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STRATIGRAPHIC AND PALEOGEOGRAPHIC EVOLUTION OF A CARBONATE PLATFORM IN AN EXTENSIONAL TECTONIC REGIME: THE EXAMPLE OF THE DOLOMIA PRINCIPALE IN LOMBARDY (ITALY)

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Key-words: Norian, Paleogeography, Paleotectonic, Rifting, Carbonate platform facies.

Riassunto. Lo studio stratigrafico e sedimentologico della successione norica affiorante nel Bacino Lombardo ha permesso di ricostruire l'evoluzione paleogeografica e strutturale di questo settore: 1) al limite Carnico-Norico (non ben definito dal punto di vista paleontologico per la scarsità di fossili significativi) sono diffusi depositi di ambiente lagunare ristretto e di piana tidale (Membro basale della Dolomia Principale); 2) questi sedimenti sono ricoperti da una potente successione di piattaforma interna organizzata in cicli *shallowing upward* (Dolomia Principale inferiore), con l'eccezione del settore del Lago d'Idro, dove sono già presenti in questa fase facies di bacino intrapiattaforma; 3) la soprastante Dolomia Principale medio-superiore è interessata da una importante fase tettonica distensiva-transtensiva con individuazione al suo interno di depressioni strutturali (semigraben) caratterizzate da una marcata asimmetria delle facies. La piattaforma viene così smembrata e maggiormente diversificata, con il conseguente sviluppo di facies di margine, di pendio e facies di bacini intrapiattaforma; 4) nella parte superiore della Dolomia Principale i margini biocostruiti diventano più abbondanti e queste facies progradano parzialmente sulle facies di scarpata, pendio e bacino; le parti interne della piattaforma invece diventano aree emerse; 5) la fine della sedimentazione della Dolomia Principale è dovuta all'annegamento della piattaforma in connessione a inquinamento terrigeno fine e cambiamenti climatici all'inizio della sedimentazione delle Argilliti di Riva di Solto. Sembra ipotizzabile lo sviluppo di una *drowning unconformity* (con onlap) tra la successione argillosa ed i carbonati sottostanti.

La distribuzione asimmetrica dei margini biocostruiti e delle brecce associate alle scarpate di faglia, che affiorano sul lato occidentale dei bacini intrapiattaforma ad ovest del Lago d'Iseo e sul lato orientale nei bacini ad est del Lago d'Iseo, ha permesso di proporre un modello di un rifting ensialico asimmetrico per il Bacino Lombardo durante il Norico. Questo rifting asimmetrico può essere inquadrato in un modello geodinamico che permette di interpretare il Bacino Lombardo come un bacino di *pull-apart*, legato ad una transtensione con faglie trascorrenti principali orientate circa est-ovest.

Abstract. Stratigraphic and sedimentologic studies of the norian succession outcropping in the Lombardy Basin allowed the reconstruction of the paleogeographic and structural evolution of this area: 1) restricted lagoon and tidal flat are the most common deposits at the Carnian-Norian boundary (Lower Member of the Dolomia Principale); 2) these are overlain by a thick inner platform succession organized in shallowing upwards cycles (lower Dolomia Principale), with the exception of Idro Lake area where intraplatform basins already generated; 3) the overlying middle-upper Dolomia Principale is dissected by synsedimentary faults with subsequent widespread development of intraplatform basin, margin, and slope facies with marked asym-

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metric distribution; the inner platform was locally emerged; 4) in the uppermost Dolomia Principale buildup margins become more abundant and the platform partially prograded on the basins; 5) at last the platform drowns and terrigenous sedimentation becomes prevalent (Riva di Solto Shales). The drowning of the platform is favoured by the lack of carbonate production, due to clay pollution and climatic changes in an area with high subsidence rates.

The observed asymmetric distribution of buildup margins and fault-scarp related breccias, which outcrop on the western side of the basins west of Iseo Lake and bounding the eastern side of the basins east of Iseo Lake, allows us to propose a model of norian ensialic asymmetric rifting for the Lombardy Basin. This asymmetric rifting could be explained by interpreting the Lombardy Basin as a pull-apart basin, linked to transtension with E-W trending faults.

Introduction.

The Norian succession of the western Tethys is dominated by carbonate shelf deposits and associated intraplatform basin facies, which can be traced from Spain to Greece. These platform deposits are almost completely dolomitized and form, in the Southern Alps, the Dolomia Principale (Hauptdolomit in the Northern Calcareous Alps). The present study mostly deals with the Dolomia Principale of the Lombardy Basin, where the formation shows thicknesses up to a maximum of 2000 m. The Dolomia Principale peritidal platform is dissected by intraplatform basins, particularly towards the upper part of the succession: this complex paleogeographic setting is controlled by syndepositional extensional tectonics.

