasing input of terrigenous materials, recorded by the TL and the LSE, and by the sharp contact with the SV-MB1 shales and marls, at the top of the LSE itself. In the paraconformable successions of some basinal settings (Breggia, Bruntino, Capriolo; Fig. 2), the units involved in this transition are replaced by a hiatus. In these situations, the hiatus is preceded by glauconite and phosphates concentrations, and by the development of indurated surfaces, at the top of the Maiolica Fm. (Weissert, 1979). The overlaying Upper Aptian part of SV-MB1, is tipically depleted of carbonates, and usually red-colored by hematite concentration. This complex paraconformity, that is present in different locations throughout the basin, is the consequence of combined condensation, carbonate-to-clastic transition and enhanced bottom current activity (Weissert & Lini, 1991).

The role of bottom current erosion in generating submarine unconformities on the basin floors, has been stressed by Haq (1991), who suggests the correlation with the relative sea-level falls and the ensuing lowstands, and therefore with the origin of sequence and supercycle boundaries.

The deficiency of carbonate in ocean waters has been related to interglacial times, or highstand periods, by several Authors (see Haq, 1991, for a review). In particular dissolution of carbonates would occur in the deep sea during the early highstand intervals, while during the late highstands, corresponding to depositional regressions on shelves and margins, the transition from the corrosive mode to normal rates of sediment accumulation would occur (Haq, 1991). This suggests a possible interpretation of the carbonate-depleted parts of the SV-MB1. However, concerning some coeval and similar red intervals of Tethyan sequences, characterized by negative carbon isotope events, Weissert & Lini (1991) proposed that they represent times of decelerated carbon cycling, cooler climate ("icehouse episodes") and consequent sea-level lowstand.

Storage and preservation of organic matter.

The oceanographic significance of the Livello Selli has been recently compared to that of the Livello Bonarelli by Coccioni et al. (1992), i.e. it would represent a high fertility event on a global scale, whose relations with sea-level fluctuations have not been clarified.

More generally, the organic-rich units in basinal and pelagic successions have been interpreted like transgressive deposits by several authors.

In the Vocontian Basin, the Aptian and Albian anoxic events (Goguel and Paquier layers; Bréhéret, 1985, 1988) have been interpreted as representing the peak transgression within 2nd order transgressive/regressive cycles, on the basis of field-supported sequential analysis (Bréhéret, 1988; Jacquin et al., 1991). In some DSDP drilling sites of the Pacific Basin, Sliter (1989) recognized two Aptian black shales, the lower one of which was easily correlated with the OAE1a and with the Livello Selli. By comparison with Vail's sea level curve, the Author proposed that the OAE1a could fall within the condensed sections associated with rapidly rising sea-level.

A correlation with the more recent generation of sea-level curves by Haq and coworkers, suggested to Weissert & Lini (1991) that, in the Alpine Tethys, the Aptian OAE occurred during times of transgression (transgressive system tracts), within a framework of low-frequency variations of the Early Cretaceous global climate (period of more than 5.5 MA). The periods of increased organic matter storage would represent "greenhouse" episodes in the Cretaceous climate.

At last, several other Authors correlate pre-Cretaceous times of production, storage and preservation of organic matter in the deep sea, with periods of transgression and/or sea-level rise (see for example Jenkyns & Clayton, 1986; Myers & Wignall, 1987, about the Toarcian anoxic event).

However, as it has been shown with the only exception of the Cretaceous of the Vocontian Basin, in all the quoted cases a 3rd order framework of depositional sequences could not be established independently, and the interpretation of the eustatic significance of black shales was based on correlation with the available sea-level curves. In all these cases, the variations of sedimentary, geochemical and biological parameters were reported at a several million years scale, that is not a proper scale for correlation with the typical 3rd order rank of the Cretaceous depositional sequences and system tracts. The latter is also the case of the Lombardy Basin, where only large scale units, like those introduced above, can be distinguished with confidence by means of physical stratigraphy.

Interpretation.

The main features of the uppermost Barremian-Upper Aptian unit of the Lombardy Basin are listed below (Fig. 6).

1) The unconformity at the base of the unit is related to the absence of a stratigraphic interval in basinal settings, suggesting submarine erosion by bottom currents.

2) In the conformable successions, the organic-rich layers of the LSE develop from a pelagic turbiditic interval, and are followed by hemipelagic marls and shales. Above the "upper critical interval", the SV-MB1 is progressively depleted of carbonates. The latter directly overlap the unconformity in the paraconformable successions.

