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ASYMMETRIC CYCLES IN THE RHAETIC FACIES OFE SOUTHERN ALPS: PLATFORM-BASIN INTERACTIONS GOVERNED BY EUSTATIC AND CLIMATIC OSCILLATIONS

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Riassunto. Le formazioni retiche marnose del Sudalpino si depositarono nel Bacino Lombardo fortemente subsidente. Esso era controllato da una attiva tettonica sinsedimentaria ed era limitato ad est ed ad ovest da piattaforme carbonatiche peritidali (parte superiore della Dolomia Principale veneta, Dolomia del Campo dei Fiori). La maggior parte della successione retica è caratterizzata da cicli asimmetrici decametrici, prevalentemente fangosi, ciascuno dei quali è suddivisibile in tre parti: una porzione inferiore argillitico-marnosa; una mediana rappresentata da alternanze di livelli marnosi e livelli calcarei, questi ultimi sempre più spessi verso l'alto; una porzione superiore quasi completamente carbonatica. Le osservazioni sulla storia diagenetica suggeriscono che le alternanze calcari-marne sono fondamentalmente primarie e sono solo parzialmente modificate da una ridistribuzione diagenetica del carbonato. I cicli decametrici sono il risultato della sovrapposizione di un segnale asimmetrico a più bassa frequenza (durata stimata circa 100.000 anni) che controllava l'accumulo di fango carbonatico, e di un segnale sinusoidale ad alta frequenza relativo all'apporto di fango terrigeno. Il fango carbonatico è prevalentemente alloctono ed era fornito dalle piattaforme adiacenti; la modulazione asimmetrica del segnale era indotta da fluttuazioni eustatiche che erano registrate nelle aree più prossime alla superficie dalla diretta e ripetuta esposizione subaerea di sedimenti subtidali. Queste fluttuazioni regolavano infatti la produttività delle piattaforme carbonatiche e la ridistribuzione del fango calcareo nei bacini adiacenti. Tale esportazione era pressochè trascurabile durante la fase di massimo approfondimento, tanto che nelle aree più depresse si accumulava prevalentemente fango argilloso; aumentava poi gradualmente durante la successiva evoluzione *shallowing* della piattaforma per la sua aumentata produttività e per la crescente influenza di onde e correnti. La simultanea emersione di larghe porzioni della piattaforma alimentatrice interrompeva bruscamente la produzione ed il conseguente arrivo di fango carbonatico nei bacini. Il segnale relativo all'apporto argilloso era probabilmente modulato da variazioni climatiche che controllavano le precipitazioni e le portate solide dei corsi d'acqua nelle aree emerse. L'elevato tasso di sedimentazione che caratterizza le formazioni retiche ha permesso la registrazione e la preservazione di questo segnale climatico, che presenta una frequenza più alta di quelle previste dalla teoria di Milankovitch.

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Abstract. The Rhaetic facies, as developed in the Southern Alpine region of Italy, were deposited in a strongly subsiding, fault-dissected trough (the Lombardian Basin) bounded by carbonate platforms. The main part of the Rhaetic succession consists of decametric scale, stacked asymmetric cycles, each divided into three parts: a lower shale portion, a central rhytmic portion consisting of repeated marl-limestone couplets, the limestone part of which gradually thickens upward, and a wholly carbonate upper unit. A study of the diagenetic history demonstrates that these marl-limestone alternations are fundamentally depositional in origin. This decametric cyclicity is identified as deriving from the superposition of a lower frequency (period of about 100,000 years) asymmetric carbonate mud signal with a high frequency sinusoidal argillaceous mud signal. Evidence is produced indicating that the basinal carbonate mud is predominantly allochthonous in origin, having been derived from the adjacent carbonate platforms. The associated asymmetric carbonate signal was a response to eustatic fluctuations which affected the characteristics of the subtidal "carbonate factory" in the platformal areas. These fluctuations are indicated by the repeated direct subaerial exposure of subtidal muds in shallow areas. The basinward exportation of carbonate muds was negligible in the deepening phase, increased during the shallowing evolution and was finally stopped by the emersion of large platformal flats. In contrast, the higher frequency argillaceous mud signal was probably climatically modulated; fluctuations of a higher frequency than those defined in Milankovitch theory affected hinterland precipitation and run off. The rapid subsidence and depositional rates allowed the preservation of this effect.

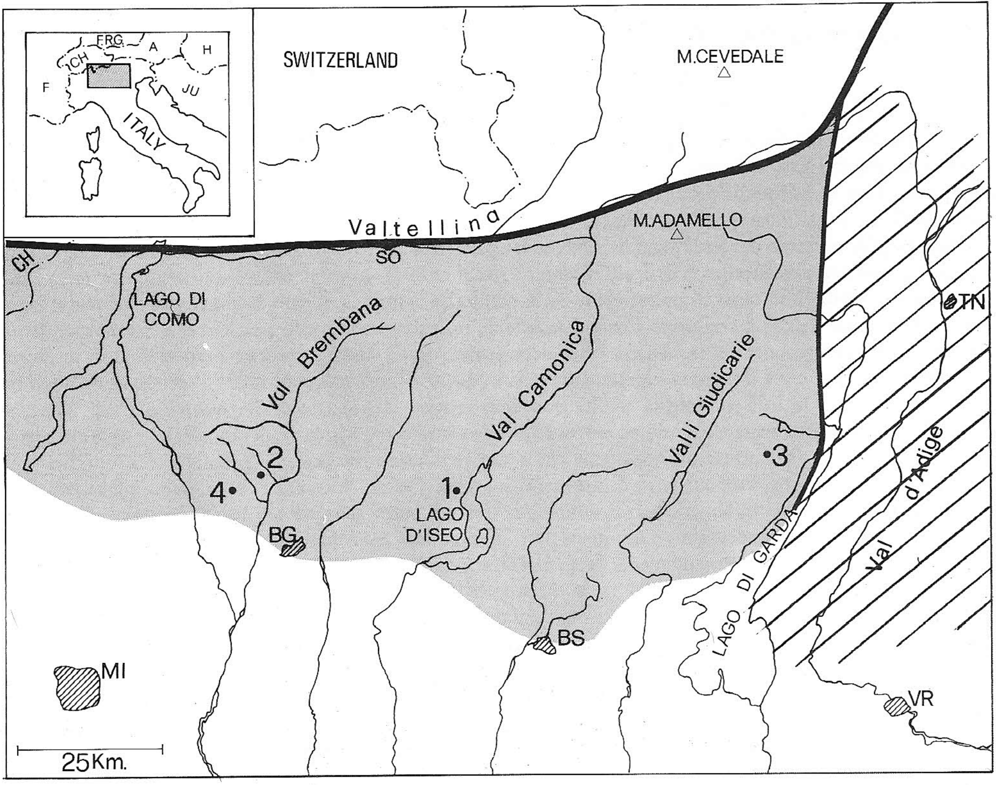

Fig. 1 - Location map of the study area withe indication of the main paleogeographic elements. Grey area) marly Rhaetic formations of the Lombardian Basin; diagonal ruling) carbonate, peritidal facies of the Trento Platform. Featured sections: 1) Fonteno; 2) Laxolo; 3) Tremalzo; 4) Valcava.

Introduction.

The data upon which this article in based were collected from the shale-rich Rhaetic (upper Triassic) formations of the Western part of the Southern Alpine Region (Fig. 1). These Rhaetic facies of the Lombardian Basin were deposited in a locally deep environment, but always in close proximity to carbonate platforms; the successions also indicate a strong terrigenous influence.

The depositional theme is very complex, being controlled by many interacting factors. Climate affected carbonate production and argillaceous supply, whilst bathymetric fluctuations controlled the generation of shallowing-up vertical sequences in shallow water areas and the interaction between carbonate platforms and adjacent basins. The sum of these factors governed the deposition of repeated asymmetric cycles (Fig. 2) consisting predominantly of limestone-marl couplets (Fig. 3) in which the limestone beds show a thickening-upward arrangement. In a former work (Masetti et al., 1988), metric-scale marl-limestone cycles were described from the Rhaetic formations of the "Dolomiti di Brenta" and a climatic origin with a eustatic component was suggested for their genesis.

