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Discontinuities in carbonate successions: identification, interpretation and classification of some Italian examples

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Abstract

The growing use of unconformities as bounding surfaces for new types of stratigraphic units seems not to be matched by a corresponding effort on process-oriented researches on unconformities themselves. This paper aims at giving a contribution to classification and understanding of discontinuities in carbonate successions from the outcrop perspective, based on some Italian examples. A number of integrated criteria (geometry, sedimentology, diagenesis, biostratigraphy) is proposed to recognise stratigraphic breaks. Old terms are discussed and sometimes redefined, while some new terms are introduced. The term discontinuity surface (DS) is proposed as a general one to indicate any stratigraphic interface where an interruption of sedimentation can be proved. A DS can be characterized as a firm ground or a rock ground depending on its coherence at the moment of the renewal of sedimentation. Polygenic and simple omission surfaces are separated within firm grounds if a recognizable gap is either present or not; a third kind of firm ground, revealed only by biostratigraphy, has been called hidden discontinuity surface. Two categories of rock grounds are also distinguished: hard grounds and inherited rock grounds if, respectively, generation of the DS and/or deposition of the overlying sediments took place in the same environment of the underlying sediments or not.

A genetic interpretation for each type of discontinuity is proposed. The largest variety of DS's occurs in pelagic sediments. Some discontinuities (hard grounds and simple omission surfaces) are attributed to increased bottom-current activity during sea-level falls; others (polygenic omission surfaces and hidden DS's) are interpreted as submarine slide scars either with or without the overprint due to exposure on the seafloor. The DS's separating different facies (e.g. platform and pelagic ones) are interpreted to be due to tectonics. The relevance of the recognized DS's to sequence stratigraphy is briefly discussed.

1. Introduction

In recent years there has been a growing interest in using unconformities as tools to recognize and define new types of stratigraphic units such as: *depositional sequences* (Vail et al., 1977); *unconformity-bounded stratigraphic units* (Chang, 1975; International Subcommission on Stratigraphic Classification, 1987; Salvador, 1994) or *allostratigraphic units* (North American Commission on Stratigraphic Nomenclature, 1983). Allostratigraphic units and UBSU are rarely used.

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Depositional sequences, on the other hand, are largely employed, and hence 'unconformities and their correlative conformities' are commonly used to subdivide stratigraphic records into discrete sedimentary bodies (depositional sequences) whose architecture is interpreted as the result of global sea-level changes (e.g. Van Wagoner et al., 1988). In spite of this, few recent papers address directly the problems involved in the recognition, genetic interpretation, definition and classification of unconformities in outcrop (Shanmugan, 1989; Hesselbo et al., 1990; Doglioni et al., 1990; Walker and Eyles, 1991). Recognition and correct interpretation of a discontinuity may in fact be problematic for field stratigraphers. Difficulties arise in particular when trying to transfer some of the concepts born in seismic stratigraphy to the outcrop scale. Where outcrops are few and of poor quality, large-scale geometrical relationships cannot be observed and most of the criteria utilized by seismic stratigraphers are not available. Moreover, it has been shown that downlap and onlap surfaces, and drowning unconformities, apparent in seismic profiles, may correspond, at outcrop, to a quite thin stratigraphic unit below the seismic resolution power and not to an individual surface (Schlager, 1989, 1993; Erlich et al., 1990; Biddle et al., 1992; Cartwright et al., 1993).

During our field research on Mesozoic and Cenozoic carbonate successions in Northern and Central Italy (Clari et al., 1984; Della Bruna and Martire, 1985; Clari and Pavia, 1987; Martire, 1989, 1992; Dela Pierre and Bruzzone, 1991; Dela Pierre, 1992, 1994; Dela Pierre and Clari, 1994), we found a wide spectrum of discontinuities separating many different carbonate facies. Existing classifications, based on geometrical relationships of beds, were of little help, since most discontinuities would have been classified as paraconformities. Moreover, it was impossible in the field to rank and group the discontinuities according to their duration and genesis. The aim of this work is to document the occurrence of stratigraphic breaks in Italian carbonate successions in order to define criteria for their identification, classification, genetic interpretation and possible use in sequence stratigraphy.

2. Some considerations on unconformities and discontinuities

Names used by stratigraphers to define sedimentary breaks are relatively few. Nevertheless many conceptual and semantic problems arise from the different meaning and significance given to these names. Some terms need to be redefined in order to avoid confusion and misinterpretations.

The term most commonly used to describe stratigraphic breaks is *unconformity*. It was initially used to denote the contrast of attitude among strata, and is now generally known as angular unconformity (for an exhaustive discussion of its use see Schoch, 1989). In fact Grabau (1913) felt the need to define a new term, *disconformity*, in order to distinguish stratigraphic breaks in which there was no deformation of the underlying beds. Such terminology was universally used until Dunbar and Rodgers (1957) first attempted to define a more complete nomenclature for the description of sedimentary breaks. These authors assigned a more encompassing meaning to unconformity ('a temporal break in a stratigraphic sequence') and distinguished four cases on the basis of the angular relationships of beds and the geometry of the surface of unconformity. In spite of this proposal, an implication of angularity in the term unconformity persists in the British literature (e.g. Roberts, 1982).

Through time the attention of many authors shifted from the conceptual aspect of missing time towards the physical expression of this omission, that is to the surface separating two unconformable units. Unconformities became surfaces (*stratigraphic planes:* Weller, 1960; *surfaces of erosion and / or non-deposition:* ISSC, 1987; *surfaces of erosion:* Shanmugam, 1989) representing a significant temporal break in the stratigraphic record.

A quite different meaning was given to unconformity in sequence stratigraphy: a surface separating younger from older strata, along which there is evidence of subaerial erosional truncation (and in some areas, correlative submarine erosion) or subaerial exposure, with a significant hiatus indicated (Van Wagoner et al., 1988). Doglioni et al. (1990) more recently proposed to use the expression *stratal discontinuities* to indicate all surfaces underlining a break in the stratigraphic record. Stratal discontinuities are defined as "physical surfaces that either separate strata with different angularity or separate parallel strata where a significant hiatus is present" (Doglioni et al., 1990, p. 84).

A key point which is common to all definitions is the existence of a significant hiatus between the rocks below and above the surface of unconformity. The meaning of the word *significant* was never exactly defined: generally it is considered as being recognizable and quantifiable through biostratigraphic analysis, but biostratigraphic resolution does not have an absolute value. Equivalent time gaps, which are recognized and defined as unconformities in the pelagic domains of a basin may remain undefined or even unrecognized in the shallower parts due to the different resolution of pelagic versus shelf biostratigraphy.

On the other hand, field geologists need a general term for those surfaces which prove a break in the stratigraphic record, independently of the possibility of biostratigraphic quantification of the missing time therein. Moreover, the recognition and classification of stratigraphic breaks should not necessarily be based on the relative attitude of beds and biostratigraphic data but also on evidence derived from sedimentologic, diagenetic, taphonomic and ichnologic studies. Surfaces that show such evidence result in fact from very significant physico-chemical changes in environmental parameters: therefore they must be distinguished from simple bedding planes since they bear proofs of breaks in sedimentation relevant to stratigraphic interpretation.

Following Bates and Jackson's (1987) definition of discontinuity, we suggest the name *discontinuity surface* as the best general term for surfaces along which a sedimentary break occurs. A discontinuity surface (DS) is defined as follows: a surface which separates younger from older sedimentary rocks where evidence based on geometric, sedimentological, diagenetic, or biostratigraphic criteria, enables to infer a break in sedimentation, of whatever length.

The present definition of discontinuity surface differs substantially from that given by Bromley (1975) who limited the use of this term to the sedimentary breaks "... more minor in rank than disconformities".

For sake of simplicity, rocks, respectively, laying below and above the discontinuity surface will

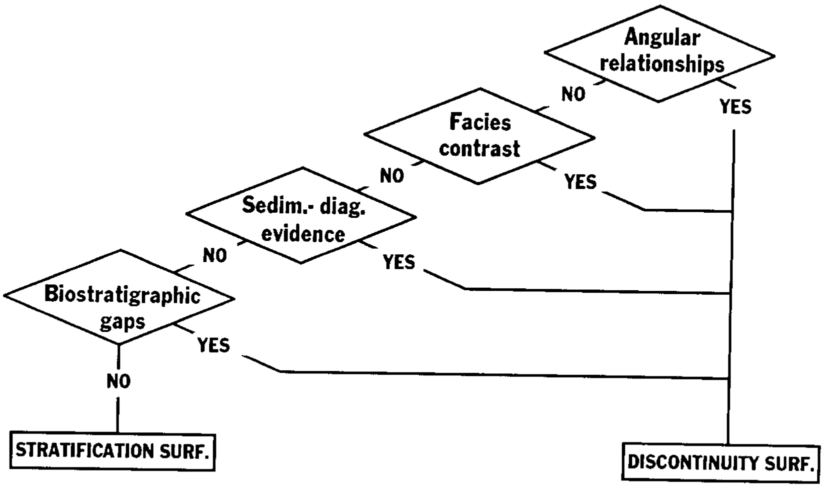


Fig. 1. Distinction between simple bedding planes and DS. Four criteria, progressively less evident in the field, have been taken into consideration.

be henceforth referred to as underlying rock (UR) and overlying rock (OR).

3. Recognition of a discontinuity surface in outcrop

In the Italian successions studied, the recognition of a DS in outcrop has been based on four kinds of evidence (Fig. 1): (1) geometrical relationships; (2) facies contrast; (3) depositional and/or diagenetic features; (4) biostratigraphic data.

3.1. Geometrical relationships

The presence of a DS is often revealed by the angular relationships between bedding planes of UR and OR or between the discontinuity surface and bedding. As a rule, only angular unconformities and disconformities with erosional truncation of strata are evident in limited outcrops, while onlap and offlap patterns are rarely recognizable. DS's underlined by angular relationships do not necessarily correspond to important regional discontinuities, as can be demonstrated by subsequent careful biostratigraphic analyses. This is the case, for example, for many discontinuities recognizable in slope settings due to downslope sliding of semi-consolidated sediments (Davies, 1977; Cook and Mullins, 1983).

3.2. Facies contrast

A compelling evidence for a DS is the direct superposition of facies contrasting the Walther rule; a sharp change in the depositional environment across the surface and a prolonged break in sedimentation may be reasonably inferred. Violations of the Walther rule can take place both within a depositional system or between two different depositional systems. In the first case, for example in a platform environment, the direct superposition of cross-bedded oolitic grainstones on lagoonal mudstones points to a sharp change in the environmental conditions which may suggest the presence of a DS. The relevance of this DS is however quite difficult to assess. The DS is obvious when sediments pertaining to two different depositional systems are directly superposed (e.g. platform facies on pelagic ones, Fig. 2).