The Lombardy Basin is structurally very different from the adjacent Varese (to the west) and Trento (to the east) structural highs, being characterized by higher subsidence rates. Westwards of Garda Lake, in the Trento Plateau, the norian succession is less thick and intraplatform basins are not common. A similar situation occurs westwards of the Lombardy Basin, where the succession shows again reduced thicknesses indicative of slow subsidence rate. Southwards the Basin is bordered by another structural high (probably inherited from the Southern Mobile Belt; Brusca et al., 1982) as inferred from subsurface data (Errico et al., 1979; Cassano et al., 1986; Bongiorni, 1987). Therefore, the Lombardy Basin has a more complex paleogeographic and sedimentary evolution with respect to the adjacent areas. Works by Assereto & Casati (1965), Casati & Gaetani (1979), Jadoul & De Bonis (1981), Jadoul (1986), Gaetani et al. (1987), Cirilli & Tannoia (1988), Picotti & Pini (1989), Bertotti (1991) and Frisia (1991) put to evidence that the paleogeographic and structural evolution of the Lombardy Basin fits in a tectonic framework characterized by regional extension.

Paleogeographic-stratigraphic evolution in the Norian.

The stratigraphic analysis of the norian succession in Lombardy (Fig. 1) allowed the recognition of the following evolutionary steps:

1) About the Carnian-Norian boundary (which is not yet well defined on the basis of paleontological data), sedimentation took place in restricted lagoons and tidal flats, now represented by dark bedded laminated dolomites locally with stromatolitic

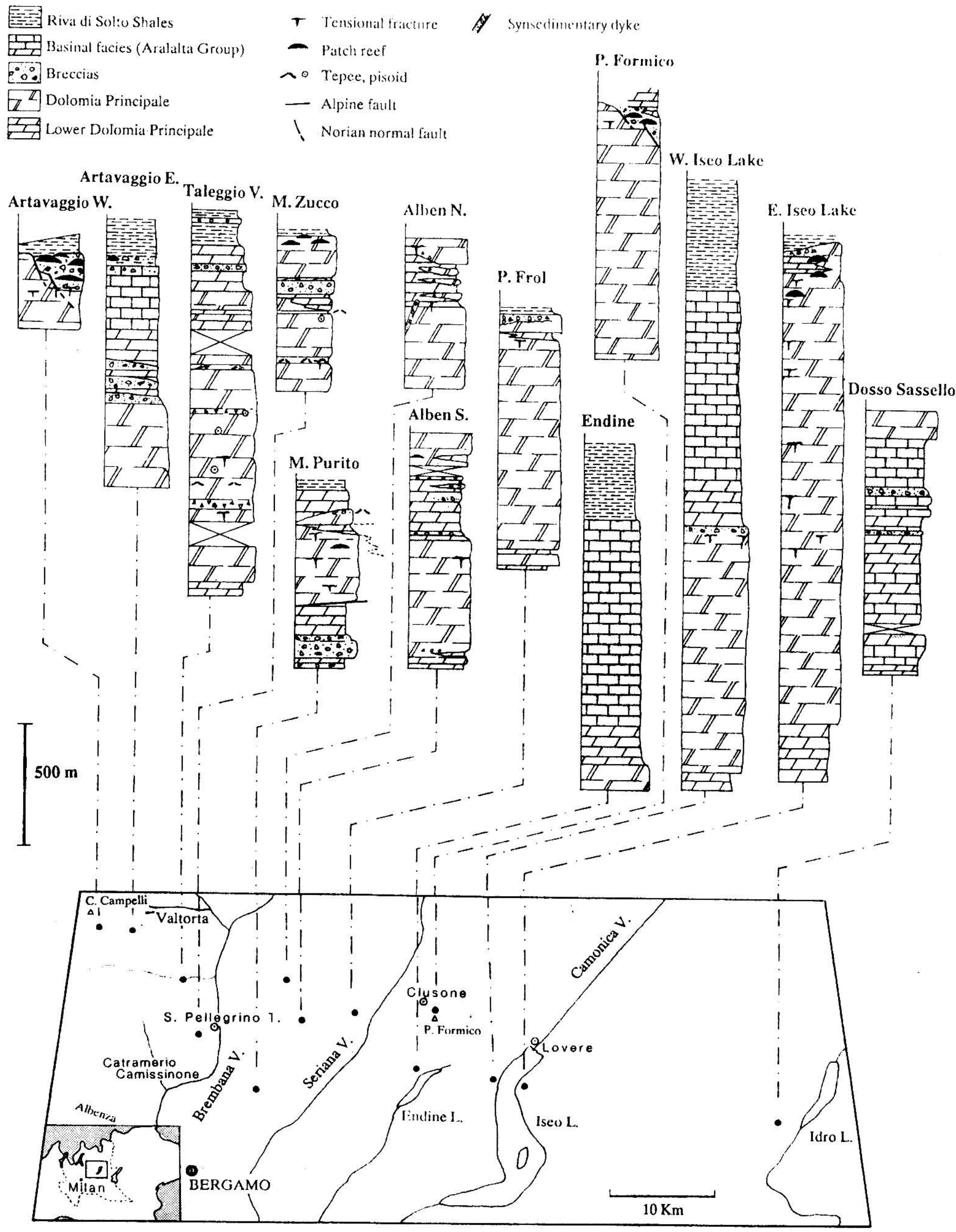


Fig. 1 - Logs of stratigraphic sections of the norian succession in the central-eastern Lombardy Basin and map showing the location of each section. The major depocenter corresponds to the present Iseo Lake.

laminae. These depositional environments developed in areas which were previously subjected to high subsidence rates and where the deposition of fine limestones and intraformational breccias (Castro Formation; Jadoul et al., 1992) occurred in the Late Carnian. The lagoons were probably bounded westwards (Val Torta) by fault scarps, the location of which is marked by the presence of carbonate breccias. Maximum thickness of dark lagoonal lithofacies is about 200-300 m.