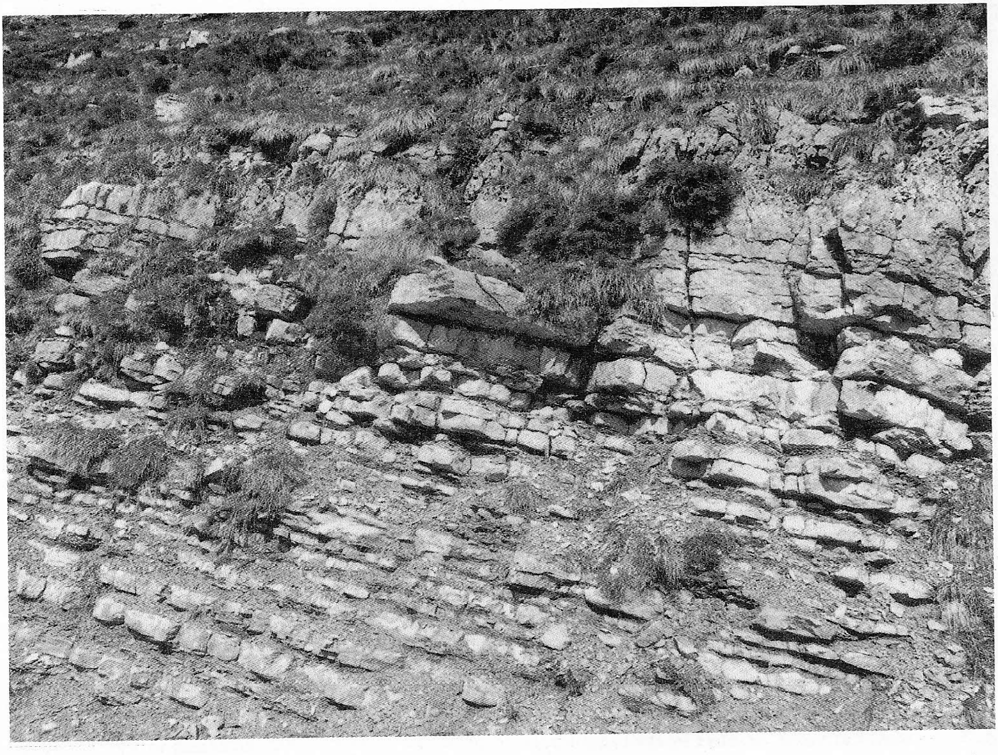

Fig. 2 - An example of the Rhaetic asymmetric cyclicity. Note the thickening-upward trend of limestone layers reflecting the enrichment in micrite.The visible thickness is about 6 metres. Road from Tremalzo Pass to Vesio (Brescia Province).

The purpose of this new paper is to unravel the complex array of sedimentary factors controlling the deposition of the Rhaetic formations and to give a genetic model for the asymmetric cyclicity, which is a ubiquitous feature of these shale-rich facies in the Alpine chain. To do this we have had not only to analyse the cycle periodicity in a vertical sequence but have also had to examine the lateral relationships between different environments by using facies analysis criteria. As mentioned above, this contribution is mainly focussed on evidence collected in the Southern Alps; however, much information has been collected from other areas and we consequently believe that the ideas presented here are reconciliable throughout the whole of the Alpine and Apennine chains.

Stratigraphic framework.

During the Norian, the Southern Alpine and Austroalpine regions experienced tectonic movements, mainly distensive in character (Bernoulli, 1964; Assereto & Casati, 1965; Bosellini, 1965), which dissected the widespread Dolomia Principale carbonate platform into a series of peritidal highs interspersed with partially anoxic basins. Such

Fig. 3 - Marl-limestone couplets in the central portion of the asymmetric cycle illustrated in Fig. 5A. (The circle indicates a hammer used as a scale). The sharp top-surface of the micritic layers is a consequence of the vertically adjacent marl layers preventing the further upward ejection of carbonate-rich waters. Road from Laxolo to the Forcella di Berbenno (Bergamo Province).

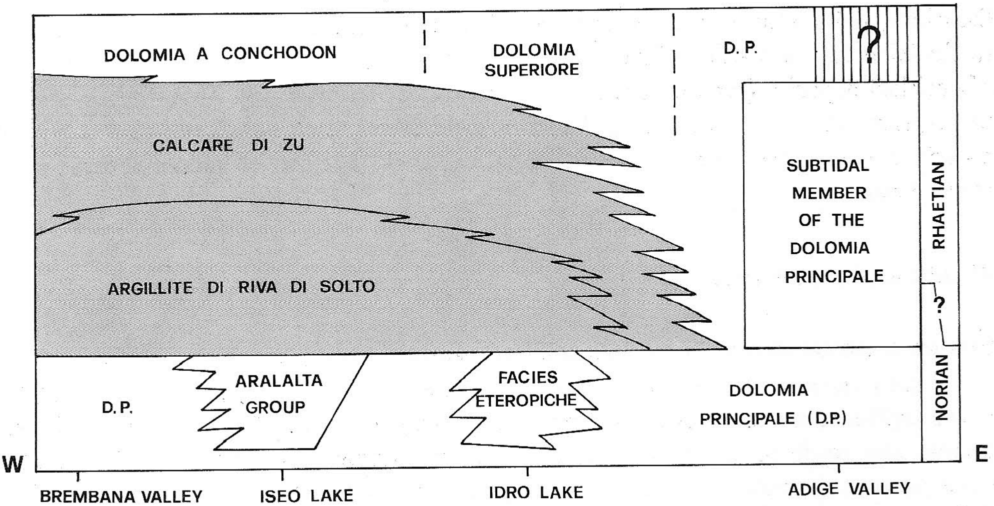

Fig. 4 - Chronostratigraphic scheme of the Norian-Rhaetic formations through the Lombardian Basin and the adjacent platform areas. The grey part indicates the marly Rhaetic formations.

small basins, characterized by thick fully carbonatic deposits (Facies Eteropiche, Boni & Cassinis 1973; Gruppo dell'Aralalta, Jadoul, 1986) are the forerunners of the wider Rhaetic basin (Fig. 4). These limestones are often rich in organic matter, especially near the contact with the overlying Rhaetic facies.

The initiation of the Rhaetic depositional sequence was marked by a generalized bathymetric deepening, and by an abrupt introduction of terrigenous mud that fossilized the older, wholly carbonate, paleogeography. This event began the sedimentation of the organic-rich Argillite di Riva di Solto, which consists mainly of argillaceous shale, with subordinate marls and micritic limestones, deposited in rather deep and poorly oxygenated environments.

The Rhaetic basinal successions can be divided into a general three-fold scheme: a lower, almost exclusively argillaceous unit, making up the lower part of the Argillite di Riva di Solto; a central portion, of which the most characteristic feature is the superposition of repeated asymmetric thickening-upward cycles, pon which this study is focussed; and an upper, wholly carbonate portion. This gradual enrichment in limestone provides the transitional boundary between the Argillite di Riva di Solto and the overlying Calcare di Zu (Gnaccolini, 1965). The accumulation rates of these facies were extremely high, possibly exceeding 500 m/Ma after compaction in the Iseo Lake depocentre. Much lower sedimentation rates characterized other shallower areas, such as the Brescia Province. At the top of the Calcare di Zu the terrigenous input completely stopped and the Rhaetic succession ends with shallow water carbonates (Dolomia a *Conchodon*, Corna).

The Lombardian Rhaetic basin was bounded to the west and east by muddy shallow water carbonate platforms. In particular, on the eastern platform, the sedimentation of the Dolomia Principale continued, generally characterized by a peritidal cyclicity

(Bosellini, 1967). However in the upper portion of this formation, which can be referred to the Rhaetic, the so-called "subtidal facies" are developed, which are completely free of peritidal deposits. (Hardie et al., 1986; Bosellini & Hardie, 1988). This Rhaetic member consists of hundreds of stacked metre- scale cycles, each consisting of a subtidal muddy unit directly overlain by a subaerial cap rock that carries vadose cement and teepee structures.