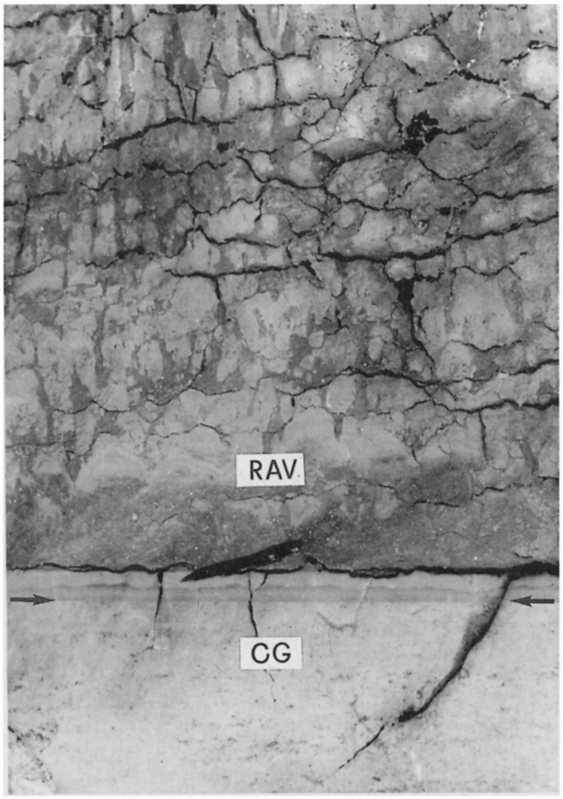


Fig. 2. Clear-cut DS (arrow) between Domerian lagoonal facies, characterized by dissolution vugs (Calcari Grigi, *CG*), and Bajocian pelagic nodular limestones (Rosso Ammonitico Veronese, *RAV*). The first centimetres of RAV are made up of a pink, flat, stromatolitic layer. Altopiano di Asiago, Southern Alps (pencil is 14 cm long).

3.3. Depositional and diagenetic features

A variety of depositional and diagenetic features characterize DS's. The major physico-chemical changes in the sedimentary environment, responsible for the interruption of sedimentation, deeply affect sedimentary and diagenetic mechanisms as well as biological behaviours. DS's may develop both in submarine and subaerial environments. The most common evidence for submarine discontinuities are: erosional truncation of grains

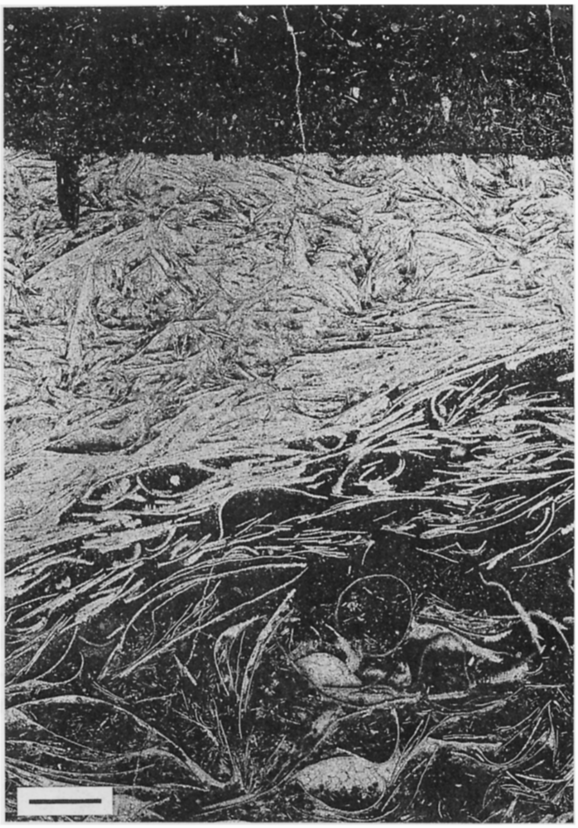


Fig. 3. Bioerosion (probably due to achrothoracic cirripeds) along a DS (HG) separating an early cemented thin-shelled bivalve coquina from wackestones with sparse, fine bivalve debris. Middle Jurassic RAV, M. Lessini, Southern Alps (scale bar = 2 mm).

and cements (Fig. 3) or boring and encrusting organisms along the surface; neptunian dykes in the UR; stainings, crusts and nodules of authigenic minerals (Fe and Mn oxides, glaucony, phosphates). The most common features indicating the presence of a DS due to emersion are: root horizons, karstic surfaces, palaeosoils and bauxitic horizons.

Further evidence for a DS may come from the contrast between compactional features of UR and OR (e.g. stylolites in the UR versus fitted fabrics and/or dissolution seams in the OR: Buxton and Sibley, 1981; Bathurst, 1987) showing that only the UR suffered an early cementation phase.

3.4. Biostratigraphic data

Biostratigraphic analysis is essential to assess the temporal importance of a DS, and may be the only means available to identify the existence of a discontinuity in those instances in which all other kinds of evidence are lacking. Care must be taken, however, in separating through taphonomic criteria, reworked fossils which may bias the evaluation of the sedimentary break (Fernandez Lopez, 1985, 1991; Gomez and Fernandez Lopez, 1994). In fact, the failure to distinguish reworked fossils in the OR palaeontological associations results in the underestimation of the chronostratigraphic gap.

4. Types of discontinuity surfaces: firm grounds, rock grounds and other grounds

Some simple field criteria allowed to differentiate and classify discontinuities in Italian successions without resorting to difficult and time-consuming evaluations about environment, genetic processes and duration of gap. They are: (a) degree of hardness of the UR at the renewal of sedimentation; (b) contrast versus similarity of facies between UR and OR.

Studies on both present-day and fossil environments have resulted in the definition of three main types of seafloors: (1) soft grounds; (2) firm grounds; and (3) rock grounds (Seilacher, 1981).

(1) *Soft grounds* never experienced any kind of process leading to the acquisition of a certain degree of coherence and are characterized only by deposit-feeder burrows (e.g. *Chondrites*, *Zoophycos*; Bromley, 1975). Sedimentary surfaces showing uniquely soft-ground features are obviously not often encountered along DS's except for special situations, as will be discussed later.

(2) *Firm grounds* typically contain a network of burrows, which are up to several centimetres in diameter (e.g. *Thalassinoides*; Bromley, 1975; Fürsich, 1979) revealing the transition to an ecosystem dominated by suspension-feeding organisms. According to Bromley (1990), the stabilization of the sediment is due only to dewatering and compaction during very shallow burial with-

out any cementation. A subsequent erosion leads to the exposure of a firm ground. In contrast, other authors think that some cementation may take place before or during firm-ground burrowing (e.g. Kennedy and Garrison, 1975; Brett and Brookfield, 1984).

Regardless of how they formed, DS's corresponding to ancient firm grounds have been called *omission surfaces* following Bromley (1975, 1990). When the faunal content of UR and OR is studied in detail, two different cases can be further distinguished. In the first no gap between UR and OR is detectable, even with the most refined biostratigraphic scale. In the second case, a gap, obvious in terms of missing biozones, is present despite the absence of all sedimentological evidences of a prolonged exposure at the sediment–water interface (Figs. 4 and 5). These two cases cannot be distinguished directly in the field, since both appear as omission surfaces with firm-ground features. Nevertheless, they result from two different processes and thus need to be distinguished. We used the term *simple omission surface* (SOS) for the first and *polygenic omission surface* (POS) for the second type because there is no simple mechanism which can explain a very long gap underlined only by firm-ground features.

A third type of DS could be distinguished from simple bedding planes only by means of the significant biostratigraphic gap detectable along them. Even though they show no evidence of firm grounds, a certain degree of firmness has to be inferred as will be discussed later (Figs. 4 and 6). This particular kind of DS is called *hidden discontinuity surface* in analogy with the 'hidden hiatus' of Hadding (1958).

(3) *Rock grounds* correspond to seafloors along which well-lithified sediments were exposed. Evidence of UR lithification are: the presence of encrusting organisms, borings, neptunian dykes, and truncation of rigid bodies, like shells and cements (Fig. 3). Two terms, hard ground and rock ground, have been used in the literature to indicate such hardened seafloors. The term hard ground was introduced, during the HMS *Challenger* cruise, to indicate rocky seafloors which

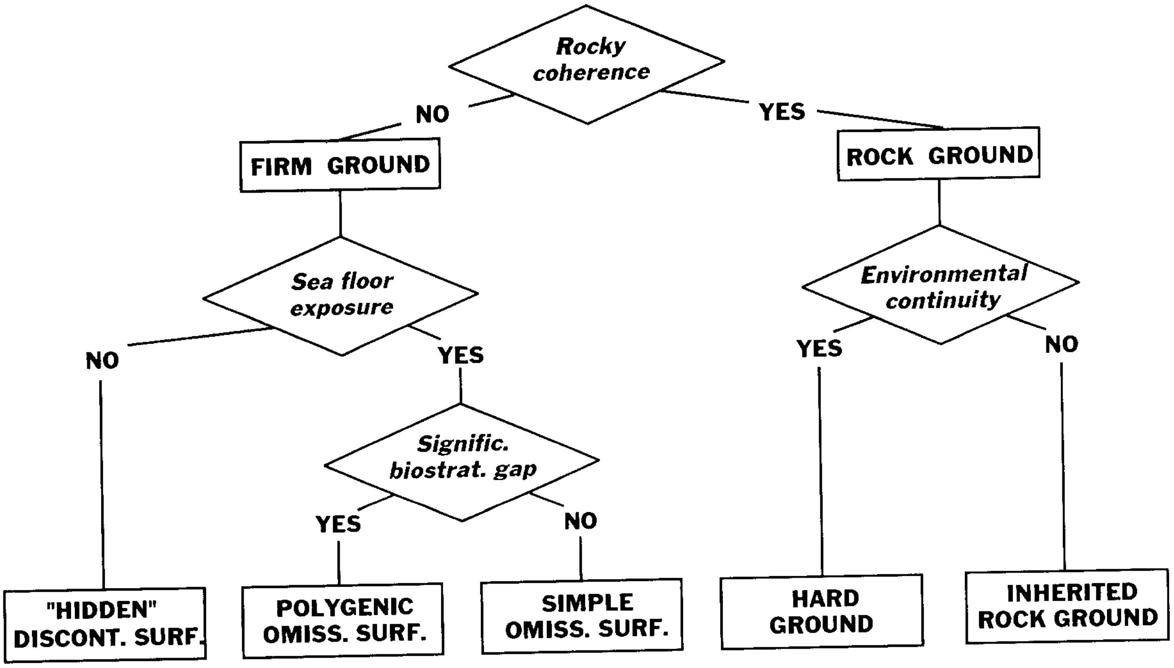


Fig. 4. Flow chart showing criteria used to distinguish different types of DS's. First, only the coherence of the UR is considered, then the conclusions about the environment of deposition and diagenesis of UR, DS and OR are integrated.