2) The deposition of a thick (up to 700 m) succession of cyclic inner platform peritidal lithofacies followed. This part of the Dolomia Principale consists of 5 to 25 m thick shallowing upwards depositional cycles, each composed by several peritidal cycles, of decimetric to metric scale. The upper part of some peritidal depositional cycles is characterized by tepee structures and breccias cemented by dark-rimmed pisoids. Similar lithofacies are widespread throughout the Southern Alps and may be considered equivalent to the peritidal lithofacies distinguished by Bosellini & Hardie

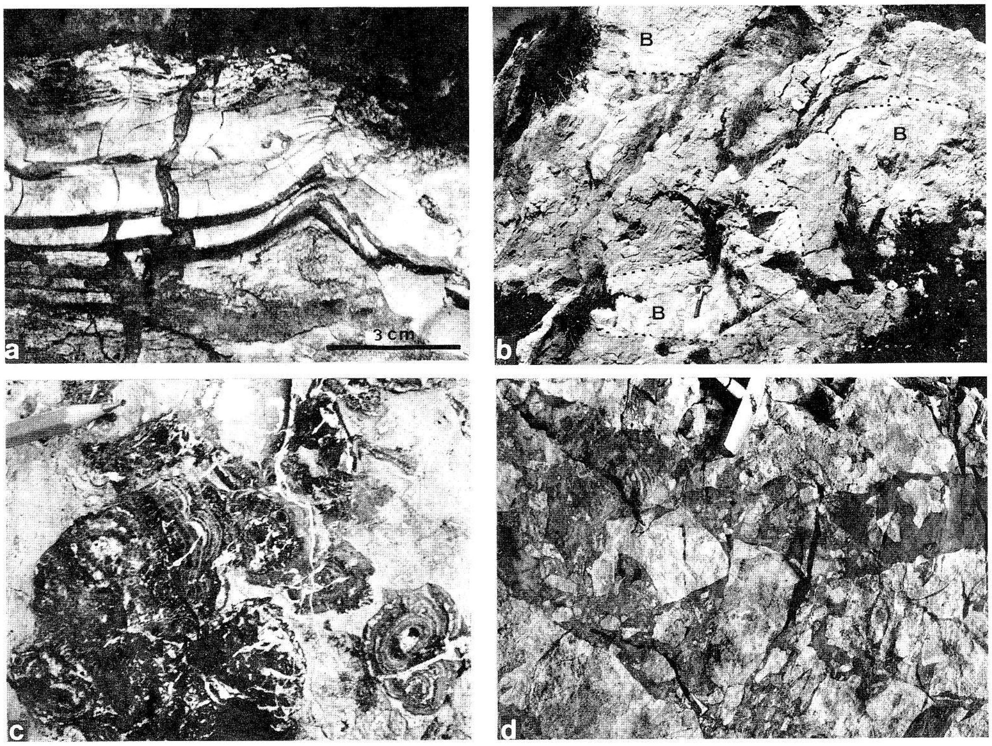


Fig. 2 - Particular lithofacies characterizing the evolution of the upper Dolomia Principale.
a) Small tepee with fractures filled by black internal sediment. Selvino-M. Podona. b) Megabreccia with large blocks of margin and inner platform-derived lithofacies. Artavaggio-C.ma Piazzo tectonically controlled platform margin. c) Particular of bioclastic-oncolitic breccia. Note early fracturing of the clasts. Upper slope of Pizzo Formico-Pizzo Casnigo Dolomia Principale-Aralalta Group depositional system. d) Synsedimentary E-W oriented dyke system with dark internal sediments. NE margin of Alben carbonate platform.

(1988) in the lower-middle part of the Dolomia Principale of the Venetian Alps. Within this part of the Dolomia Principale, the presence of sedimentary dykes of centimetric scale, locally of metric scale (Fig. 1, 2a, 2d), is indicative of the beginning of extensional tectonics phenomena, which will characterize the upper part of the norian succession. A different situation can be observed in eastern Lombardy (Brescia area) where intraplatform basin facies already developed at the initial stage of deposition of the norian succession (Lumezzane Member, "facies eteropiche" of the Dolomia Principale; Boni & Cassinis, 1973; Frisia, 1991). These facies will persist almost for the whole time interval considered (Fig. 3).

3) The upper part of the peritidal platform was disrupted by the development of synsedimentary faults and subsequent generation of intraplatform basin facies in many areas of the Lombardy Basin, to be related with extensional tectonics. The structural highs between the basins are bordered by breccias and megabreccias (Fig. 2b) and/or reef facies (Fig. 4). Well bedded dark dolomites and limestones (Aralalta Group; Jadoul, 1986) characterize the thick basinal successions. Intraplatform basin lithofacies are mostly represented by calcareous diluited turbidites alternating with organic-rich, laminated rhythmites. In some areas adjacent to the platforms, debris flows and mass flows can be observed. The presence of organic-rich rhythmites (often bearing vertebrate fossil fauna; Tintori et al., 1985) can be ascribed either to local phenomena (for example sediment bypass) or, more probably, to the starvation of the basin following a low rate of carbonate productivity on the platform. This latter phenomenon may be linked to the periodic subaerial exposures controlled by sea level changes which affected the Dolomia Principale as documented by paleosoils observed both in the Brenta Dolomites and Venetian Alps (Bosellini & Hardie, 1988; Frisia, 1991). Preservation of delicate laminae, absence of bioturbation and abundant organic matter indicate anoxic sea floors and absence of benthic fauna.