3) These hemipelagites are unconformably overlaid by the siliciclastic turbidites of the MB2, that represent the base of the following uppermost Aptian-Upper Albian unit.

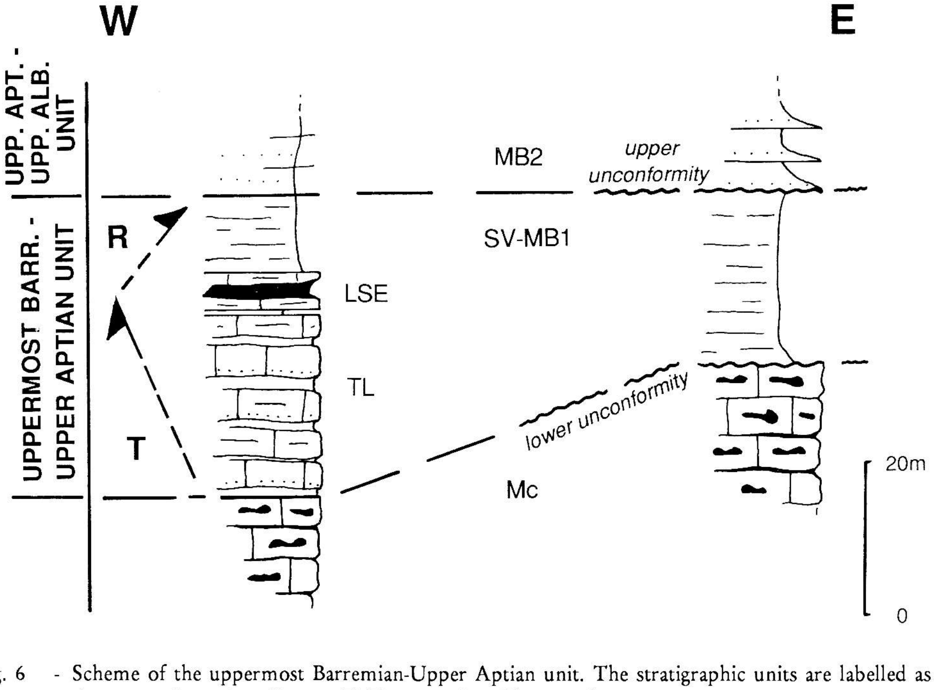

Fig. 6 - Scheme of the uppermost Barremian-Upper Aptian unit. The stratigraphic units are labelled as in the text and previous figures. T) Transgression; R) regression.

Taking into account the stratigraphic data, and the previous discussion, it can be observed that:

- the deposition of pelagic turbidites (TL), controlled by the local basin evolution, followed a major relative sea-level drop (lower unconformity) and therefore occurred in the lower part of the transgressive interval of the unit. The following enhanced input of very fine grained siliciclastics and the storage of organic carbon, leading to the origin of the LSE, was induced by a climate change, during ongoing transgression;
- the rapid shift towards exclusively fine grained, terrigenous, hemipelagic, organic carbon- and carbonate-poor, sedimentation (LSE/SV-MB1 boundary), probably represents a minor discontinuity (basinal equivalent of maximum flooding or boundary of a third order sequence?), that follows the peak transgression, opening the regressive part of the cycle (SV-MB1);
- the following onset of deposition of siliciclastic turbidites (MB2), and the related discontinuity, mark the boundary of the overlaying uppermost Aptian-Upper Albian unit.

The architecture of the uppermost Barremian-Upper Aptian unit has been determined by the regional tectonic evolution, the environmental and climatic variations and the biological turnovers, acting at the scale of several million years. Therefore, the proposed unit represents a 2nd order unit, comparable to the supercycles of the sequence stratigraphy model (Haq et al., 1988), and can be considered the basinal expression of a transgressive-regressive cycle.

Superimposed over this large scale modulation of stratigraphy, are the higher frequency sea-level cycles and the controls exerted by fluctuating orbital parameters, in the Milankovich band of frequencies. The sedimentary signature of the latter can be more easily recognized than the eustatic signal, that is probably the most difficult factor to identify in such an environment.

Probably some of the observed features can be related to the 3rd order eustatic signature. One of these is the sharp boundary above the top of the LSE, that could be related to a time of maximum flooding. If this is true, the LSE could represent the transgressive system tract of a depositional sequence, in agreement with the opinion of Weissert & Lini (1991), but there is no independent proof for this interpretation. The following are then still open questions: does the whole LSE (and the Livello Selli of other basins) belong to one depositional sequence? does its architecture represent a stack of condensed sections, on the whole belonging to peak transgression conditions of a higher rank unit (2nd order) (Fig. 6), but individually corresponding to different transgressive and/or highstand system tracts?