Rhaetic asymmetric cyclicity.

General characteristics of the cyclicity and environmental setting.

Each asymmetric cycle (Fig. 5) can itself be seen to consist of three parts: a) A lower argillaceous unit consisting almost exclusively of black or dark grey shale. b) A middle unit made up of repeated superposed limestone-marl couplets, with the limestone portion showing a general thickening-upward arrangement. c) An upper, wholly carbonate unit.

In general, the asymmetric cyclicity is on a metric scale, with a minimum thickness of 3 m and a maximum of 30 m, depending predominantly on local sedimentation rates. The upper and lower limits of each cycle are generally very sharp.

The depositional environment of the Rhaetic formations can generally be referred to gently sloping muddy ramps connecting peritidal highs to basinal areas. The lateral and vertical transitions between carbonate platforms and terrigenous basin are commonly very gradual, without the interposition of high energy margins or built-up bodies (Stefani & Golfieri, 1988). In the deep areas, sediment gravity flow deposits fed by platforms are completely unknown. This ramp morphology is not necessarily at variance with active syn-sedimentary tectonics; the strong sediment supply draped fault surfaces preventing their morphologic expression as steep, by-pass scarps, thus smoothing out the topography.

Variations within the asymmetric cycles.

The following descriptions are from some sample localities in Lombardy (Fig. 5). These asymmetric cycles are not coeval; they were chosen to show how the general or-

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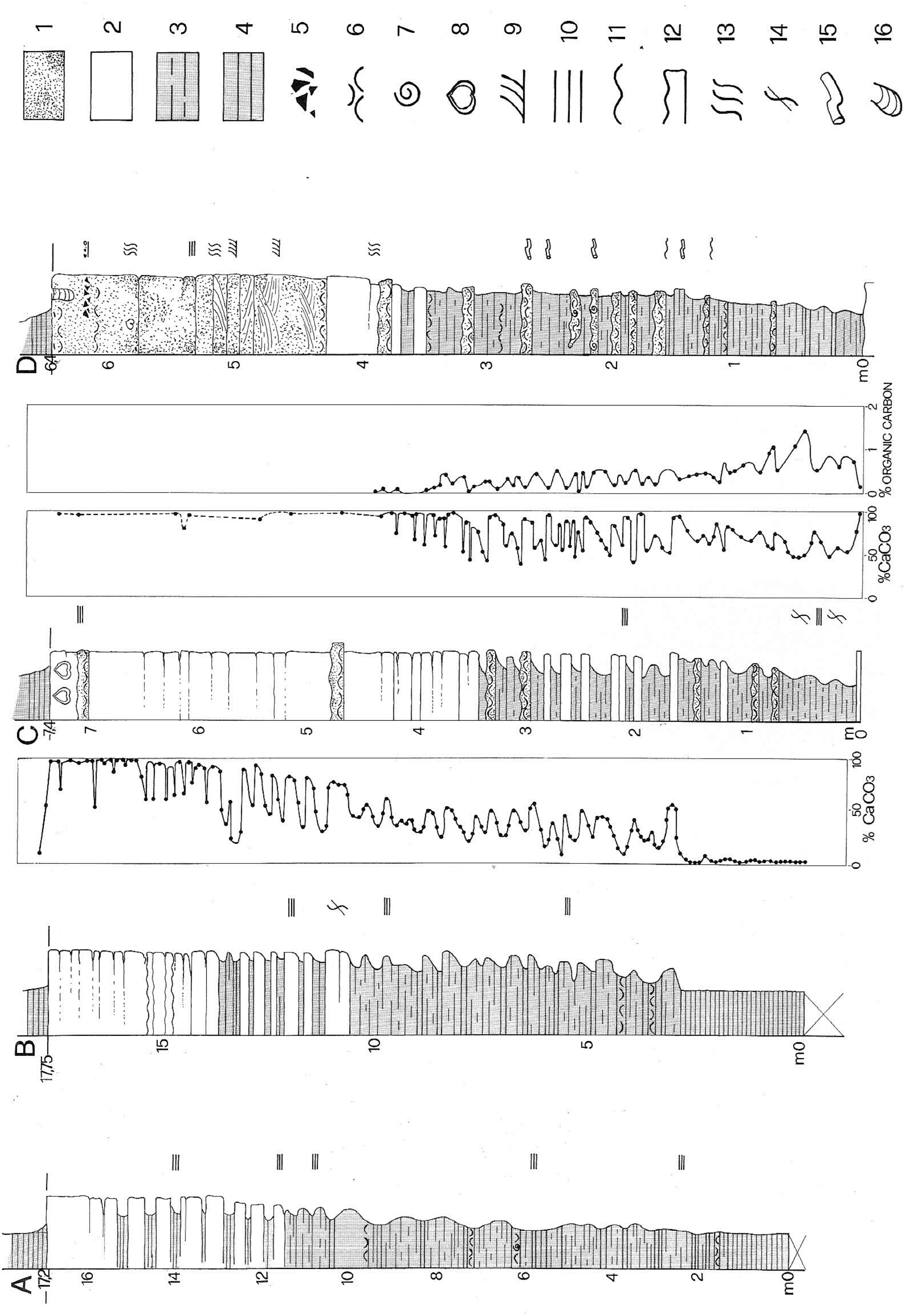
Fig. 5 - Variations within the Rhaetic asymmetric cycles. (Note the various scale of the drawings). The clear differences in thickness were mainly related to differential subsidence. The deepest cycles are wholly muddy (A, B, C) and show a gradual upward enrichment in carbonate. The coarsening- and shoaling-up expression of the shallowest one (D) suggests all cycles reflect the same depositional trend. The calcimetric log of Laxolo cycle (B) shows clear calcimetric fluctuations superimposed upon a gradual enrichment in carbonate. The logs of Tremalzo cycle (C) exhibit an inverse covariation of carbonate and organic carbon. 1) Grain supported limestone; 2) mud supported limestone; 3) marl; 4) claystone; 5) intraclasts; 6) bivalves; 7) gastropods; 8) megalodonts; 9) cross stratification; 10) parallel lamination; 11) erosional base; 12) storm layer; 13) biogenic amalgamation; 14) unbioturbated layer; 15) horizontal burrow; 16) *Diplocraterion*.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ganization described above varies locally as a consequence of decreasing depositional depth.

In the deepest sectors of the Rhaetic basin (Fig. 5A, Fonteno section, upper part of the Argillite di Riva di Solto in its stratotype on the West side of the Iseo Lake), the overall grain size of the asymmetric cycle is always very fine, with the exception of benthic fossil remains. Referring to the three fold division, the lower portion of the cycle consists of fairly pure claystone with subordinate argillaceous marls, which are poor in mollusc remains. The middle unit consists of repeated alternations of argillaceous and slightly calcareous marls with gradational boundaries. The upper carbonate-rich unit consists of decimetric alternations of marls and micritic limestone beds of varying purity. Geochemical analysis shows that carbonate rich layers are poor in organic matter and vice versa. There is generally a good direct correlation between the iron and the organic carbon concentrations. SEM studies show that the clay assemblages appear to contain remnant detrital illite, as well as being rich in a later, diagenetic illite phase. The organic matter is mainly terrestrial in origin, though the high diagenetic rank would tend to emphasize the woody tissue content. These facies were deposited in a deep, poorly oxygenated, and rapidly subsiding sea floor in the Iseo depocentre, and underwent mini-