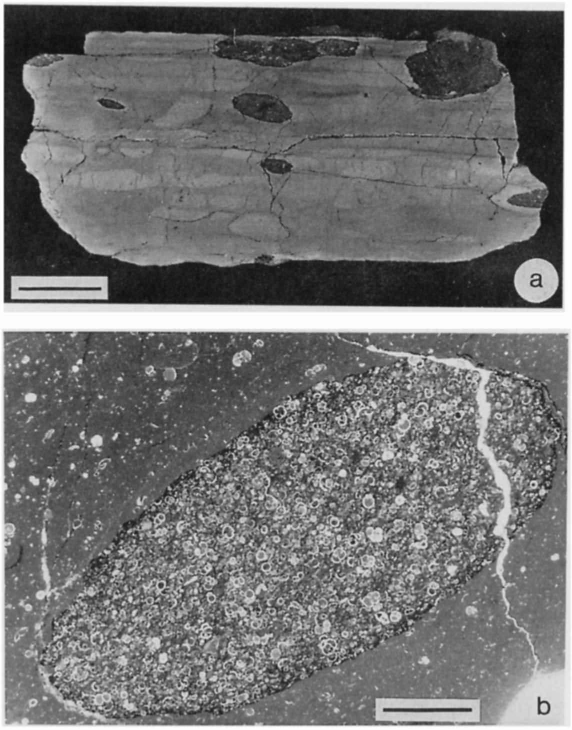


Fig. 5. (a) Polygenic omission surface in Tertiary, pelagic, wackestones of the Scaglia Fm. Light-coloured soft-ground burrows are cross-cut by firm-ground ones filled with dark red, foraminiferal packstones (scale bar = 2 cm). (b) Photomicrograph of one of the firm-ground burrow fills. The age of the encasing rock is Late Eocene whilst that of the burrow fill is Late Oligocene. Gran Sasso d'Italia, Central Apennines (scale bar = 1 mm).

failed to return a mud sample on the sounding lead (Murray and Renard, 1891). Both Bromley (1975) and Kennedy and Garrison (1975) agree in stating that this term has since been used to indicate surfaces of synsedimentary, intraformational lithification in marine sediments showing evidences of seafloor exposure. Furthermore, DS's stained and encrusted by Fe–Mn oxides are ubiquitous in the condensed pelagic succession of the Tethyan Palaeozoic and Mesozoic, and have been chosen by many authors as type examples for hard grounds (e.g. Jenkyns, 1971; Tucker, 1973; Wendt, 1988).

The term rock ground was proposed by Fürsich (1979) as opposed to hard ground, and defined as “a rocky seafloor, whose lithification was not synsedimentary, representing older layers of rock which through erosion or submersion formed the seafloor”. He stated that the lithification of a rock ground “belongs to a different depositional sequence” and cited as an example the surface separating Bajocian deposits from Carboniferous limestones at Mendips (Southern England).

These original definitions reveal some weakness. In the definition of hard ground neither ‘synsedimentary’ nor ‘intraformational’ may be considered truly characteristic. ‘Synsedimentary’ literally means ‘contemporaneous with sedimentation’ which is never the case with DS's. ‘Intraformational’, then, can be used only in connection with formal, lithostratigraphic subdivisions of the stratigraphic column which, to a certain degree, are subjective and may change with time and knowledge.

For what concerns Fürsich's definition of rock ground, the UR of a DS is always made of ‘older layers of rock’ than the OR: this characteristic is not useful in distinguishing between rock- and hard-grounds. Secondly, erosion, along with cementation and mineralization, is intimately connected with submarine omission surfaces to the extent that not only hard grounds but also firm grounds would not exist without erosion (Brom-

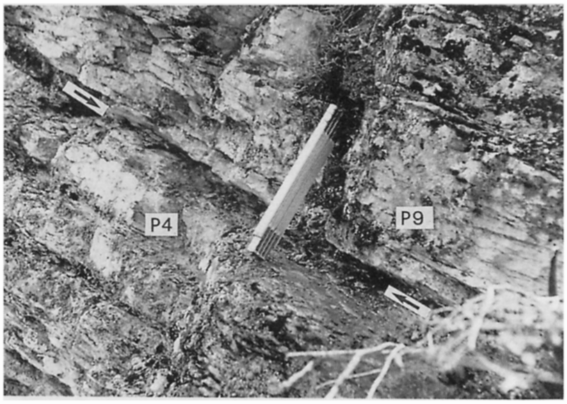


Fig. 6. Hidden discontinuity surface (arrows). Biostratigraphic analysis proves that along this simple bedding plane, within Palaeogenic pelagic sediments (Scaglia Fm.), a gap of about 5 Ma is present corresponding to the absence of four foraminiferal biozones (P5–P8). Gran Sasso d'Italia, Central Apennines (ruler is 20 cm long).

ley, 1975, 1990; Kennedy and Garrison, 1975). Moreover, submersion per se is not a proof of the complex history necessarily implied in a rock ground.

Although all these definitions appear plausible and can be readily applied in the majority of cases, they are not rigorously accurate and need to be revised in order to avoid confusions. We define *rock ground* as every surface which, regardless of its origin and characteristics, was hardened before deposition of the immediately overlying sediments. This purely descriptive wording is consistent with the other two (soft- and firm-grounds) which possess a strong and accepted ecological characterization (e.g. Seilacher, 1981).

Unlike soft- and firm-grounds, whose genesis is relatively simple, rock grounds result from different processes which may either last for a short time and act in the same environment (of deposition) or last even for millions of years and develop in different environments. Two terms are here proposed in order to distinguish these end members: *hard ground* (HG) and *inherited rock ground* (IRG). In order to discriminate between HG and IRG, the criterion of 'environmental continuity' among UR, DS and OR is suggested (Fig. 4). If deposition of UR and OR sediments took place in the same depositional system and the (dia)genesis of the DS may be attributed to only limited variations of the same environmental parameters, then the corresponding rocky DS is defined as a hard ground. This definition includes those previously used for hard grounds but is more strict and avoids the ambiguities of 'synsedimentary' and 'intraformational'. Also the sedimentary surfaces of the innermost parts of a carbonate platform, lithified during short-lived emersions (e.g. beach-rocks, microkarsts) fall within the so defined hard grounds.

IRG, on the contrary, applies to the cases in which either UR and OR deposition pertains to different depositional systems, or an environmental contrast between the (dia)genesis of the DS and the deposition of UR and/or OR may be recognized. Hence all DS's bounding very different facies (e.g. pelagic on platform deposits or vice versa) or carrying evidence of long-lasting environmental changes in an otherwise homogeneous succession (e.g. deep palaeokarstic 'surfaces', bauxites in platform limestones) are IRG for definition.

Both IRG and HG, may be mineralized. Mineralization does not change the overall picture anyway, that is to say that a rock ground cannot be considered as a HG only because of the pres-

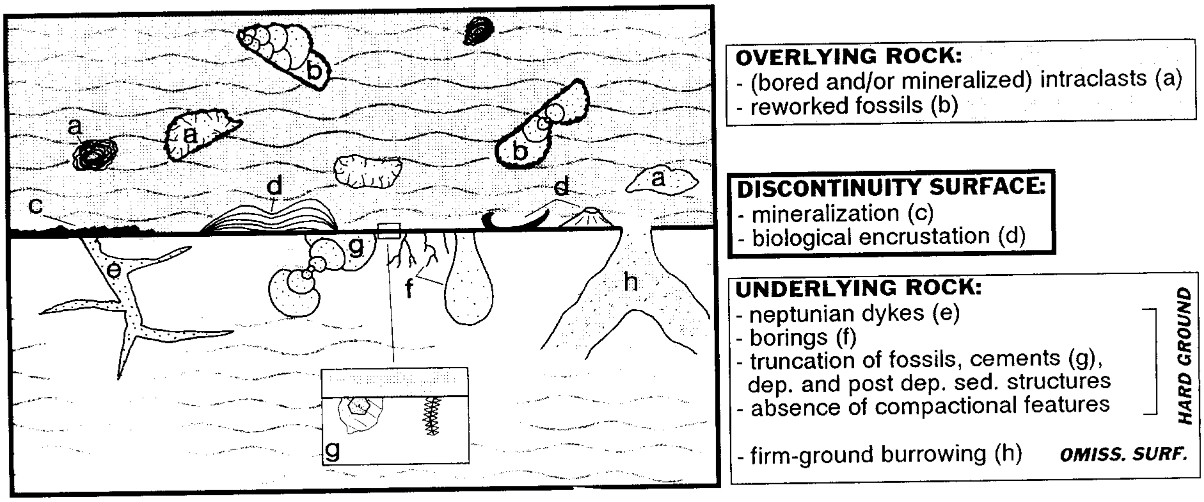


Fig. 7. Synoptic sketch of the diagnostic features of a DS within pelagic sediments. Every clue per se is proof of the existence of a DS.

ence of peculiar, authigenic products of submarine diagenesis like Fe–Mn oxides crusts: they may be only the last overprint and overestimating their importance could result in the incorrect classification of the DS.

5. Discontinuity surfaces in Italian carbonate successions: description and interpretation

The described five types of DS's may be found in many carbonate depositional environments, i.e. in both shallow- and deep-water settings. In order to facilitate the description of the Italian examples studied, we distinguish three cases on the basis of OR and UR facies: (1) DS within pelagic sediments; (2) DS within platform sediments; (3) DS separating pelagic and platform sediments. For each group the most recurrent of the five types of DS's distinguished in the present paper are evidenced, their diagnostic features described, and a genetic interpretation is proposed.

5.1. Discontinuity surfaces in pelagic sediments

Description

The identification of DS's in carbonate pelagic sediments is complex: the facies contrast between UR and OR is generally not striking, angular unconformities are uncommon and the surface itself may be inconspicuous though the missing chronostratigraphic interval may be important. Omission surfaces, both SOS and POS, are revealed by firm-ground burrows and do not offer evidence of prolonged seafloor exposure. Rock grounds, instead, are revealed by diverse evidence of an indurated seafloor (Fig. 7).

(1) Sharp, erosional contacts between UR and OR which cut through allochems and/or early cements and display flat to irregular geometries (Fig. 3).