Conclusions.

The uppermost Barremian to Upper Albian succession of the Lombardy Basin consists of three large scale depositional units. The boundaries of the two lower units (uppermost Barremian-Upper Aptian and Upper Aptian-Upper Albian), are discontinuities and the corresponding bases of turbiditic units; the third one (Upper Albian) begins with the onset of pelagic turbidite deposition. Each unit is characterized by black shale layers, corresponding to the three Oceanic Anoxic sub-Events 1a, 1b, 1c.

In the central part of the uppermost Barremian-Upper Aptian unit, an organic - rich interval, up to 3 m thick, is recorded. It represents the equivalent of the Livello Selli (Coccioni et al., 1987) in the Lombardy Basin (LSE), as can be deduced on the basis of stratigraphic position, age and lithological analogies.

The succession including the LSE is not continuous through all the Lombardy Basin, and probably is never complete, due to the presence of two merging discontinuities. The older discontinuity is the lower boundary of the uppermost Barremian-Upper Aptian unit, and can be related to concurrent regional tectonic activity and bottom current erosion; the upper discontinuity reflects the definitive carbonate-to-clastic turnover, and could have been developed during a time of maximum flooding.

The uppermost Barremian-Upper Aptian unit can be interpreted like a transgressive-regressive cycle, in the centre of which the LSE represents the peak transgression.

The definition of eustatic cycles and depositional sequences in the basinal environment is strongly dependent on the interpretation of the significance of the sedimentary and biological events. For these reasons, the identification of depositional units, based on the recognition of unambiguous sedimentary features (discontinuities, boundaries of turbidite bodies, black shale horizons), can be useful for comparisons between successions from different basins and regions.

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Appendix

Description of the Cesana quarry stratigraphic section.

The section is measured along the westernmost quarry-road cut, in the Cesana quarry of the Merone Cement Factory, on the subvertical, E-W trending, southern limb of the Flessura Frontale anticline. The exposure starts from the top of the Barremian Maiolica and ends about 10 m above the base of the Scaglia Variegata/Marne di Bruntino. The overlaying succession is decolled by a presently subvertical fault, cutting downsection from the Cenomanian to the Lower Albian units.

At the base, Maiolica

- thin to medium bedded calcilutites, light grey to cream in color, with black chert nodules and layers. Black shale layers, up to 10 cm thick are frequently interbedded. In the upper 5 m, strata are disturbed and rotated, and thick bedded slumps are present;

Maiolica/Scaglia Transitional Lithozone (TL)