Slumpings, both at millimetric (laminae) and at meter scale, can be locally observed within the basin lithofacies.

The setting of margin and slope facies allows for the reconstruction of the geometry of the intraplatform basins. In fact, the distribution of these facies is asymmetric (Fig. 3, 5) both within each basin and at a regional scale, and two margin types can be distinguished: 1) a tectonic one, characterized by thick breccia and megabreccia deposits due to the tectonic collapse of the platform margin connected with extensional tectonics and a possibly relatively low sea level stage; 2) a physiographically more gentle and stable or prograding margin with scarce breccia deposits. The presence of both margin types within each single basin can be explained by interpreting the basins as semigrabens.

The physiographic setting of the two margin types seems to follow a precise scheme (Fig. 3): in western and central Lombardy (Lualdi & Tannoia, 1986; Jadoul, 1986; Gaetani et al., 1987; Cirilli & Tannoia, 1988; Bini et al., 1991) tectonically controlled margins (marked by the presence of breccias and megabreccias bodies) are mostly located at the western border of the basin, while east of Idro Lake the breccias

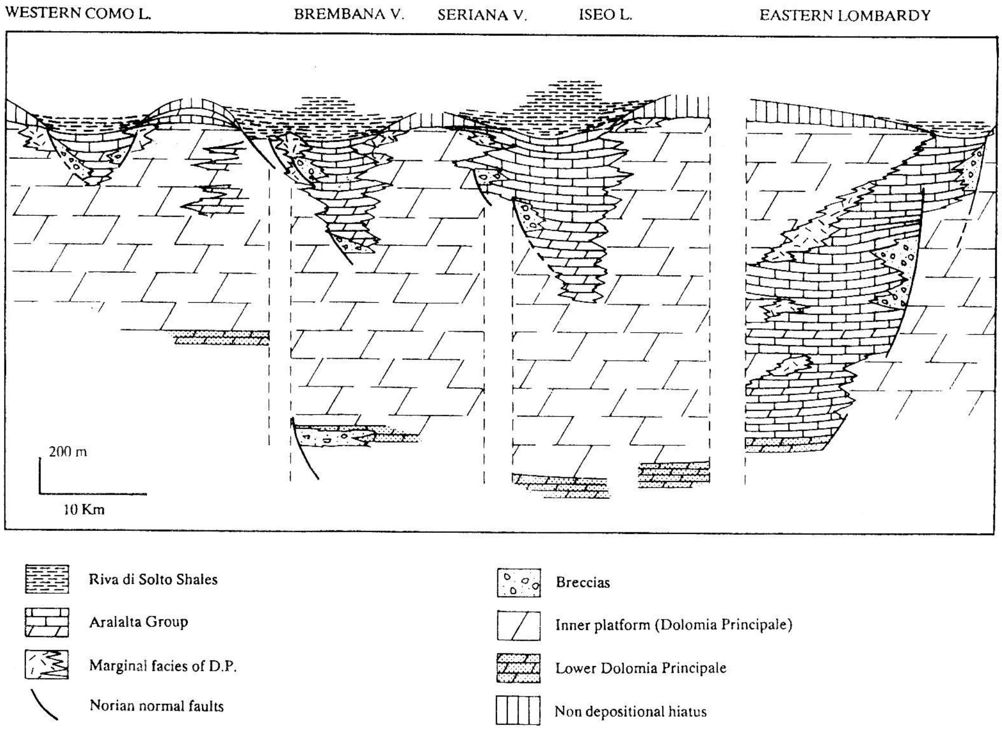


Fig. 3 - Schematic cross-section across the norian succession in Lombardy showing the lateral and vertical relationships between platform-margin-slope-basin facies. Note that fault-scarps developed westwards on the western side of the intraplatform basins, while eastwards the faults bounded the basins on the eastern side. The non depositional hiatus corresponds to the deposition of the lower Riva di Solto Shales in the troughs.

mostly occur at the eastern margin of the basins (Picotti & Pini, 1989; Frisia, 1991). Eastwards and westwards of the Lombardy Basin, the Dolomia Principale platform is not affected by the development of intraplatform basins because the carbonate productivity keeps pace with a lower subsidence rate. However, we hypothesize that even in those areas an increase in subsidence rate operated. The presence of prevalent subtidal cycles both in the Brenta Dolomites, Brescia region and Venetian Alps (Bosellini & Hardie, 1988; Frisia, 1991) may by the response to relative higher subsidence rates. However, in the Trento plateau and margin area such increase occurred in steps and it is not as regular as it is in central Lombardy. This is documented by the periods of subaerial exposures that affected with different degrees of intensity the carbonate platform and are responsible for the development of paleosoils which overlie directly the subtidal part of the cycles. Thickness and frequence of the paleosoils varies from one stratigraphic section to another, documenting the different behaviour of diverse blocks.

The norian extension (probably middle Norian, on the basis of paleontological data; Wild, 1989), which dissected the Dolomia Principale carbonate platform, was, therefore, particularly effective in Lombardy. At least four major troughs with asymmetric margins developed (Val Menaggio, Val Brembilla-Val Taleggio, Val Cavallina-Western Iseo, Idro Lake) (Fig. 5b).