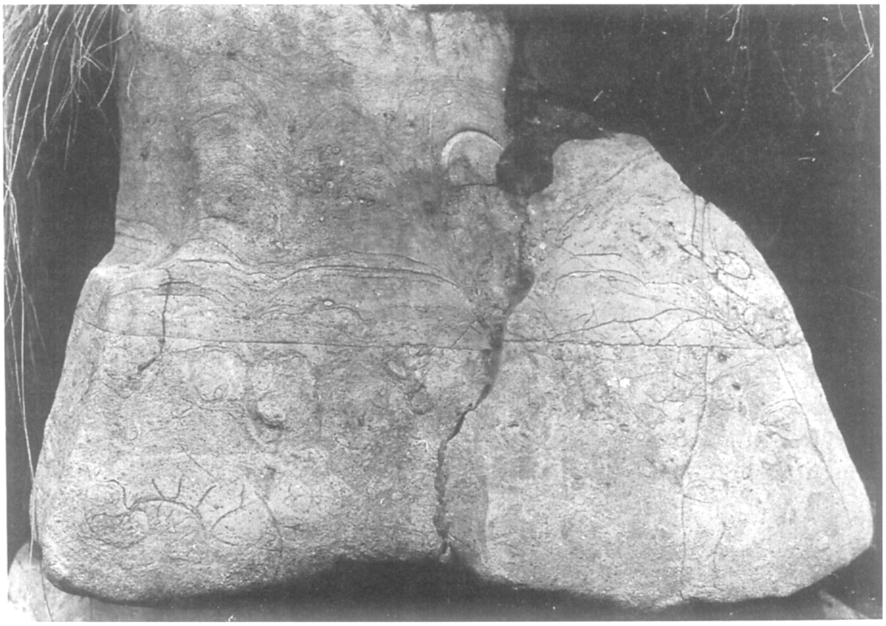


Fig. 8. A clear-cut DS (HG), within pelagic, ammonite-bearing, red nodular limestones is overlain by a continuous layer of LLH stromatolites. Middle Jurassic RAV, M. Lessini, Southern Alps. Outcrop width of about 60 cm.

(2) Lag-deposits made up of intraclasts and/or reworked fossils. The intraclasts may consist of fragments of the UR or of lithologies not represented in the local stratigraphic column because of total erosion. The reworked fossils show breakage, abrasion, coatings, boring or encrustations of the internal mould, random geopetal structures, and/or lithological differences between moulds and encasing rocks (Fernandez Lopez, 1985). Both intraclasts and reworked fossils result from discontinuous sedimentation alternated with cementation and erosion.

(3) Microborings, probably made by light-independent organisms such as fungi or bacteria (e.g. Golubic et al., 1984), are very common along our DS's or on the outer surface of bioclasts and intraclasts. Fe–Mn oxides commonly stain the borings indicating a prolonged exposure at the seafloor.

(4) Bioencrustation. Only one particular kind has been found in the studied DS's in pelagic sediments. It characterizes many portions of the Rosso Ammonitico facies (Massari, 1981; Clari et al., 1984) and has been called 'stromatolite' owing to the morphological similarity to blue-green algal boundstones (Fig. 8).

(5) Stainings and/or coatings of authigenic minerals such as glauconite and phosphate or brownish red to black oxides–hydroxides characterize most of the recognized DS's (Fig. 9). Commonly, these polymetallic deposits show internal lamination and domed shapes which have been related to chemiotrophic microbial colonies (Monty, 1973; Janin, 1987).

(6) Neptunian dykes crossing the UR were easily recognized due to their clear-cut boundaries with the enclosing rocks and to differences in texture and colour of the fillings. Polyphasic fillings, often showing delicate laminations, are indicative of repeated infiltration of sediments into cavities open to bottom waters for a long time.

Genetic interpretation

Two sets of cases may be distinguished according to the duration of the missing interval and to the consequent processes (Fig. 10).

(a) In hard grounds and simple omission surfaces the importance of the hiatus is consistently revealed by physical evidence of seafloor exposure and erosion. Several processes have been invoked to explain the genesis of these surfaces. (1) Chemical dissolution of calcium carbonate linked to depth fluctuations of the CCD (e.g. Mayer et al., 1986; Keller et al., 1987). This hypothesis implies large and abrupt changes in depth of the CCD in order to explain the genesis of DS's, which should be accompanied by a thin layer of insoluble siliceous or phosphatic skeletons. (2) Emersion and karstification of the seafloor. This hypothesis assumes a shallow depth

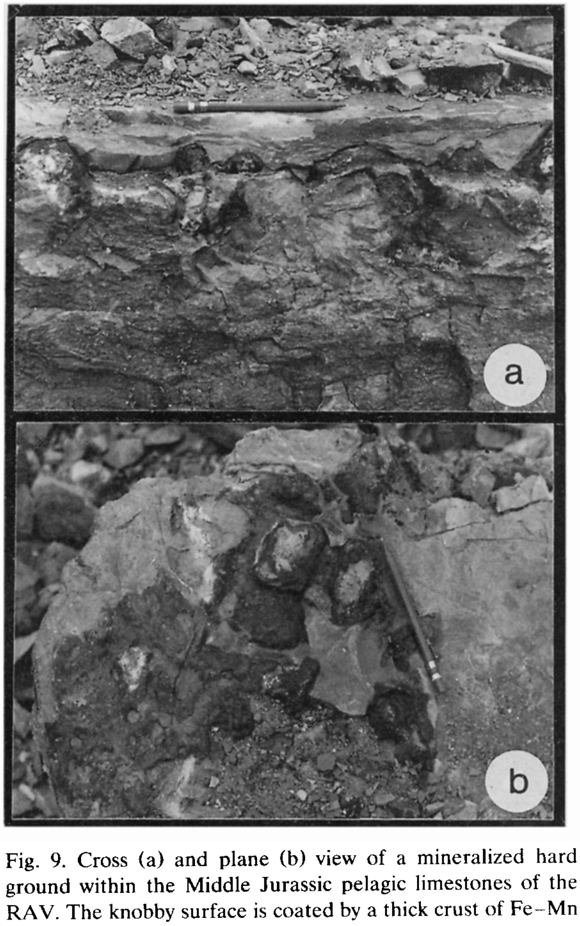


Fig. 9. Cross (a) and plane (b) view of a mineralized hard ground within the Middle Jurassic pelagic limestones of the RAV. The knobby surface is coated by a thick crust of Fe–Mn oxides. Altopiano di Asiago, Southern Alps (pencil is 14 cm long).

for pelagic plateaus and the concomitant effect of tectonic uplift and eustatic sea-level fall (e.g. Farinacci et al., 1981; Vera et al., 1988). This interpretation is substantiated when large-scale karstic dissolution features are found. (3) Sediment bypassing due to increased current activity which may prevent sediment accumulation or sweep the bottom, resuspending and carrying away the already deposited oozes. The action of currents in generating hard grounds has been both recognized in present environments (Pinet and Popenoe, 1985; Mullins et al., 1988) and suggested for fossil counterparts (e.g. Jenkyns, 1971; Ramsay et al., 1994).

In the examples studied, evidence of current activities is ubiquitous, and proofs of both emersion and dissolution in deep-marine settings are absent. Therefore the hypothesis that relates DS's to periodic current increases is preferred.

(b) In POS and HDS, the observed features of the DS do not match the large age difference between UR and OR (Fig. 10). The lack of evidence for prolonged exposure at the sediment–water interface (cementation, mineral encrustations, etc.) is difficult to explain. Possible mechanisms responsible for the genesis of these DS's might be: absence of cementation of exposed surfaces due to high clay/$CaCO_3$ ratios (Zankl,

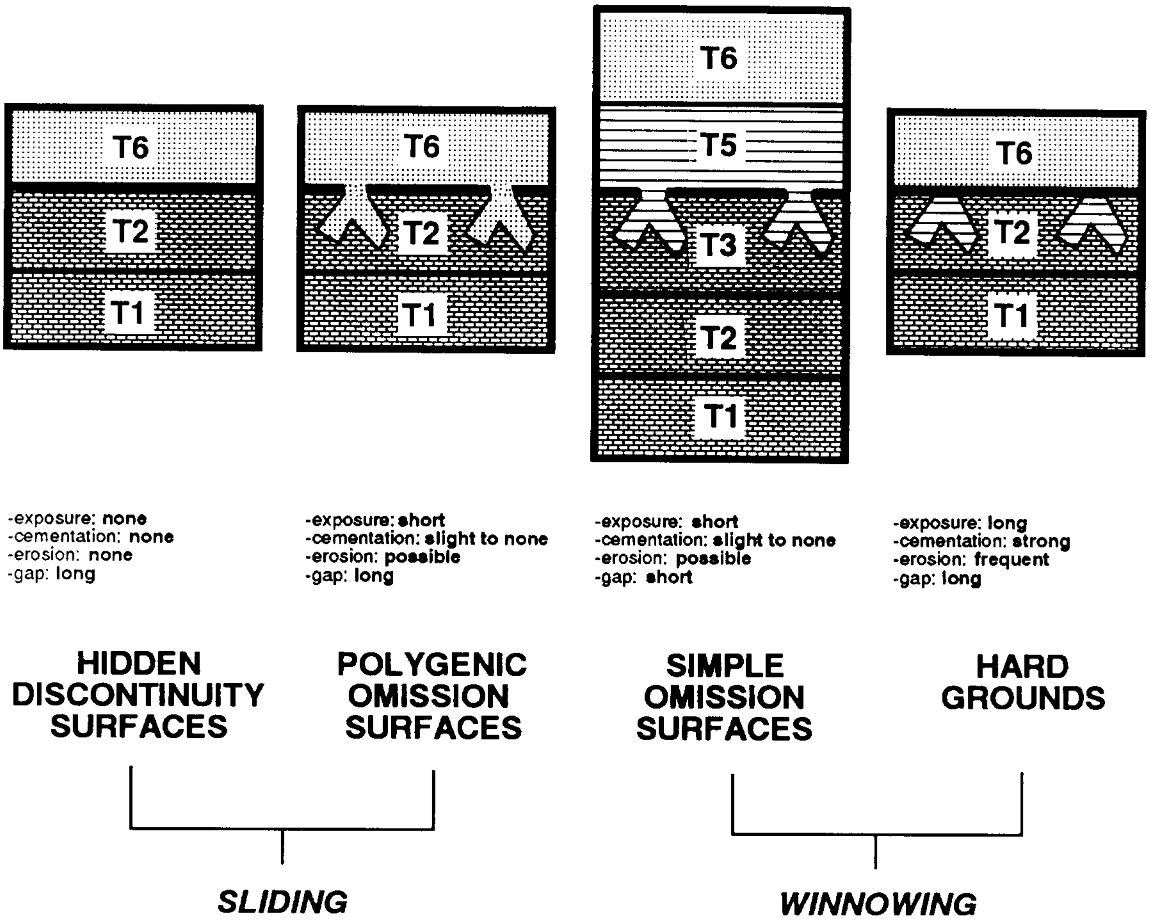


Fig. 10. Schematic logs and main distinctive features of different kinds of DS in pelagic sediments. *T1*, *T2*, etc., refer to successive time intervals and are purely indicative.