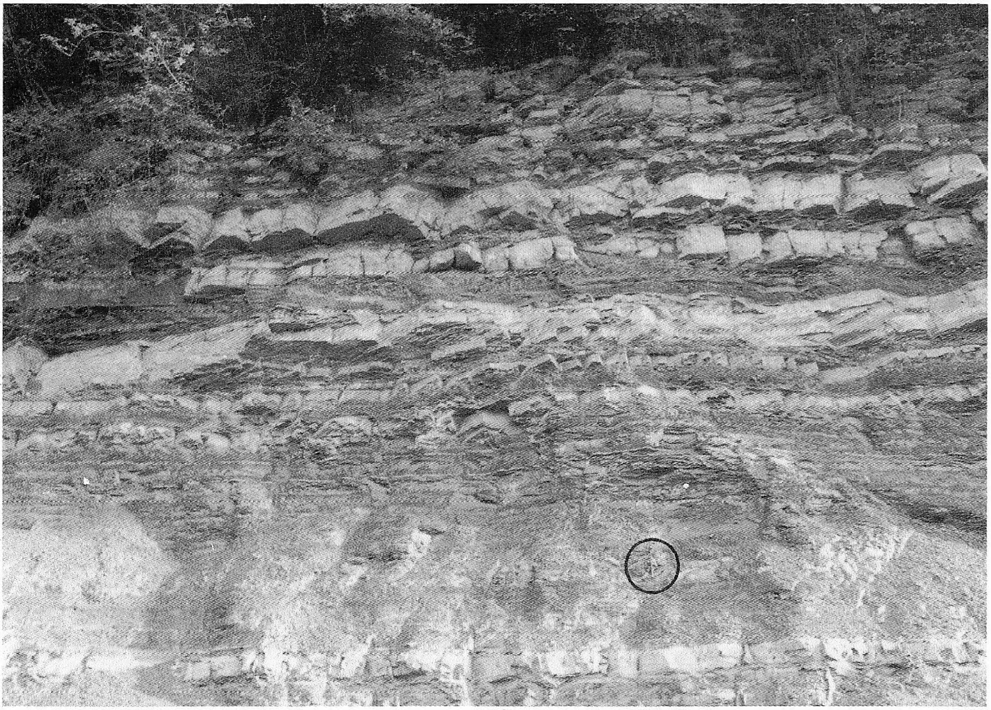


Fig. 6 - The asymmetric cycle near Laxolo illustrated in Fig. 5B and described in the text.

mal reworking. As a consequence, the cycles here are very thick (average = 30 m) and originally contained abundant organic material due to the low energy conditions and minimal primary oxidation.

Near the village of Laxolo (Brembilla Valley, Fig. 5B), the arrangement of asymmetric cycle outcropping in the upper portion of the Argillite di Riva di Solto (road from Laxolo to Sella di Berbenno) is similar to that previously described for the Fonteno section. However, the shallower sea-floor allowed the deposition of millimeter-scale bioclastic storm layers which are more frequent in the lower part of the cycle.

The faunal associations in the marls of the lower portion and in the limestones of the upper member are very different. The fossil assemblage of the marls is dominated by small endobiontic pelecypods such as *Nucula*; coprolites such as *Bactryllium* are also very common. The fossil association in the upper portion of the cycle is conversely dominated by epibiontic pelecypods such as *Pinna* or *Cassianella*. Similar contrasting faunal associations such as these were described by Gaetani & Tintori (1979), a few tens of metres higher in the stratigraphic succession.

Diagenetic and weathering patterns tend to emphasize the lithological alternation in the central part of the cycle, but, as can be seen from the detailed log (Fig. 5B), clear calcimetric fluctuations occur throughout the entire cycle, superposed upon a general upward enrichment in carbonate. This cycle was deposited in a low energy, deep ramp environment. The concentration of thin storm bioclastic layers in the lower part of the cycle suggests an accumulation of events during a period of reduced sedimentation. The major faunistic diversification in the upper calcareous unit is clearly related to changes in primary paleoecological factors, such as alternations in the mechanical properties of the sea-floor or an increase in the water oxygenation.

The asymmetric cycle (Fig. 5C), seen near Tremalzo (Lombardy- Trentino border, at the beginning of the gravel road to Vesio), was deposited in a much shallower environment than those previously described. The sea-floor was clearly beneath the fair weather wave base, but was strongly reworked by the largest storm waves that emplaced well developed storm coquinas, sometimes more than a decimetre thick, in the central portion of the cycle (Fig. 9). However, the lack of day-to-day wave reworking and of any strong currents allowed the quiet deposition of both argillaceous and calcareous muds, even in the upper calcareous unit. The upper member of this asymmetric cycle consists of grey micritic limestone shifting from mudstone to wackestone-packstone with abundant pellets, fine micritized mollusc bioclasts and a few echinoderm remains. Towards the top, there are large endobiont pelecypods with thick closed valves, sometimes in life position; the top of the cycle is extremely sharp. The calcimetric and organic carbon logs (Fig. 5C) clearly show that there is an inverse covariation of carbonate and organic carbon such that the marly layers are richer in organic debris than the adjacent limestones. However the relatively high diagenetic rank may again have severely modified the amount and nature of the organic carbon.

The asymmetric cycle (Fig. 5D) outcropping in the uppermost marly Rhaetic along the quarry road that descends from Valcava to Burligo (the Albenza Mountain)

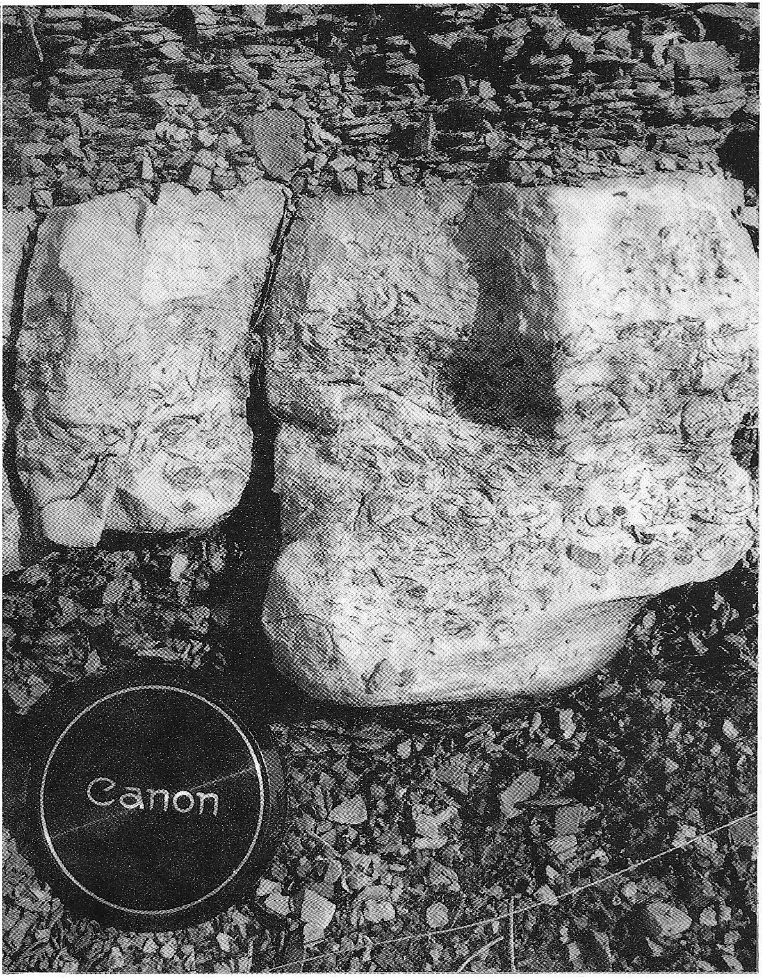


Fig. 7 - Storm layer in the middle part of an asymmetric cycle outcropping in the northern slant of Tremalzo Mountain. Note the erosional base with gutter casts penetrating into the underlying marls. The lithology is a pelecypods coquina passing upward into a calcarenitic unit.