4) Patch reefs and organic mounds develop on structural highs (possibly connected with tilted blocks originated in the preceeding phase) adjacent to the troughs, the most typical lithofacies of which are: oncoidal rudstones (Fig. 4a), bafflestones, bindstones with serpulids, dasycladacean *Algae*, *Porostromata* (Fig. 4b), *Spongiostromata*, cyanobacterial mats, and foraminifers. In the upper part of the Dolomia Principale there were also rare corals. The presence of these organisms, here more abundant than in the lower and middle parts of the platform, may be ascribed to both the overtaking of ecologic barriers (such as unfavourable salinity and insufficient oxygen content in the waters) and the connection between different intraplatform basins.

The margin facies often attempted to prograde both on slope breccia deposits (Fig. 2c) and, more rarely, on the Aralalta Group facies. These progradational facies were areally limited and did not block passageways between intraplatform basins, therefore forming narrow belts of small buildups about the carbonate platform structural highs. Progradation phenomena were more evident on the margins opposite the fault scarps (Picotti & Pini, 1989).

Several can be the factors responsible for the paleogeographic situation described: 1) relative sea level fall which may allow the mounds and reef builders productivity to match the subsidence rate, with subsequent progradation phenomena; 2) temporary relative tectonic stability (with lower subsidence rate); 3) a change in circu-

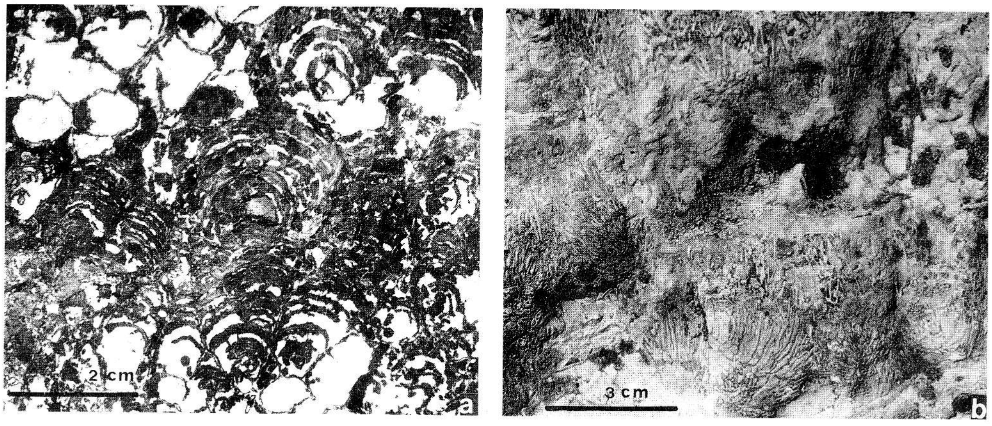
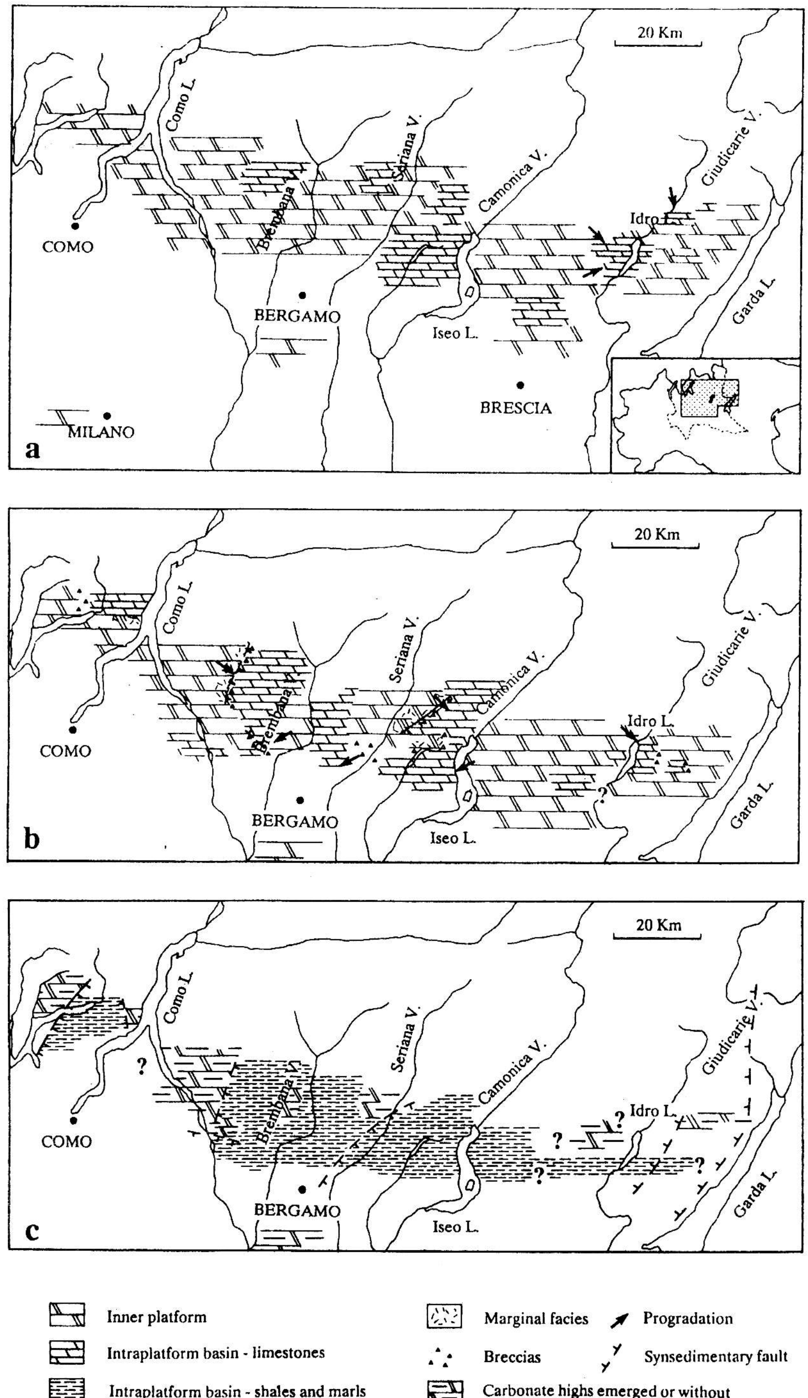