1969); absence of cementation due to undersaturation of sea water (Pomerol and Premoli Silva, 1986); increased bottom-current activity (Premoli Silva et al., 1991); important mass gravity movements (slides) along slopes (Alvarez et al., 1985; Coniglio, 1986).

The first two mechanisms seem unlikely in the cases studied where early cementation has been frequently observed in the same formations. Current activity, then, is excluded as no evidence of cementation, mineralization and/or scouring is present. The slide hypothesis, which is supported

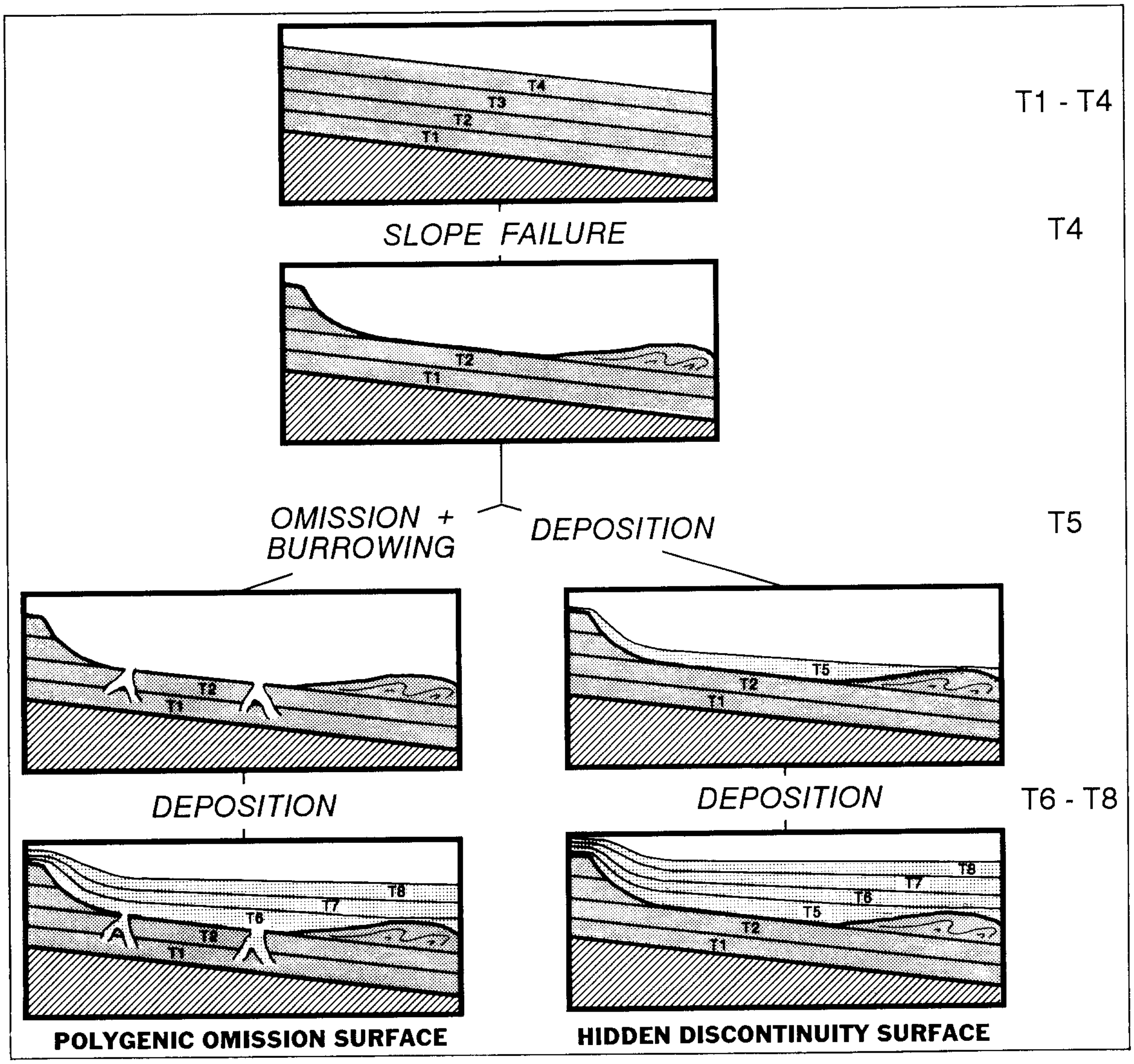


Fig. 11. Genesis of polygenic omission surfaces and of hidden discontinuity surfaces. *T1*, *T2*, etc., refer to successive time intervals and are purely indicative. For more details, see text.

by small-scale, synsedimentary deformation structures often associated with these discontinuity surfaces (Coniglio, 1986; Dela Pierre, 1992) is here favoured. As a consequence of sliding, part of the buried successions, which acquired a firmground consistency through dewatering and incipient compaction, were exposed. Depending on the thickness of the slumped volume of sediments and on the average sedimentation rates, gaps of variable extent were generated. After the slide event, if sedimentation was hindered for a period of time, a community of suspension-feeders colonized the exhumed ground giving rise to a POS (Figs. 5 and 11). A HDS developed, instead, where the sedimentation immediately followed sliding or where the bottom was not oxygenated or flushed enough to make life possible for bottom-dwellers (Figs. 6 and 11). The flat and perfectly conformable geometry of these slide-scars, at least at the outcrop scale, in the Apennines examples (Dela Pierre, 1992), suggests that relatively thin but areally extensive slumps occurred along bedding-parallel mechanical discontinuities.

5.2. Discontinuity surfaces in platform sediments

DS's in carbonate platform facies are frequent and well known (e.g. Esteban and Klappa, 1983; James and Choquette, 1987). We have not studied these DS's in detail and hence we will only briefly highlight some of their aspects useful for following discussions.

Two basic categories of DS's in platform sediments have been distinguished in Italian Mesozoic and Cenozoic carbonates.

(1) IRG, corresponding to long-lasting breaks in sedimentation due to episodic, prolonged, phases of emersion of the platform. These DS's are revealed by well-developed palaeokarstic horizons, red-clay to bauxite deposits (Fig. 12) and generally correspond to biostratigraphically significant gaps.

(2) HG and SOS, developed either in submarine environments, owing to an increase in hydrodynamic energy resulting in erosion and early cementation, or during short-lived emersions correlated to high frequency cyclic sea-level changes. Evidence of emersion are desiccation features, microkarst, selective leaching, calcrete, dolocrete, palaeosoils, root horizons, depending on climate. Evidence for submarine DS's is the same cited for pelagic sequences. In most cases, due to both to the short duration of the phase of emersion and to the low resolution of shallow-water platform biota, the time duration of the sedimentary gap cannot be assessed.

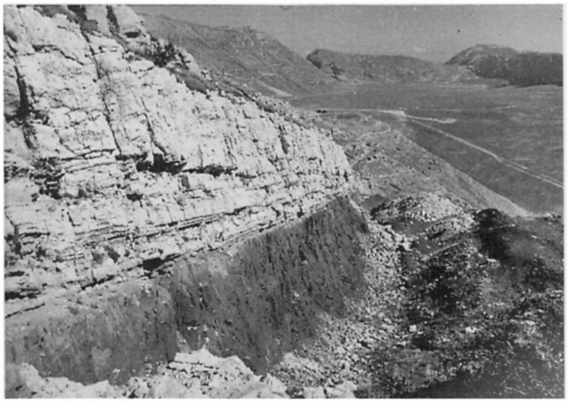


Fig. 12. Thick bauxitic deposits, interlayered within Lower Cretaceous platform limestones, mark an important halt in sedimentation, due to a prolonged emersion. Monte Orsello, Central Apennines.

In both categories of DS's, the subaerially exposed UR may experience a second erosional phase during the marine transgression (ravinement surface of Nummedal and Swift, 1987) that precedes the deposition of the OR. The resulting erosional surface can cut deeply into the UR and wipe out most, if not all, traces of the preceding subaerial phase.

5.3. Discontinuity surfaces separating pelagic and platform sediments

These DS's are the best examples of IRG: rock-ground evidence is ubiquitous, the facies contrast is always striking and the DS is often a polyhistory surface which underwent several phases of erosion and diagenesis in different sedimentary environments after the deposition of the UR and before deposition of the OR. In both the