was deposited in a shallow environment, well above storm wave base but beneath low tide level. The lower portion of the cycle consists of bioturbated marls, bearing only a poor association of small pelecypods which are sometimes concentrated in thin storm layers. The central portion of the cycle shows irregular alternations of limestone beds with calcareous marls; some of these beds show micritic textures, but the majority were produced by storm concentration of bioclasts. The "proximality" of these storm layers clearly increases upwards. Large burrows descend from both the micritic and bioclastic layers into the underlying marls. In the central part of the upper calcareous member there is a thick stratoset of peloidal grainstone with concave tangential foresets produced by unidirectional traction currents. The remaining beds of this unit are dominated by fine peloidal limestones with rare storm intercalations. The top of the unit is very sharp and is marked by a metallic oxide crust, bored by hard substrate dwelling organisms. The increasing tempestite proximality, coarsening - up trend and development of unidirectional traction currents in the upper unit, are related to the shallowing - up evolution of these cycles, which is not obvious when looking at the deeper environments. The shallow sea bottom was reworked too regularly by the action of waves and currents to properly record the simple marl-limestone couple; the asymmetric cyclicity is on the other hand clearly developed. The sharp top of the cycle is probably related to a non-depositional hiatus developed between two adjacent cycles. The shallowing-up trend of the asymmetric cycles is also confirmed by the finding of stromatolitic and desiccation structures at the top of the cycle in the shallowest areas of the basin (Engadine Dolomites and Trentino-Lombardy border).

There are a few variations upon the themes described above which help to clarify the interpretation of the cyclicity given later in the paper: in the Bergamasc Prealps, the lowermost three or four asymmetric cycles in the Argillite di Riva di Solto often do not show the superimposed marl-limestone couplets in the centre of the cycle, but instead show a smooth and gradual increase in carbonate content from argillaceous shales at the base to pure micritic limestones at the top. In addition,we can rarely identify gradational tops to the cycles over two or three metres, which give a partly symmetric organisation.

Concluding remarks.

Facies analysis clearly shows that the asymmetrical cycles have a coarsening- and shallowing-up expression in the most peripheral areas of the Rhaetic basins and we can assume that all the cycles reflect this same depositional trend. The bathymetric fluctuations produced coarsening-up cycles in shallow areas, but only repeated asymmetric fluctuations of the carbonate mud content in the deeper sediments. It is thus clear that whatever caused the gradual enrichment of carbonate mud during each basinal cycle, did so during a shallowing-upward evolution of the basin.

Discussion on marl-limestone rhythms.

The importance of diagenesis.

Primary origin.

There is much evidence to suggest that these Rhaetic marl- limestone alternations are of a primary sedimentary nature. Comparing different lithological layers, we can often observe not only strong geochemical fluctuations, but also important faunal differences; burrows regularly introduce limestone into marls and vice versa; bedding is sometimes deformed and folded by synsedimentary structures such as slumping, loading and water escape, especially in the lower part of the Rhaetic sequence. In addition, there is a strong correlation at different sites, between the total thickness of the Rhaetic deposits and the corresponding thickness of each asymmetric cycle, which strongly suggests a primary origin. Finally, diagenetic unmixing, if not controlled by primary compositional variations, is unlikely to have produced a form of cyclicity with such a demonstrably regular pattern over tens of metres with regard to the elementary couple, and several hundred metres of section for the asymmetric cyclicity.

Diagenetic overprinting.

It is clear, however, that diagenetic overprinting took an important part in producing the present distribution of calcium carbonate, at least on a decimetric scale. In the clay-rich lower member of the asymmetric cycle there are often diagenetic calcareous nodules, the surrounding lithology appearing to be depleted in carbonate for several decimetres. More carbonate-rich beds show transitional boundaries, but their profile becomes gradually sharper upwards through each cycle. The sharp top of similar beds (Fig. 3) in the central portion of the cycle is probably related to the low permeability threshold in the overlying marly bed that prevented the upward ejection of carbonate rich waters during compaction. In the upper calcareous member, strong diagenetic mobilization from the interbedded clay layers generated the sharp profile of limestone beds.

In the Tremalzo and Valcava sections, compaction measurements based on deformation of bioturbation structures (Ricken, 1986) give values of 65-75% for compaction in argillaceous marls against 40% or less in the interbedded micritic limestone. If the boundaries between adjacent lithologies are gradational, it is found that compaction values also change gradually, whilst at sharp boundaries, there is an abrupt variation in the compaction ratio between the two successive lithologies. These different characteristics are clearly related to diagenetic carbonate leaching and reprecipitation; a significant component of the carbonate was mobilized from the more clay-rich horizons to purer calcareous layers, where early calcite cements were precipitated in such a way that the levels enriched in carbonate underwent little compaction (Ricken, 1986). Thus, whilst before diagenetic ex-solution the contrast in carbonate content between adjacent layers of a couple would have only been a few percent, subsequent diagenesis emphasized this fluctuation to around 20% or more. Detailed analysis shows that some of the calcareous layers in the lower marly unit derived from the diagenetic "fusion" of formerly separated calcareous beds, which were originally subdivided by marl-rich levels. This kind of diagenetic modification partly reduced the thickening-up trend of calcareous beds throughout the cycle.

Diagenetic carbonate redistribution has strongly exaggerated small primary compositional fluctuations but does not prevent or invalidate the analysis of sedimentary cyclicity: we are thus still able to investigate the original depositional dynamics.

Steady state versus event sedimentation.

Many lines of evidence support the supposition that the origin of the marl-limestone rhythms was related to gradual changes in the carbonate/clay ratio, rather than individual discrete depositional events, such as turbidites or tempestites. When not enhanced by diagenetic unmixing, the boundaries between beds are always gently transitional, with the lower contacts never showing erosional features such as gutter of flute casts, even in unbioturbated portions. The calcareous layers often appear to be deposited by many small episodes, each one creating a single- lamina microbed (Campbell, 1967). Another important point against a local "event" origin for the lithological rhythms, is the fact the single asymmetric cycles may be correlatable throughout the entire basin, with little or no proximal/distal variation from presumed source areas. On the other hand, it is clear that storm reworking was important in the shallower areas of the Rhaetic basin, introducing irregular calcareous bioclastic beds (Fig. 9) into the rhythmic marl-limestone succession and often obliterating this simple pattern by reworking the depositional couplets; the general trend of the asymmetric cycle nevertheless remained intact.

Compound signal model for the Rhaetic cyclicity.

The dual signal.

It is suggested that the Rhaetic cycles derive from the superposition of a low-frequency asymmetric signal of carbonate supply over a high frequency rhythm of clay input (Fig. 8). The calcareous supply was negligible at the base of the asymmetric cycle but increased upwards to reach a maximum at the very top, rapidly returning to zero at the base of the following cycle. This asymmetric fluctuation had superimposed upon it a high frequency fluctuation of argillaceous mud supply that produced the marl-limestone couplets on a decimetric scale. The thickness of each limestone interval between shale increases upward as a consequence of the steadily increasing amount of carbonate supplied per unit time. The lowermost part of the asymmetric cycle lacks these lithological couplets, since there was no carbonate being introduced into the depositional site. Hence, differing supply rates of argillaceous mud simply produced a single pure clay layer. This model is also supported by the existence of asymmetrical cycles completely lacking minor couplets.

Spectral analysis and dating consideration.