1) dark grey, thin to medium bedded calcilutites, parallel laminated to burrowed, with mm-thick shaly interbeds; strata are disturbed and rotated in the lower part of the interval (6.6 m);
2) eight parallel bedded and sharp based strata, consisting of laminated calcisiltite, grading up to burrowed calcilutite with mm-thick marlstone caps. Some light grey wavy bedded chert layers, with granular texture are present (1.04 m);
3) burrowed, grey-cream calcilutite (0.4 m);
4) dark grey, laminated marlstone, with sharp boundaries (0.11 m);
5) alternation of sharp-based, graded calcilutites, thin to medium bedded, with light grey, homogeneous calcilutites and mm-thick marly interbeds. Light grey chert nodules are present (2.46 m);
6) dark grey, laminated marlstone, with sharp boundaries (0.12 m);
7) sharp-based, graded and laminated calcilutites, with mm-thick, grey marly interbeds (1.30 m);
8) dark grey, intensively burrowed, homogeneous, marly calcilutite (0.41 m);
9) dark grey clayey marlstone with laminated to burrowed marlstone couplet, with sharp boundaries (0.16 m);
10) dark grey to olive green clayey marlstone to marly limestone, parallel laminated, with transitional boundaries; woody fragments are abundant (0.28 m);
11) grey, burrowed, marly calcilutite, with transitional boundaries (0.30 m);
12) thin to medium bedded, light grey, homogeneous calcilutites, in alternance with graded and laminated calcisiltites with burrowed top. Dark grey marlstone and shale interbeds are up to 5 cm thick (2.25 m);
13) dark grey to black, laminated clayey marlstone, with a more calcareous core parting (0.31 m);
14) five sharply bounded, homogeneous, calcilutite layers; the central bed is thicker and more light colored than the adjacent (0.73 m);
15) light grey-brown, parallel laminated, clayey marlstone, with a marly limestone core; glauconite and woody fragments are frequent (0.16 m);
16) six graded, calcisiltite-calcilutite strata, with sharp lower boundaries and parallel lamination; grey marlstone interbeds are up to 4 cm thick (0.85 m);
17) two calcilutite strata, homogeneous and light grey colored, with sparse burrows and mottles (0.47 m);
18) alternance of thin bedded, marly calcilutites, with sharp base and burrowed top, and grey to black marlstones, with parallel laminae; a partly silicified layer is present at the base of the interval (0.88 m);
19) alternance of thin bedded, burrowed, marly calcilutites and dark grey, laminated marlstones with transitional boundaries (0.82 m);
20) light grey, burrowed calcilutite with sharp boundaries (0.36 m);
21) dark grey-black, laminated marlstones and shales, with very thin bedded, graded calcilutites (0.47 m);
22) five light grey, graded calcilutite strata, with sharp bases (0.64 m);
23) grey, laminated marlstone, passing upwards into burrowed marly calcilutite (0.15 m);
24) grey, marly calcilutite strata (0.4 m), gradually passing upwards into
25) dark grey-black, laminated marlstone (0.26 m);
26) graded-laminated calcisiltite, with sharp base (0.11 m);
27) light grey calcilutite with sparse black burrows (0.41 m);
28) dark grey, laminated, shaly marlstone, with woody fragments and glauconite particles (0.15 m);
29) three light grey calcilutite beds, with chert nodules; pirite in the clayey interbeds (0.33 m);
30) two white calcilutite beds, abundantly burrowed at the top (0.48 m);
31) thin bedded, dark grey, marly calcilutites, alternating with laminated, black clayey marlstones (0.56 m);
32) two olive green/grey, laminate to burrowed, calcilutite strata, with sharp bases, grading up to grey marlstone (0.67 m);
33) alternance of thin bedded, grey, marly calcilutites, and laminated, grey to dark grey marlstones; a black shale layer is present close to the top (0.92 m);

"Lower critical interval"

34) alternance of dark grey marlstones, laminated to burrowed, 5-20 cm thick, and thin-bedded laminated shales and clayey marlstones, dark grey to black, rich of silt-sized quartz, radiolarians, muddy intraclasts, woody fragments and glauconite particles (0.96);

35) sharp-based and graded, marly calcilutites, with parallel laminae, grading up to dark grey shales, rich in coarse-grained woody fragments (0.48m);

Livello Selli Equivalent unit (LSE)

36) dark grey to olive-green, laminated, clayey marlstone (0.11 m), gradually passing to

37) dark grey, silty marlstone, rich of organic matter particles, with laminated base and top (0.09 m), gradually passing to

38) dark grey, laminated marlstone (0.11 m), gradually passing to

39) grey-green, homogeneous to laminated, marly calcilutite (0.21 m), gradually passing to

40) dark grey, laminated shale (0.05 m), gradually passing to

41) dark grey to olive green, laminated, silty marlstone, rich of woody fragments (0.14 m), gradually passing to

42) grey, laminated, calcareous marlstone, grading up to dark shale (0.13 m);

43) graded to laminated calcisiltite bed, with sharp lower boundary, grading into burrowed marly calcilutite; silt-sized intraclasts, radiolarians and organic matter particles are abundant at the base (0.44 m);

44) laminated to homogeneous marlstone, grey to olive green and brown in color (0.30 m);

45) dark grey, laminated marlstone (0.15 m);

46) three marly calcilutite strata, light to dark grey in color (0.16 m);

47) sharp based, marly limestone bed, olive green to dark grey in color, intensively burrowed in the upper 10 cm (0.37 m);

48) three laminated black shales, gradually interbedded with cm-thick, grey marlstones (0.24 m), gradually passing to

49) dark grey to black, marly limestone, burrowed to laminated (0.30 m), gradually passing to

50) two laminated black shales, with a grey marly interbed (0.21 m);

"Upper critical interval"

51) five dark grey, marlstone to marly limestone beds, discontinuously separated by dark grey clayey marlstones/shales; the strata show gradational boundaries and parallel-laminated divisions, grading up to burrowed intervals. Silt-sized organic matter particles and radiolarians are frequent (0.71 m).

Sharp boundary

Scaglia/MB1 lithozone

52) grey-green marlstones, alternated with dark grey, cm-thick, shales and silicified marlstones/calcilutites (1.4 m);

53) olive-green, burrowed marlstones, with cm-thick dark shaly interbeddings. Intense fracturation (1.45 m). End of continuous exposure.

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