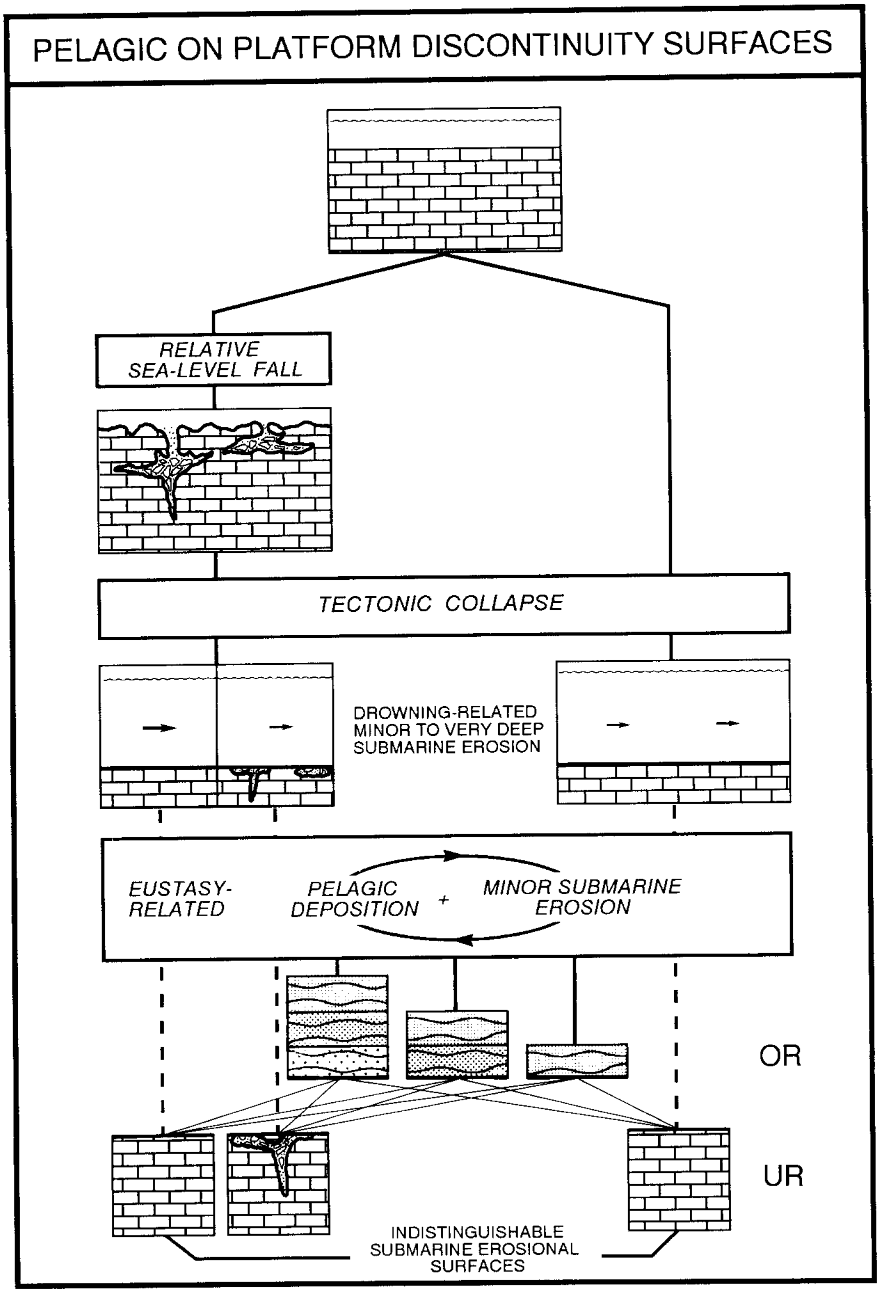


Fig. 13. Genesis of DS separating pelagic from platform facies. Platform drowning, related to tectonic collapse, may be preceded by a phase of emersion. DS results from current-related erosion in pelagic setting and may cut more or less deeply into the UR. In this way the possible clues of a previous subaerial exposure are wiped out and a submarine erosional surface is generated which can hardly be distinguished from a DS due to sediment bypassing in the pelagic realm. Lateral differences in the OR stratigraphy result from the local balance between deposition and erosion.

Southern Alps and Central Apennines two opposite cases have been distinguished which will be described independently: (a) pelagic facies resting on carbonate platform ones; (b) carbonate platform sediments resting on pelagic facies.

5.3.1. Pelagic on platform discontinuities surfaces

Description

Two examples of this kind of DS have been observed. In the Central Apennines the Mesozoic Lazio–Abruzzo carbonate platform was drowned in late Cretaceous time and covered by a carbonate pelagic succession (Scaglia formation, Upper Cretaceous to Palaeogene) (Dela Pierre, 1994). The DS separating platform sediments from pelagic ones shows the following features.

(a) Striking facies contrast across the DS: the planktic foraminifer wackestones of the OR rest on an irregular, scalloped surface, sculptured in the massive rudist rudstones of the UR.

(b) Fe–Mn oxide or glauconite crusts and neptunian dykes, providing evidence of rock-ground conditions. The dykes are filled with breccias of angular lithoclasts both of neritic and pelagic limestones in a pelagic matrix.

(c) The hiatus associated with the DS varies laterally, from a minimum of 4 Ma to a maximum of 40 Ma. Some depositional phases are testified only in erosional pockets associated with the DS or in pelagic clasts contained in neptunian dyke-filling breccias.

A second, classic example comes from the Jurassic of the Trento Plateau in the Southern Alps (Gaetani, 1975; Winterer and Bosellini, 1981). This DS shows a great variability from place to place owing to different ages and facies of both the OR and the UR. A more diffuse treatment of this DS will be given in a next section; here the attention is restricted to the most common situation. The OR, consisting of red, nodular, ammonite-bearing limestones of Ammonitico Rosso facies, is separated from the white to yellow open platform facies of the UR by a surface perfectly flat over long distances (Fig. 2; Clari and Marelli, 1983; Barbujani et al., 1987). This DS corresponds to a gap of about 5 Ma (Sturani, 1964) and shows clear evidence of rock-ground conditions such as: truncation of depositional and diagenetic features; neptunian dykes filled with red crinoidal grainstones; bivalve borings and microborings; Fe–Mn coatings.

Genetic interpretation

The sharp superposition of pelagic sediments on carbonate platform ones records the abrupt drowning of the carbonate platform below maximum carbonate production depth (‘drowning unconformities’ Schlager, 1981, 1989). The generation of this kind of IRG results from several processes acting during three distinct phases (Fig. 13): (1) end of shallow carbonate sedimentation and drowning of the platform; (2) formation and modification of the DS; (3) pelagic sedimentation.

(1) End of carbonate platform sedimentation. Several mechanisms have been proposed in literature in order to explain the demise of a carbonate platform and the generation of a drowning unconformity: (a) a rapid sea-level rise or the tectonic collapse of the platform (e.g. Schlager, 1981, 1989); (b) lack of reef building organisms, causing a sharp decrease in the rate of carbonate production on the platforms, thus fostering their drowning when subsidence or sea-level increase (Bice and Stewart, 1990); (c) ‘Killing’ of carbonate platforms by waters polluted with siliciclastics and/or volcanoclastics (Schlager, 1989); (d) flooding of platforms by nutrient-rich waters, causing the eutrophication of the carbonate system and a drastic reduction of its growth potential (Hallock, 1988; Follmi, 1989).

In the examples studied, drowning was not generalized, as shallow-water carbonate sedimentation kept on in adjacent sectors (Lazio-Abruzzi and Friuli platforms in the Apennines and Southern Alps, respectively) suggesting that large-scale, palaeoceanographic factors are at least not the only ones responsible for drowning. In both the Apennine and Alpine cases, geometries and facies relationships point to a tectonic phase of break-up of the platform and tilting of its margins (Castellarin, 1972; Winterer and Bosellini, 1981; Dela Pierre, 1992, 1994). An alternative hypothesis, which calls upon palaeoceanographic factors, has been recently proposed for the Trento Plateau (Zempolich, 1993).

(2) Formation of the DS. Existing evidence indicates that a prolonged phase of erosion, acting in the pelagic realm, is responsible for hampering sedimentation and sculpturing the surface. Such submarine erosion, however, might have wiped out all the clues of a phase of emersion, preceding the platform drowning. Both sequences of events could result in fact in indistinguishable submarine erosional surfaces (Fig. 13).

(3) Renewal of sedimentation. When current activity slowed down and eventually stopped with increasing depth, pelagic sediments were preserved over the DS. The age of the first pelagites may however vary from place to place as the Apennine example shows. It can be suggested that, on an irregular seafloor, the more elevated parts were affected by a current activity strong enough to erode locally previously deposited sediments or to totally hinder sediment accumulation for longer time spans.

5.3.2. Platform on pelagic DS's

Description

In the Central Apennines, a DS separates Miocene platform limestones from Middle Eocene planktic foraminifer wackestones (Scaglia Fm.; Dela Pierre, 1992). The UR is cut by small neptunian dykes, filled by the OR sediments. The DS, with a gap of at least 15 Ma, is an irregular, scalloped surface, impregnated with phosphates and glaucony, and floored by large mineralized and bored clasts of the pelagic lithologies (Fig. 14).

Another well-studied example of this kind of IRG is present at the Mesozoic–Cenozoic boundary on the Trento Plateau (Southern Alps) (Premoli Silva and Luterbacher, 1966; Luciani, 1989). A sedimentary gap of variable extent separates pink pelagic limestones of Late Cretaceous age (Scaglia Fm.) from overlying white, Middle Eocene calcarenites with large benthic foraminifers (Fig. 15). The overall geometry of the DS is flat but locally it cuts deeply (up to 50 m) in the pelagic UR. Both firm-ground burrows, filled with Paleocene–Eocene biomicrites with Fe-coated lithoclasts (Fig. 16), and rock-ground features as small borings and mineralized crusts, are present in the UR. The Eocene calcarenites of the OR may either rest directly over the Cretaceous biomicrites, with the interposition of a single goethitic crust, or a complex lag of phosphatized, angular micritic lithoclasts occurs at the base of the OR.

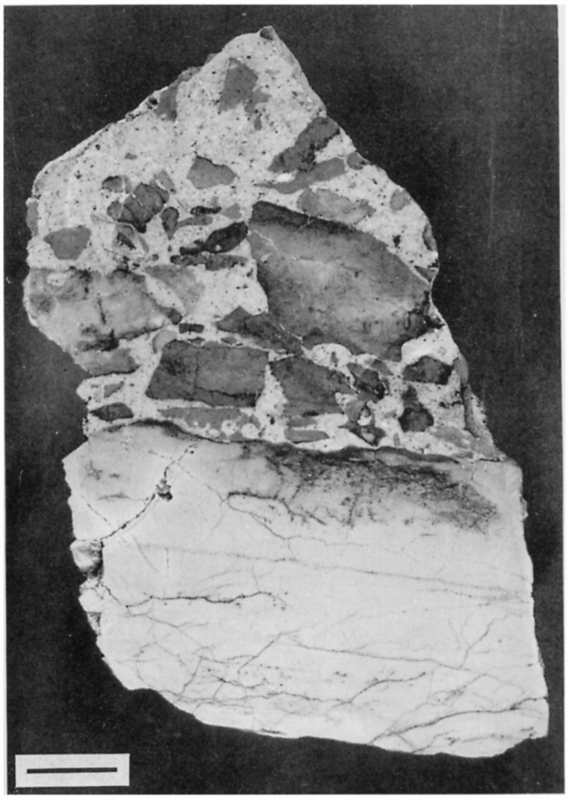


Fig. 14. Glauconitized lag in a matrix of Miocene, platform, foraminiferal packstone resting on a mineralized IRG cutting Eocene pelagic wackestones (Scaglia Fm.) (scale bar = 2 cm). Monte Nuria, Central Apennines.

Genetic interpretation

Both the above-described IRG's are the result of processes acting during three phases (Fig. 17): (1) during the end of pelagic sedimentation; (2) during production and modification of the DS; (3) during renewal of sedimentation in a platform environment.