Power spectra (Fischer & Schwarzacher, 1984; Weedon, 1985) using both calcimetric and lithological features, were generated for a range of Rhaetic stratigraphic sections in order to test the relative importance of the different cyclic components in the compound "basinal" signal. The spectra are complex due to the presence of many harmonics which are related to the strong cycle asymmetry and the dispersion of couplet thickness. Despite this, the power spectrum of the Tremalzo section (Fig. 9) shows

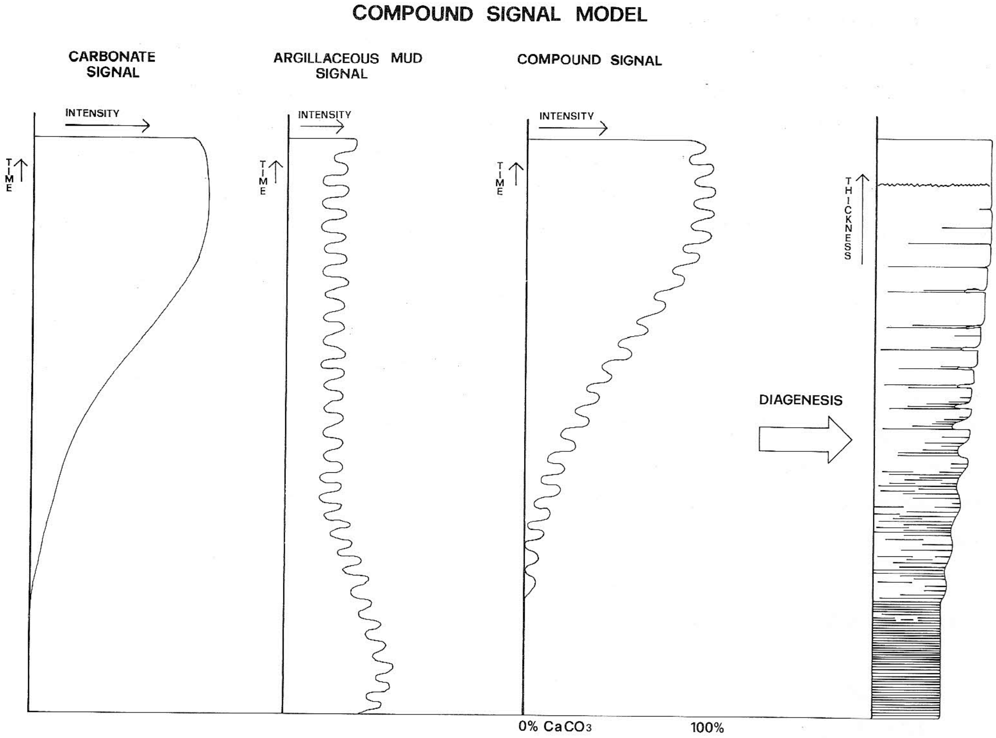


Fig. 8 - The compound signal model for the Rhaetic cyclicity. The asymmetric perturbation was generated by the interference of a high frequency sinusoidal argillaceous mud signal (centre) and a lower frequency asymmetric carbonate mud signal (left).

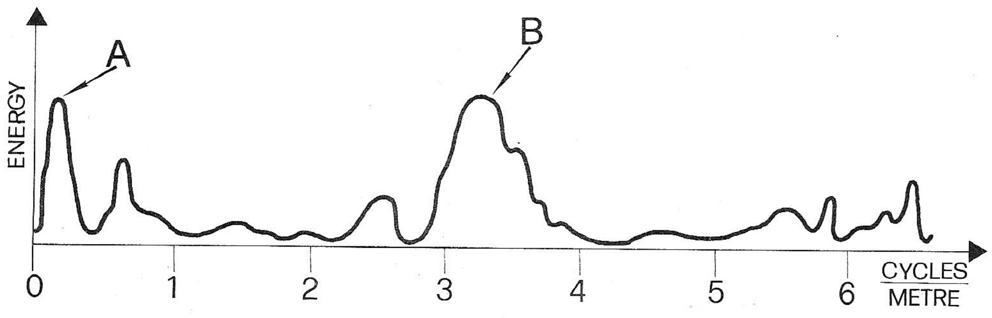


Fig. 9 - Power spectrum of a 26 m thick calcimetric log of the Rhaetic section outcropping along the road from the Tremalzo Pass to Vesio (Brescia Province). "Energy" values can be regarded as a function of the importance of the corresponding frequencies in the compound signal. The dispersion of the high energy peaks is partly related to the strong asymmetry of the cyclic signal. The peaks A and B correspond respectively to the major asymmetric cycle, and to the elementary couple.

that the ratio between the low frequency component corresponding to the asymmetric cycle and the high frequency peak related to the couplets is about 20. If the Rhaetic cyclicity is related to climatic fluctuations, then the frequency power peaks may possibly be related to some known paleoclimatic cycle. This ratio above is similar to that between the 413 Ka long eccentricity cycle and of the 20 Ka precession cycle. In the Rhaetic sequence, there are about 60 basinal asymmetric cycles. Therefore, these two paleoclimatic frequencies are not strong candidates for Rhaetic cyclicity since, according to recent dating, a duration of about 25 million years for the Rhaetic appears much too long.

There are many uncertainties concerning the chronostratigraphic "meaning" of the Rhaetic stage, or substage, due to the lack of suitable biostratigraphic markers. Some consider this stage as equivalent to the *Choristoceras marshi* zone, whilst others consider it as corresponding to both the *Choristoceras marshi* (above) and the *Rhabdoceras suessi* (below) ammonoid zones. According to our observations the Southern Alpine Rhaetic sections can often be subdivided on the basis of the foraminiferal content into two units: a lower "*Glomospira- Glomospirella*" zone and an upper *Triasina hantkeni* zone (Masetti et al., 1988). Ciarapica (1985) considered the *T. hantkeni* zone as an equivalent of the *C. marshi* zone. On the other hand Michalík (1980) also referred the underlying "*Glomospira*" unit to the Marshi Zone.

Recent chronometric scales record a duration of 4 Ma for the Rhaetic stage or substage (Odin & Letolle, 1982; two ammonoid zones), 5 Ma (Haq et. al., 1987; two ammonoid zones), or 6 Ma (Harland et. al., 1982; one ammonoid zone). In the Rhaetic facies of the Southern Alps there are about 60 asymmetric cycles, and therefore the mean duration of each cycle may well be in the range 100,000 and 80,000 years. Obviously, this value is a rough average with large uncertainties, and can only be used as an order of magnitude figure. If we assume, as a working hypothesis, a 100,000 years duration for the asymmetric cycles, each lithological couplet should cover a 5,000 years time span, a fluctuation in the "sub-Milankovitch" domain.

The provenance of the basinal sediments.

Argillaceous mud.

The mineralogical associations consist predominantly of illite with other subordinate clay minerals, and rarely, fine quartz grains, possibly of aeolian origin. This assemblage reflects a subaerial weathering of crystalline rocks in the provenance area. The size of the rare terrigenous grains is always very fine, never exceeding the size of fine silt. In non-bioturbated layers, the argillaceous mudstones often show thin parallel lamination, poorly visible in weathered outcrops. The deepest portions of the Rhaetic basins show a greater amount of clay-mudstones than the surrounding shallower environments, this is partly related to low density currents that carried clay muds downslope, possibly as flocculates. The general paleogeographic framework suggests a provenance from northern areas, although the detail of these areas is poorly known because of the strong alpine tectonic overprint. Tectonic movements, Rhaetic in age, are well known in many parts of the Alpine Chain, and it is probably these deformations that produced the structural highs that were the terrigenous source areas for both the alpine marly Rhaetic and the Germanic delta deposits over the so called "Eocimmerian" discordance (Ziegler, 1982).

Calcareous mud.

With regard the origin of the calcareous muds, we can identify three possibilities: a) a pelagic source, b) a local basinal production, c) an allochthonous source from shallow platformal areas.

a) The calcareous muds appear not to have originated from pelagic sources for a number of reasons. Firstly, SEM studies failed to reveal any evidence of the remains of calcareous nannoplankton tests, nor did normal petrographic methods reveal any debris with an open sea source. Planktonic and nektonic organisms, such as radiolarians or ammonoids, are almost completely unknown in Italian Rhaetic facies, except for the La Spezia region, where we have observed rare, small ammonoids. In addition, no known pelagic source would have been able to support such a high sedimentation rate as the Rhaetic one, especially since in the upper Triassic, calcareous nannoplankton were at a very early evolutionary stage and comprised only a few species. Lastly, there is an obvious lack of a mechanism for regularly varying the pelagic productivity 50 times or more over intervals of the order of 100,000 years.

b) The indigenous benthic productivity was active only in the shallow peripheral areas of the Rhaetic basins. Facies analysis shows that the great majority of the Rhaetic depositional environments in Lombardy were below the euphotic zone, so that algal benthos was negligible. In addition, marl-limestone alternations are also very common in the lower part of the Rhaetic facies in levels deposited in completely anoxic environments.

c) Sedimentary structures, in some cases, suggest a lateral transport of calcareous muds; thin, often micrograded, parallel laminations are likely to be found in the limestone. The thickness of the laminae varies from a few tens of microns to a millimeter or more. These features are probably related to low density suspensions, the "distal" expression of storm rinsing of muddy platforms. However the day to day off-platform transport of carbonate mud is thought to have been tidally influenced. With these facts in mind we suggest that the calcareous muds were produced on the neighbouring carbonate platforms and then exported into the adjacent basins.