Fig. 4 - Patch reef lithofacies of the progradational margin of the uppermost Dolomia Principale platform. a) Stromatolitic-oncoidal structures consisting of mimetic, aphanitic dolomite laminae. Late diagenetic coarse sparry dolomite (white) partially replaces the oncoids. Pizzo Formico. b) *Porostromata*, the occurrence of which is a distinctive character of the topmost Dolomia Principale. Piani d'Artavaggio.


20 Km
Como L.
Seriana V.
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COMO
BERGAMO
Iseo L.
Garda L.
BRESCIA
MILANO
a
b
c
Inner platform
Intraplatform basin - limestones
Intraplatform basin - shales and marls
Marginal facies
Breccias
Carbonate highs emerged or without sedimentation
Progradation
Synsedimentary fault

lation pattern and nutrient distribution in marine waters, possibly connected with climatic fluctuations. In our opinion, the most important factor seems to be the relative sea level fall, recorded in the evidence of subaerial exposures (disconformity and breccia pockets at the top of Dolomia Principale) of parts of the carbonate platform (Albenza-Camissinone; Jadoul & De Bonis, 1981) about which these progradational margins developed. In the Lombardy Basin the presence of emerged platform areas, at this stage, is documented by finding of herbivorous terrestrial reptiles in the uppermost Aralalta Group (top of the Zorzino Fm., Wild, 1989; Renesto S., pers. comm.). Further proof of relative sea level fall may be found in the recovering of prevalent peritidal cycles deposition towards the top of the Dolomia Principale in some areas of the Venetian Alps (Bosellini & Hardie, 1988).

5) In the Late Norian (Wild, 1989, though precise dating is still debated, due to insufficient biostratigraphic control), sedimentation of clays began abruptly (Riva di Solto Shales) covering both the Dolomia Principale and the Aralalta Group (Fig. 6). This terrigenous input, related to the Late Norian transgression, brought to an end the production on the carbonate platform. At the same time, an increase in subsidence rate created a wider accomodation space as indicated by the great thicknesses of the Riva di Solto Shales which are present not only in the troughs but on marginal sectors of structural highs (Albenza-Val Imagna). In fact, the presence of shales on the structural highs implies that even at the top of the platform there was sufficient space to accomodate the terrigenous sediments.

Therefore, we may postulate the presence of a drowning unconformity (Schlager, 1989) between the carbonate platform deposits and the overlying shales. Although this unconformity between Riva di Solto Shales and underlying units is not evident in the field, its existence can be suggested from the common occurrence of slumpings marking the transition Aralalta Group-Riva di Solto Shales. The high concentration of slumpings in this stratigraphic interval could be ascribed to the different slope angle of the clays with respect to the underlying carbonates (Schlager, 1989). These slumping horizons can also be explained with intense syndepositional tectonic activity (Jadoul, 1986). Furthermore evidence for the drowning of the platform is the local presence of rare manganese and/or hematite crusts on some structural highs (Catra-merio, Cima Campelli). The nature of this drowning unconformity may be related to several effects: 1) a tectonic collapse with drowning of the central-eastern Lombardy area due to the rifting itself; 2) lack of carbonate production on the platform related to clay pollution and climatic changes. This particular situation, in a subsidence scenario, may explain the drowning of middle-late Norian carbonate platform highs in Lombardy. Only a few marginal areas and local structural highs were still emerged and not affected by the progressive onlapping of the Riva di Solto Shales

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Fig. 5 - Norian paleogeography of the Lombardy Basin at the time of deposition of the middle (a) and upper portion (b) of the Dolomia Principale and (c) during the deposition of the lower part of the Riva di Solto Shales.

(Fig. 6 b). Locally small patch reefs continued to grow during the deposition of the basal Riva di Solto Shales (Artavaggio Member; Jadoul, 1986).

The provenance of the terrigenous input and the causes of its mobilization are still debated. The abrupt beginning of the deposition of the Riva di Solto Shales is clearly linked to the final crisis of the carbonatic production, which came to an end in a relatively short period.