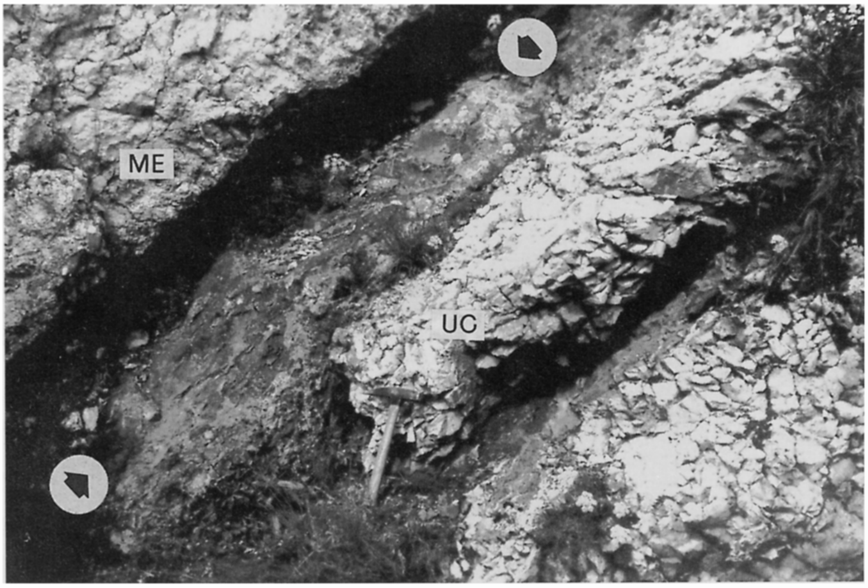


Fig. 15. Heavily mineralized DS (arrows) between pelagic biomicrites (Upper Cretaceous Scaglia Fm., *UC*) and foramol platform packstones (Middle Eocene, *ME*). M. Altissimo di Nago, Southern Alps.

(1) The end of pelagic sedimentation. The superposition of platform limestones and the UR features suggest that the end of pelagic sedimentation was due to the uplift of the bottom to shallow depths, where continuous, strong bottom currents actively prevented sediment accumulation before carbonate-platform sedimentation started. In both the above-described examples, the uplift is to be related to transpressive movements (e.g. Doglioni and Bosellini, 1987) that in the Southern Alps example triggered downslope sliding of sediments. Irregularities of the UR have been interpreted as scars left by such sliding (Luciani, 1989).

Fig. 16. Close-up view of the UR in Fig. 15. A complex network of polyphasic soft- and firm-ground, cross-cutting burrows, is filled with Paleocene–Eocene micrites with abundant small mineralized lithoclasts.

(2) The production of the DS. The complex features of the Southern Alps case may be interpreted as the result of the successive development of different types of DS's along the same stratigraphic horizon during a long time span. Firm-ground burrows reveal the development of an omission surface at the top of pelagic sediments. Such omission surface was later transformed into a HG: the burrows were filled by pelagic sediments bearing mineralized lithoclasts, and the surface was bored and mineralized. The result of this rather long history has been locally erased by one or more erosional phases which gave rise to an apparently simple DS. A similar succession of events may be envisaged for the Apennine case where a longer gap corresponds to a simple mineralized DS.

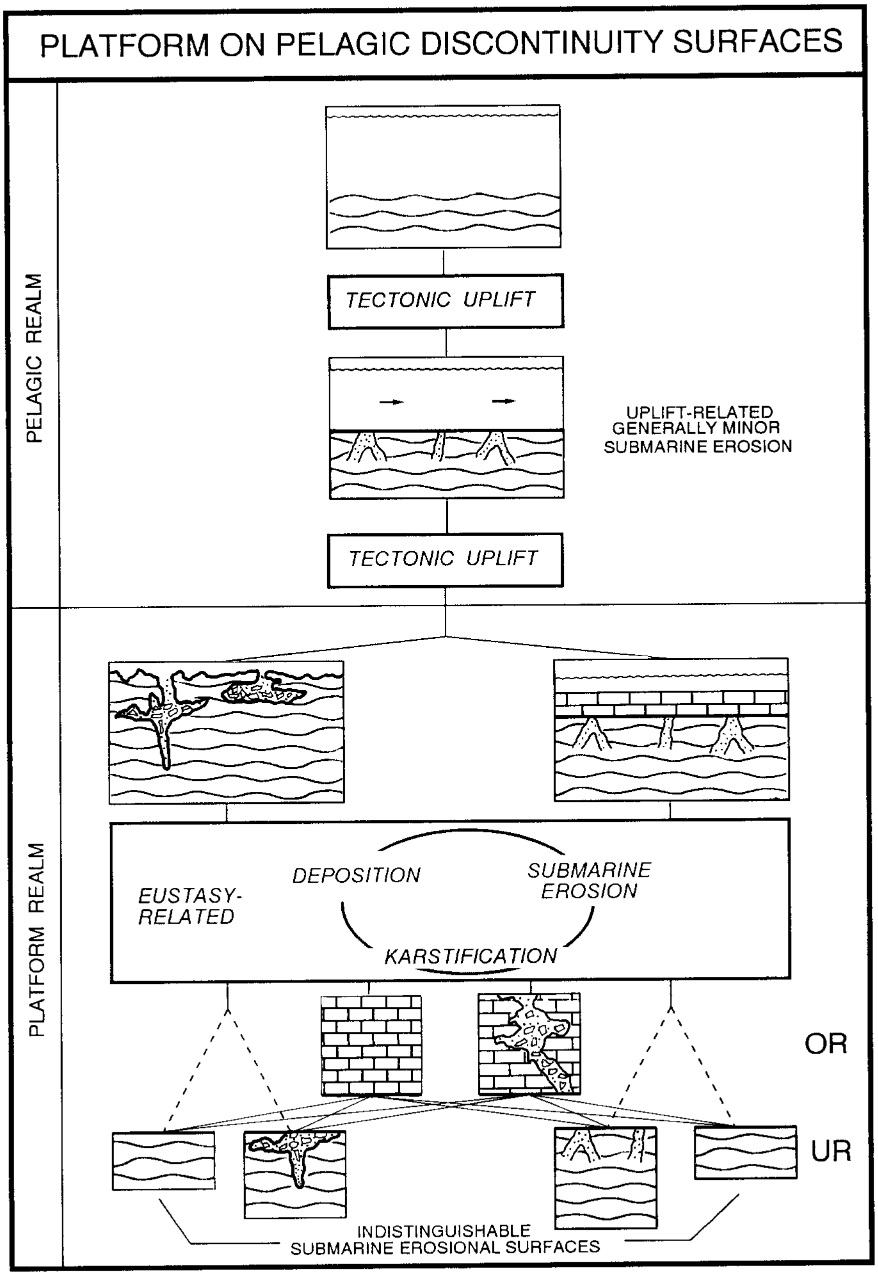
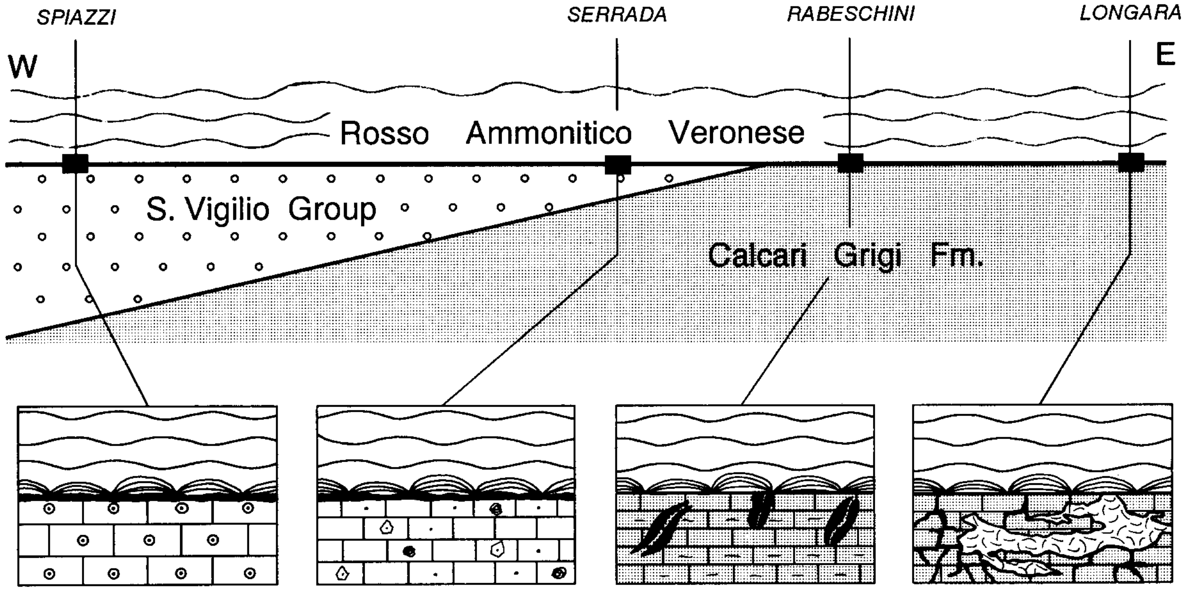


Fig. 17. Genesis of DS separating platform form pelagic facies. Sharp facies contrast between the UR and the OR results from the tectonic uplift of the pelagic sea bottom. The production of the DS may be due to emersion or to current erosion in the pelagic realm. Final modification of the DS and deposition of the OR take place in a platform environment, deeply influenced by eustatic sea-level changes. If erosion prevails all the evidence of a previous karstification are wiped out and the resulting DS is not distinguishable from the one entirely generated in submarine environments. The height of the UR blocks is inversely proportional to the degree of erosion.



OR: Upper Bajocian stromatolitic layer within red, nodular limestones.
DS: Fe-Mn coatings
UR: Aalenian white oolitic grainstones.
Min. Gap: 5 Ma

OR: Upper Bajocian stromatolitic layer within red, nodular limestones.
DS: Fe-Mn coatings
UR: Aalenian pink oncoidal-peloidal-skeletal packstones.
Min. Gap: 5 Ma

OR: Upper Bajocian stromatolitic layer within red, nodular limestones.
DS: stylolitic contact
UR: Pliensbach. lagoonal facies. Moldic cavities filled with red micrites.
Min. Gap: 20 Ma

OR: Upper Bajocian stromatolitic layer within red, nodular limestones.
DS: stylolitic contact
UR: Pliensbach. lagoonal facies. Large fissures filled with Upper Bajoc. coquinas.
Min. Gap: 20 Ma

Fig. 18. Simplified sketch of the regional discontinuity surface bounding pelagic (Rosso Ammonitico Veronese) from platform facies (S. Vigilio Group and Calcari Grigi Fm.). Four sections along an approximately W–E cross-section of the Trento Plateau, have been selected to depict variations in UR facies, features of the DS and duration of the gap. Minor changes actually present in the OR have been ignored. The tectono-stratigraphic framework is after Sarti et al. (1992). Not to scale.

(3) Renewal of sedimentation. When the sea bottom was eventually brought into shelf environments, platform sediments started to accumulate directly above the DS. Such mineralized surface, corresponding to a HG while in the pelagic realm, is transformed for definition in a IRG when covered by sediments pertaining to a different depositional environment, i.e. a carbonate platform.