A general genetic model for the asymmetric cyclicity.

Factors controlling the nature of the high frequency argillaceous mud signal.

There are three main factors that could have controlled the supply of terrigenous muds to the basinal areas: a) tectonic uplift that controlled relief in the hinterland; b) eustatic fluctuations that controlled flooding and exposure of coastal plain areas; c) climate that controlled weathering, erosional and transport processes. Of these, which factor oscillated with a period of a few Ka to produce the marl-limestone couple observed ?

a) Tectonic activity is the main factor able to control variations in terrigenous supply over long periods of time, but it is unlikely that tectonic movements could have produced regular fluctuations as high in frequency as the Rhaetic ones.

b) Regarding eustatic oscillations, it is clearly impossible that the slow eustatic changes caused by varying ocean-ridge spreading rates could have influenced either the high frequency or the major asymmetric Rhaetic cyclicity. In contrast, glacioeustatic fluctuations were relatively swift (see p. 418), especially in periods such as the Triassic, when ice accumulations were substantially less than those of the Pleistocene, and so the hysteresis of such ice systems was relatively low. Nevertheless from a hydrological point of view, glacioeustatic fluctuations as large and quick as those required to produce the Rhaetic couples are unlikely to have existed. In addition, such high frequency eustatic variations are not recorded on the adjacent peritidal platforms.

c) Profound climatic fluctuations can occur in geologically short intervals. Such rapid climatic fluctuations influence the input of continental clay by acting on drainage and vegetation cover; both factors control the fluvial delivery of fines into basins.

Thus, considering the nature of the argillaceous mud signal the above arguments demonstrate that rapid symmetric climate variations offer the best explanation for the high frequency Rhaetic rhythmicity. For instance, moist clay-producing periods could have alternated with dry periods: if we assume that the elementary couple is produced mainly by a climatically induced perturbation in the argillaceous input, then the same climatic variations could have also influenced the carbonate "factory" generating minor benthic productivity cycles.

Climatic cyclicity between the secular frequency band and the Milankovitch domain is poorly known, especially since it is often badly preserved in the stratigraphic record. Nevertheless a strong climatic periodicity of about 2,700 years, not far from that observed in the Rhaetic, is recorded in the Permian Castile Anhydrite of New Mexico (Anderson, 1984). The very high accumulation rate of the thick Rhaetic facies allowed the preservation of these high frequency fluctuations, whilst in the less subsiding and shallower areas this short periodicity was often reworked and destroyed by storm-waves and tractionary currents.

Factors controlling the nature of the low frequency calcareous mud signal.

High frequency climatic fluctuations can explain the genesis of the relatively small variations in the clay/carbonate mud ratio within the elementary couple, but not the origin of the major asymmetric cycle. As mentioned above, it is unlikely that climate variations would have been able to change the carbonate content from 0% at the bottom to roughly 100% at the top of the cycle, simply by acting on benthic carbonate productivity and continental erosion. In addition, on the basis of our present knowledge of the climatic behaviour of the Earth, it is unlikely that climatic trends as profoundly asymmetric as those required to produce the Rhaetic cyclicity could have existed. The calcareous mud input was strictly related to the productivity of carbonate platform ecosystems and to the efficiency of off-platform transport; hence we have to search in the platform ecological and sedimentological parameters for the driving force that governed the generation of the asymmetric cycles. Bathymetry is one of the most important factors controlling platform communities, but what was the relationship between the bathymetric fluctuations recorded on the shallow marine carbonate platforms and the Rhaetic basinal cyclicity?

The correlation between platform bathymetric fluctuations and basinal asymmetric cycles.

Hardie et al. (1986) and Bosellini & Hardie (1988) have described, in the Rhaetic portion of the Dolomia Principale, repeated direct subaerial exposure of subtidal muds, the so-called "diagenetic cycles". The absence of peritidal deposits rules out the autocyclic progradation of tidal flat edges (Ginsburg, 1971) as the cause of the exposure. These authors postulate a combination of small scale, high frequency eustasy and differential subsidence to explain the cyclicity and its internal variations. The period of these "diagenetic cycles" is longer than the periods involved in each of the well known, shallowing-up, peritidal cycle of other portions of the Dolomia Principale (Bosellini, pers. comm.). In the Middle Triassic of the Dolomites region, Goldhammer et al. (1987) describe metric-scale diagenetic cycles recording repeated exposure. These cycles are grouped into sets of 5 cycles, each set representing a lower frequency cyclicity with a hypothesized duration of about 100,000 years. As suggested by Goldhammer et. al. (1987) this Middle Triassic cyclic pattern is analogous to the Pleistocene sea level record, and as a consequence these authors suggest a glacioeustatic mechanism as predicted by the Milankovitch theory. We agree with the hypothesis of a glacioeustatic origin for both the middle and upper Triassic diagenetic cycles since tectonic movements are unlikely to have produced such a demonstrably regular cyclic patterns. Thus the traditional view of the Triassic as an ice free period is no entirely acceptable.

Subtidal-peritidal couplets in Upper Triassic carbonates are often grouped into sets of about three to five (Schwarzacher, 1948; Fischer, 1986; our personal observations in the Trento province). The bundle surfaces correspond to a subaerial exposure of large platform flats, often testified by residual paleosoils. We suggest that each bundle of shorter shallowing-up cycles corresponds to a single diagenetic cycle of Hardie et al. (1986) and Bosellini & Hardie (1988). The corresponding duration, according to Goldhammer et al. (1987) should be of 100.000 years. The stratigraphic registration of these bathymetric cycles is critically related to local factors, such as water depth or subsidence rates, and thus the lateral correlation of bathymetric cycles is not easy. As a working hypothesis we suggest that the bundled surfaces are recognizable over large areas while minor bathymetric episodes are fairly local irregular features, influenced by autocyclic mechanisms. We have previously proposed a duration of 100,000 years for the Rhaetic asymmetric cycles. Bearing in mind our assumption that these cycles were generated during a bathymetric drop, we suggest that they are basinal expression of eustatic fluctuations responsible for the platformal "diagenetic cycle" generation.

The model.

The sea-level changes described above indirectly controlled the sedimentary dynamics of the basinal areas by directly controlling the sedimentary behaviour of the shallow marine platforms. The cyclicity produced by these sea-level fluctuations is defined by different sedimentological features in different sedimentary environments. In the following section we will schematically describe the way in which a bathymetric fluctuation may have been able to produce both the platformal and basinal Rhaetian cyclicity previously described (Fig. 10).