Paleogeographic reconstructions of the Late Norian (Wurster, 1968; Ziegler, 1982; Funk & Wildi, 1990), show the presence of deltaic bodies prograding from N-NE to S on the European continent. The development of these deltaic bodies took place starting from the permo-triassic basins of central Europe and subsequently advancing towards the tethyan margin (Ziegler, 1982). The passage through central Europe was bounded by emerged lands (the Bohemian-Vindelic high estwards and the Armorican high westwards) which may represent a possible source of terrigenous input. Recent paleogeographic reconstructions of the Carnian-Norian (Ziegler, 1988) do not consider a possible terrigenous transport through a seaway between the Helvetic domain and the Austroalpine-Southalpine domains. In our opinion a connection was active during the Upper Norian, but now it is not recognizable because of alpine

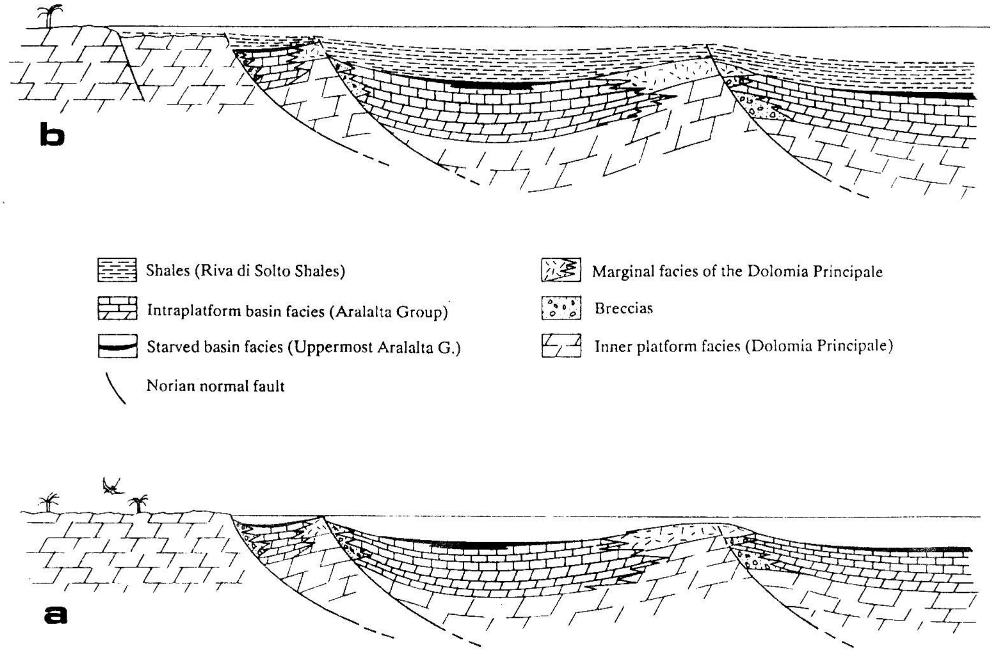

Fig. 6 - Scheme of the ideal evolution of the upper part of the Dolomia Principale and related intraplatform basinal facies. a) Period of basin starvation just before the beginning of the clay deposition. b) Time of clay deposition of the top of the Norian carbonate succession, linked with a relative sea level rise.

tectonism-metamorphism in Central Alps. The transport of the fine terrigenous to the south might have bypassed the less subsident (respect to the Lombardy Basin) Austroalpine carbonate platform that, in some unit (Ortles-Quatterval nappes) still preserves a thinner upper norian shaly succession similar to that of the western south-alpine (Pozzi, 1959; Furrer et al., 1985).

Transport and deposition of the shales in the tethyan gulf was possible because of the combination of the overcoming of topographic thresholds, as a consequence of sea level oscillations (cf. Ziegler, 1982) during a transgression which was in part tectonically controlled by the Mid-Late Norian rifting phase and climatic change, with the passage to a more humid climate. This latter is well documented, at least in land areas, by pollen and spores and the transition, all over the Europe, from gypsiferous and dolomitic horizons (Keuper) to limestones and clays (Hallam & El Shaarawy, 1982). This global phenomenon is recorded in the Lombardy Basin and adjacent areas where, when sedimentation of black shales begins, the last previously emerged, platform highs drawn. A more humid climate and a different paleogeographic setting (opening of passageways, pollution by clays) are, in turn, responsible for a reduced carbonate production at the time of sedimentation of the Riva di Solto Shales.

A renewal of carbonate production in areas adjacent to the Lombardy Basin is documented by the increase of the carbonate fraction in the Riva di Solto Shales towards the top of the formation. This phenomenon is possibly related to the washing away of carbonate from platforms (Masetti et al., 1989) which locally never ended or, more probably, from areas where sedimentation was not continuous (condensed peritidal cycles, hiatus in the upper Dolomia Principale, Campo dei Fiori Formations; Varese area and eastern Brenta Group).

Conclusions.

The stratigraphy of the norian succession in the Lombardy Basin and the evolutionary trend of intraplatform basins can be now analyzed with respect to the geodynamic setting. The geometry of intraplatform basins, genetically linked to an extensional tectonic phase (norian rifting), which preludes to the liassic opening of the "Pennidic Ocean", is asymmetric. In particular, east of Idro Lake the tectonic margin bounds the basins to the east, while in central-western Lombardy it is the westward margin to be tectonically controlled. Furthermore, the areal extension of basins with an eastern tectonic margin is much lower than that of the basins with a western tectonic one. These considerations allow the inference of a norian asymmetric ensialic rifting in the Lombardy Basin (Fig. 7).