6. Discussion

6.1. Lateral correlation and telescoping of discontinuity surfaces

The examples presented, and especially the platform on pelagic IRG, show that in many instances along a single DS both number and type of diagnostic features change, due to the varying effectiveness of erosional phases. Moreover, if the lateral tracing of a DS is attempted, it is easily realized that either the surface results from the merging of a number of DS's or it coalesces with others to form a composite DS. As a consequence, the correct comprehension of the genesis of a DS and its complete 'exploitation' in basin analysis can be accomplished by only tracing laterally the surface itself, and studying in detail every single point of outcrop.

The case of the pelagic-on-platform DS of the Trento Plateau, already cited, will be here discussed in further detail (see also Sturani, 1971; Winterer and Bosellini, 1981; Bosellini, 1989; Sarti et al., 1992; Zempolich, 1993). This IRG separates different platform facies from a quite uniform OR consisting of red, nodular pelagic limestones of the Rosso Ammonitico Veronese Fm. whose deposition started synchronously (Uppermost Bajocian) over the whole Trento Plateau. Owing to a tilting of the Lower Liassic platform (Sarti et al., 1992), a wedge of Toarcian–Aalenian, mainly oolitic limestones thins out to zero in the inner part of the Plateau from about 500 m on the western margin. Consequently (Fig. 18), UR facies, depositional and diagenetic features and duration of stratigraphic gaps along this DS change along an E–W cross-section. Four sections have been selected in order to show these variations. In the two westernmost sections (Spiazzi and Serrada) the UR is Aalenian in age and consists of oolitic grainstones or oncoidal–peloidal–skeletal packstones. In both cases the gap may be estimated to be about 5 Ma. In the other two sections (Rabeschini and Longara), the UR consists of Pliensbachian, lagoonal facies and a gap of about 20 Ma occurs. Mouldic cavities, due to the dissolution of large bivalves (*Lithiotis*) and filled with red micrites, are present at Rabeschini. At Longara, the situation is more complex due to the presence in the UR of a dense network of cavities mainly filled by lower and upper Bajocian bivalve and ammonite coquinas (Lumachella a *Posidonia alpina*) (Fig. 19). The DS sharply cuts through both cavity-fillings and encasing Pliensbachian rocks.

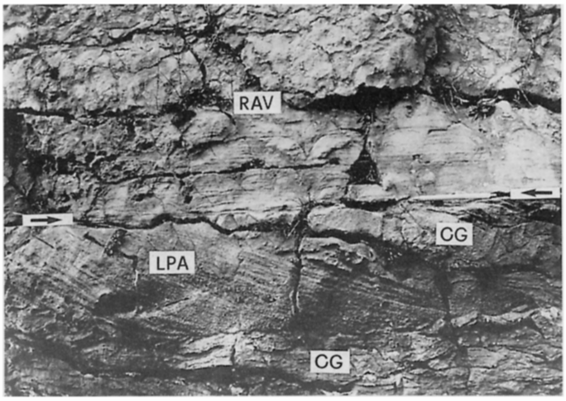


Fig. 19. Pelagic stromatolites, overlain by nodular limestones (*RAV*, Upper Bajocian), rest on a complex UR made up of Domerian, shallow-platform facies (Calcari Grigi, *CG*) crossed by large fissures filled with red, bivalve and ammonite coquinas of late Bajocian age (Lumachella a *Posidonia alpina*, *LPA*). Oblique lamination in the fissure-filling coquinas represent current-induced internal foresets. The DS (arrows) is perfectly flat at the outcrop scale and cuts through both Liassic encasing rocks and fissure fillings. M. Longara, Altopiano di Asiago, Southern Alps (pencil is 14 cm long).

The interpretation of this IRG seems relatively simple, at least in the first three localities, if each case is considered separately. At Spiazzi and Serrada the DS may be interpreted as the result of the drowning of the Aalenian platform followed by pelagic sedimentation. The same mechanism may be called upon to explain the DS at Rabeschini although the generation of the quite large mouldic cavities hardly fits such simple model. More complex is the situation at Longara, especially considering that the coquina-filled cavities have been interpreted either as karstic features (Sturani, 1971) or as slide-induced neptunian dykes (Winterer et al., 1991). It is even more difficult to figure out a single, overall interpretation for the genesis of the regional DS, holding in due consideration all the features evidenced in the different sections.

The foregoing shows that when the main objective of a study is a DS and not the rock bodies bounded by it, genetic interpretations based on local successions are often simplistic, and otherwise unsuspected depositional–erosional phases are revealed.

The same, or even higher, degree of complexity characterizes IRG where platform sediments overlie pelagic ones. Pelagic sediments are in fact uplifted to shallower depths where both submarine and subaerial erosional processes normally operate. It cannot theoretically be excluded that, before OR deposition, the pelagic seafloor may go through a karstification stage (Fig. 17), the evidence of which is partially or totally erased by the following transgression. Karstification may also take place after renewal of sedimentation at the expenses of the OR platform carbonates. The resulting karst surface may cut deeply enough to intersect the old IRG present at the top of the UR pelagic sediments, and this makes its genetic interpretation even more difficult.

6.2. Use in sequence stratigraphy

DS's are important features in defining stratigraphic units in both 'traditional' and sequence stratigraphy. The purpose of stratigraphic studies on DS's has been the correlation across the basin and the comprehension of genetic processes. Both these aspects have been already discussed. Further difficulties arise when the sequence stratigraphic approach is attempted: DS's have to be correlated with conformities in the deepest parts of the basin and a causal relationship with relative sea-level changes has to be assessed. In this section, all the types of DS's recognized in Italian carbonate successions will be considered in this perspective.

6.2.1. Discontinuity surfaces in pelagic sediments

The recognition of DS-bounded depositional sequences in pelagic successions has rarely been attempted. In fact, in absence of physical continuity with slope and shelf sequences, the definition of sequence boundary by Van Wagoner et al. (1988), referring to subaerial exposure, is not applicable. However, the more general definition of depositional sequence given by Haq et al. (1987) ("succession of sediments deposited ... from a sea-level fall ... and ending with the next fall"), allows to interpret some DS's as sequence boundaries.

A causal relationship between absolute stands of sea level, climate and ocean current speed has been suggested. Sea-level lowstands lead to deteriorated climatic conditions (e.g. Barron et al., 1980; Parrish and Curtis, 1982) which in turn accentuate current effectiveness and so prevent sediment accumulation or cause erosion resulting in the formation of DS's in pelagic environments (Haq, 1993). Highstands, on the other hand, correspond to equable climates which favour a more sluggish ocean circulation and allow the pelagic sediment input to be preserved. Local increase in current activity results also from other causes. Palaeogeographic rearrangements can open new seaways and dramatically change the pattern of ocean circulation generating important erosional hiata (Keller et al., 1987; Mullins et al., 1987). Eustatic fluctuations, moreover, can affect also the position of the current flow so that the main axis of currents may be displaced by up to several hundreds kilometres along a continental slope (Pinet and Popenoe, 1985; Mullins et al., 1988).

Major palaeogeographic modifications, however, cannot account for cyclic sedimentary breaks. Lateral shifts of current axes, then, result in gaps of different ages and ranges from place to place. When DS's are found to be synchronous over a palaeogeographic unit (Rosso Ammonitico Veronese on the Trento Plateau, Martire, 1992) or even followed from omission surfaces in the pelagic plateaus to subaerial exposure surfaces on the platform (Apennines, Dela Pierre, 1992), the link between eustatic fluctuations and sedimentary breaks is highly probable.

DS's whose genesis is due to downslope sliding (POS and HDS), have a local character and are mostly controlled by the regional tectonic activity making depositional slopes unstable. Their lateral continuity and thus their utility in sequence stratigraphy appears therefore to be nil. It has been suggested however, that other mechanisms (e.g. the effects of sea-level changes on the stability field of gas hydrates) may affect slope stability to an extent comparable to tectonically induced seismic shocks or slope oversteepening (Dunlap and Hooper, 1990; Haq, 1993).

6.2.2. Discontinuity surfaces in platform sediments

IRG's generated during long emersions of the platform are frequently interpreted to be the product of eustatic sea-level falls and hence used as sequence boundaries sensu Van Wagoner et al. (1988). Recent research, however, seems to demonstrate that many long-lasting (> 1 m.y.) subaerial exposures are more probably due to tectonic arching of carbonate platforms (D'Argenio and Mindszenty, 1991, 1992). The stratigraphic relevance of DS's generated by minor pulses in the environmental parameters, instead, varies depending on the depositional system: it is almost nil for high-frequency subaerial exposure surfaces and normally not easy to assess for submarine HG and SOS.

6.2.3. Discontinuity surfaces separating platform and pelagic sediments

Both pelagic-on-platform and platform-on-pelagic DS's are of primary interest to field stratigraphers. Their meaning to (sequence) stratigraphy is undisputable, as they represent prominent stages of the tectono-sedimentary evolution of a basin and mark impressive changes in depositional mechanisms. Consequently, they represent major sequence boundaries in the sense recently proposed by Schlager (1991).

It must be pointed out, however, that for our examples a purely eustatic origin may be ruled out. The limited lateral extension, and the often enormous unrepresented time span, corresponding to several 3rd-order sea-level cycles, are in fact a proof of a control by tectonic activity.

7. Conclusions

The main results of this study may be summarized as follows.

(1) Discontinuity surface (DS) is proposed as a general term for surfaces marking a break of whatever length in the stratigraphic record.

(2) Four classes of evidence have been recognized, enabling identification of a DS in outcrop. In order of increasing detail of analysis they are: geometry, facies contrast, sedimentological and diagenetic features, biostratigraphy.

(3) DS's are subdivided in rock grounds or firm grounds (omission surfaces) in function of the degree of lithification of the UR. Rock grounds may be further subdivided in hard grounds and inherited rock grounds. In hard grounds deposition of UR and OR and genesis of the DS have taken place in the same depositional system, whereas in inherited rock-grounds clues of important environmental changes are evident. Omission surfaces are subdivided in simple or polygenic if the time gap is, respectively, negligible or not, i.e. if it is below or above the biostratigraphic resolution. A fifth case of DS, recognizable only through detailed biostratigraphic analyses, has been defined as hidden discontinuity surface.

(4) DS's have different genesis and relevance for (sequence) stratigraphy. In pelagic sediments, HG's record enhanced current activity, likely following sea-level falls, and may therefore be considered as sequence boundaries. SOS's, instead, represent only minor current-related sedimentary breaks which cannot be easily correlated. POS's and HDS's are related to submarine sliding and have commonly a limited extent. Their importance may be great in local stratigraphic studies but is still unclear for more general stratigraphic purposes. All IRG's are of major importance because of the significant environmental changes involved in their complex genesis. They are always to be considered as sequence boundaries though not necessarily due to eustasy.

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