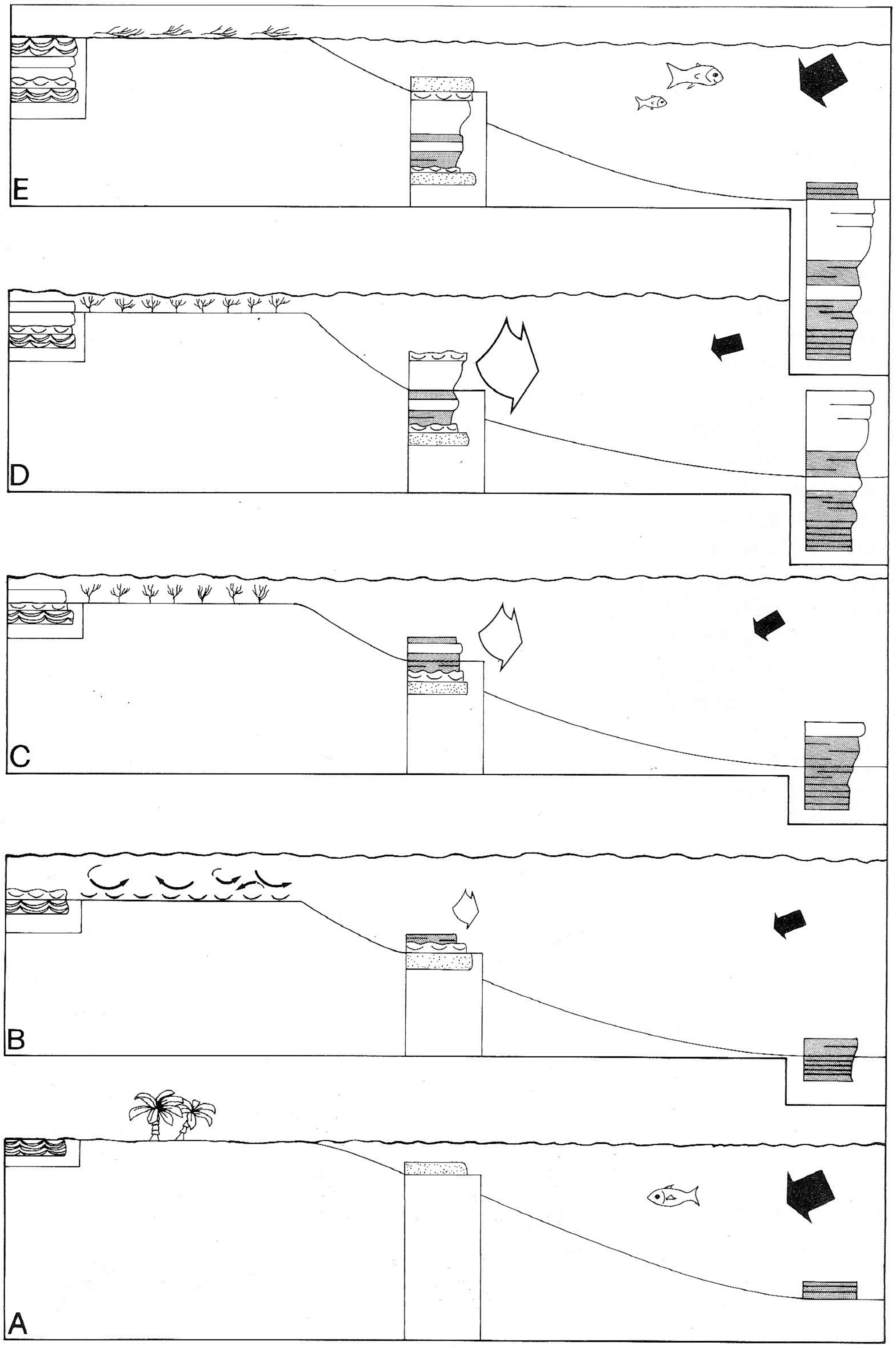
(A) When wide platform areas were under subaerial conditions, or exactly at the sea surface, the carbonate production was extremely low and the calcareous mud output was insignificant. Carbonate sedimentation persisted only in narrow grainy belts in the uppermost portion of the ramp, but the amount of carbonate mud produced was too negligible to influence the basin, and hence on the basin floor, the lower claystone layer was slowly deposited. A downward shift of the marine base level may also have increased the continental clay input derived from subaerial erosion, whilst the strong presence of argillaceous fines in the ramp environments could have inhibited benthic productivity. The subaerial exposures probably lasted several thousand years, which is the time-span required to produce the large, mature teepee structures described in the Rhaetic portion of the Dolomia Principale (Hardie et al., 1986; Bosellini & Hardie, 1988).

(B) A rise in the sea level re-submerged the platformal areas, but during the biological colonization and diversification stages the productivity remained low. The relative sea level increase generated by both the eustatic rise and the regional subsidence produced a quick environmental deepening as a consequence of the low sedimentation rate. On the platformal areas, a basal lag related to concentration and reworking of storm deposits through strong wave action, was deposited. The sea level rise drowned the narrow marginal areas in which the carbonate sedimentation was active during the low stand period and a non depositional hiatus or a thin marly layer was produced in these areas.

(C) The carbonate production gradually recovered supplying both the subtidal trap (Bosellini & Hardie, 1988) and the basinal thickening-up cycle with abundant calcareous mud. The sedimentation rate gradually increased producing a shallowing evolution on the growing platform, on the ramp, and in the recipient basin.

(D) The "room" created by the deepening phase was completely filled. The eustatic sea level started to fall again, but the productivity remained high. The calcareous muds were no longer stored in the filled platform since there was no more stratigraphic accomodation and so they were extensively exported off-bank into the adjacent basins.

(E) Finally the eustatic lowering, being faster than the subsidence, caused a new emergence of wide platformal areas which again temporarily destroyed the carbonate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mud "factory" by stopping the benthic platformal carbonate production. In the upper portion of the ramp, thin calcarenitic shoals were restored.

We have emphasized the role of sea-level fluctuations in controlling carbonate platform dynamics. However, the same eustatic fluctuations could have also influenced the terrigenous supply. Low stand periods supplied basins with more abundant terrigenous material in such a way that the calcareous and argillaceous supplies swung partly in opposition producing a thick lower shaly unit.

Discussion of the model.

Our model emphasizes the role of allocyclicity forced by eustatic variations, but it does not exclude the lateral migration and progradation of environments related to autocyclic mechanisms both on the platforms and in the shallowest portions of the Rhaetic basins. These autocyclic mechanisms likely to have played only a minor part in producing the Rhaetic basinal cyclicity. However, the traditional distinction between autocyclicity and allocyclicity (Beerbower, 1964) is not completely clear. Cycles related to the migration and progradation of sedimentary environments are undoubtedly very common in the geological record but often they are only a local response to allogenic fluctuations. In these situations, the ratio between the natural frequency of the system and the frequency of the allogenic forcing mechanism is the critical factor in determining the stratigraphic succession.

Carbonate production lags behind initial flooding; in our model a this lag produces an asymmetric cycle as a consequence of a symmetrical sea level fluctuation. Thus this asymmetry need not necessarily be the result of "geologically instantaneous relative base-level rises" proposed in the PAC theory (Goodwin & Anderson, 1985). Nevertheless, the pervasiveness throughout the geological record of regressive sequences containing few or no transgressive deposits tends to suggest the existence of widespread asymmetric eustatic fluctuations. Similar asymmetric fluctuations are well known in the Quaternary, especially from deep sea isotopic data. They testify to the swift melting of ice and a consequent eustatic rise with a 100,000 yr periodicity (Imbrie, 1985). Asymmetric shallowing-up eustatic trends have also been proposed for the Middle Triassic (Goldhammer et al., 1987). However, it is often difficult to decide if the asymmetric cycle was produced by an actual asymmetric fluctuation of the forcing environmental parameters or whether it was related to a sedimentary hiatus at its boundary.

Fig. 10 - Schematic sketch illustrating the generation of the basinal asymmetric cycle as a product of dynamic interaction between platforms and basins under eustatic control. The white arrows represent the carbonate exportation from the platform, while the black ones represent the terrigenous mud input. A) Platform exposure. Teepee formation and subaerial diagenesis of platform carbonate; calcarenitic shoal development in the upper ramp; terrigenous mud concentration in the basin. B) Platform flooding. Drowning of marginal shoals; start of a weak carbonate mud exportation into the basin. C) Recovery of platform. Shallowing upward evolution; increase of carbonate mud exportation into the basin. D) "Filled" platform. Maximum carbonate mud exportation into the basin. E) New exposure of the platform. Carbonate mud exportation ceases

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