According to the proposed model, crustal extension is responsible for the development of two different physiographic settings eastwards and westwards of the Lombardy Basin. East of Idro Lake the connection between the subsiding areas and the Trento Plateau was probably abrupt and geographically constrained. In fact, intraplatform basins with the tectonically controlled margin to the east are confined in the

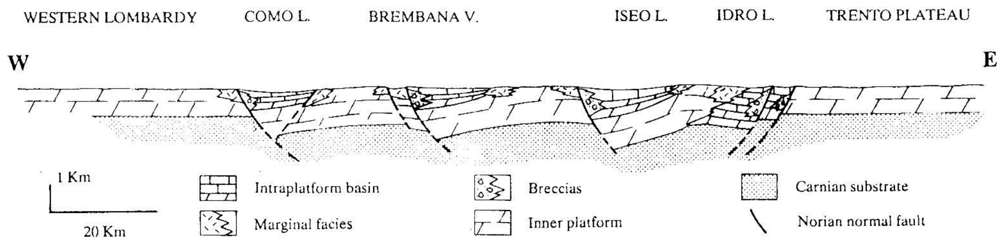

Fig. 7 - The asymmetric rifting model proposed for the norian tectonic extensional phase in Lombardy.

narrow belt between Idro Lake and Garda Lake. Therefore, an important listric fault (master fault), or a belt of listric faults, was probably active in this zone: this fault may well be the precursor of the Ballino-Garda Line (Castellarin, 1972), active during the liassic rifting. West of Iseo Lake the passage towards the western areas, characterized by low subsidence rates, occurs gradually and is marked by the progressive decrease in thickness of the succession from Iseo Lake westwards (Fig. 3). This situation can be explained with a series of listric faults which dissect the platform in several tilted blocks and cause higher subsidence rates (and subsequent maximum thickness of the succession) in the area of Iseo Lake. The westernmost of these listric faults could be sligthly more eastern precursor of the Lugano Fault (Bertotti, 1991), just east of Denti della Vecchia structural high (Lakew, 1990) (Fig. 8).

Therefore, in the Lombardy Basin an asymmetric depocentre with respect to the Trento Plateau (eastwards) and Varese region (westwards) structural highs existed during the Norian. This more subsiding area was located at first in the easternmost part of the trough (where intraplatform basin facies are present at the base of the norian succession), but then migrated towards Iseo Lake, where the norian succession is up to 3000 m thick (Assereto & Casati, 1965). In the rest of central-western Lom-

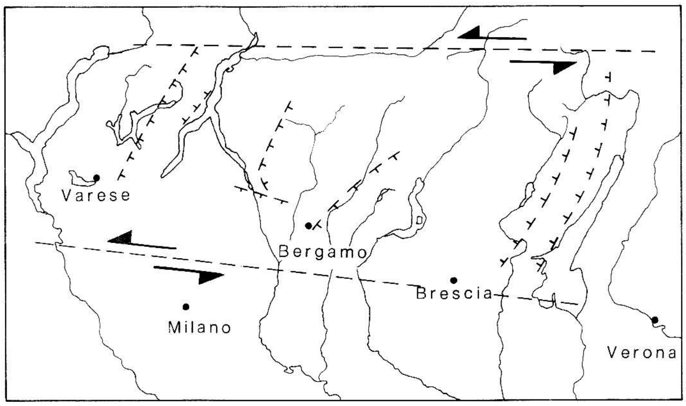

Fig. 8 - Proposed geodynamic reconstruction of the Upper Norian Lombardy Basin, interpreted as a pull-apart basin.

bardy the decreasing thickness of the succession outlines a later development of the intraplatform troughs with respect to the Iseo-Idro Lakes sectors.

The following liassic extension does not initiate in correspondence of the norian ensialic rifting, but develops further westwards, originating the Penninic Ocean.

The topography of the intraplatform basins, the distribution of the synsedimentary fault-scarps, the changes in thickness and the distribution of the facies all over the Lombardy Basin, allow the setting of the asymmetric ensialic norian rifting in a geodynamic scenario characterized by transtensional tectonics. The Lombardy Basin can be considered, during its late Triassic evolution, a pull-apart basin, bordered northwards and soutwards by W-E trending strike slip faults (Fig. 8). The reconstruction of the position of the two main strike-slip faults is difficult because of the Alpine orogeny. In Fig. 8 the position of the faults is hypothesized on the basis of the occurrence of E-W oriented sedimentary dykes (M. Alben, Fig. 2d) and on the presence of synsedimentary strike-slip faults in the norian succession (for example Val Mazzucchetta fault in Albenza area; Jadoul & De Bonis, 1981; Gaetani & Jadoul, 1988). A main strike-slip fault, south of the Lombardy Basin, can be placed in correspondence of that proposed by Doglioni (1987) for the Ladinian, which separated the northern side of the Southern Mobile Belt from the Lombardy succession (Fig. 8).

This geodynamic setting is similar to that suggested by Weissert & Bernoulli (1985) for the Southern Alps during the liassic rifting.

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