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AN ANOXIC INTRAPLATFORM BASIN IN THE MIDDLE TRIASSIC OF LOMBARDY (SOUTHERN ALPS, ITALY): ANATOMY OF A HYDROCARBON SOURCE

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Riassunto. Le rocce del Ladinico della Lombardia centrale sono costituite da estese masse di piattaforma carbonatica (Formazione di Esino), suddivise da solchi intrapiattaforma. Questi ultimi possono essere rappresentati sia da calcari scuri ben stratificati, marne e dolomie di ambiente poco o non ossigenato (Formazioni di Perledo-Varenna e Lierna), sia da calcari nodulari con selce (Formazione di Buchenstein). La subsidenza e i tassi di deposizione furono alquanto elevati (>100 m/MA), sia sulle piattaforme, che nei solchi intrapiattaforma anossici.

Lo studio sedimentologico delle rocce dei solchi anossici ha permesso di riconoscere 12 litofacies maggiori, tra cui i mudstone/wackestone, massivi o laminati, rappresentano più dei 2/3 dello spessore totale. Le brecce carbonatiche e i packstone, provenienti direttamente o indirettamente dalle adiacenti piattaforme carbonatiche, raggiungono il 6% dello spessore totale delle rocce bacinali. Le altre litofacies hanno importanza percentuale minore. Anche la micrite si ritiene sia sostanzialmente connessa alla sovrapproduzione della piattaforma carbonatica. Dal punto di vista dei processi deposizionali, si pensa che almeno i 3/4 dello spessore totale siano dovuti a processi di risedimentazione. La dolomitizzazione risulta diffusa nelle parti marginali del bacino. Non si è rinvenuta macrofauna bentonica, e solo occasionalmente il livello dell'ossigeno disciolto doveva raggiungere valori tali da consentire lo sviluppo di un'infauna senza scheletro mineralizzato. Nell'insieme della successione studiata sono state riconosciute due sequenze deposizionali, contrassegnate entrambe alla loro sommità da emersione sulla piattaforma carbonatica. La seconda fu molto significativa, tanto da portare alla estinzione del sistema piattaforma/bacino.

Il Gruppo delle Grigne è attualmente costituito da tre scaglie impilate tettonicamente. I dati concordanti di Riflettanza della Vitrinite, Cristallinità dell'Illite, e Alterazione del Colore dei Conodonti, indicano che vi è stato un aumento di temperatura entro le scaglie, procedendo da sud verso nord, e cioè da quella geometricamente piu' profonda a quella piu' elevata, che ha raggiunto il campo della diagenesi profonda, se non addirittura quello dell'anchimetamorfismo.

Abstract. The Ladinian rocks of Central Lombardy consist of carbonate platforms (Esino Formation) subdivided by intraplatform troughs represented either by dark, well bedded limestones, marls and dolomites of poorly oxic to anoxic environment (Perledo-Varenna and Lierna Formations), or by grey nodular cherty

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limestones (Buchenstein Formation). Subsidence and deposition rates were high (>100 m/MA), both on the carbonate platform and in the anoxic intraplatform troughs. Sedimentological study of the anoxic intraplatform rocks in the Grigne Mountains has identified 12 main lithofacies with mudstone/ wackestones, both massive and laminated, forming more than 2/3 of the total thickness. Packstones and carbonate breccias, all originating or fed from the neighbouring shallow carbonate platforms, represent 6 % of the total thickness in the basin. Also the dominating micrite is thought to have originated by overproduction on the carbonate platform. Concerning the depositional processes, almost 3/4 of the total thickness is interpreted as re-sedimented. Dolomitization is widespread in the marginal parts of the basin. No benthonic macrofauna is present, and only sporadically the bottom oxygen content was sufficient to support a non skeletal infauna. Two depositional sequences have been detected, both causing emersion on the carbonate platform. The younger emersion was severe and the platform/basin system ceased to exist.

The Grigne Mountains are presently arranged in three main tectonically stacked sheets. Vitrinite Reflectance, Illite Crystallinity Index, and Conodont Alteration Index, all suggest an increase of temperature within the sheets, from south to north, i.e. from the geometrically deeper to the more elevated, which has reached the field of deep diagenesis or even anchimetamorphism.

1. Introduction.

Two possible source rock units are developed in the Triassic of the western Southern Alps, both related to carbonate platform/anoxic intraplatform trough complexes. The older, Middle Triassic in age, consists of the carbonate platform of the Esino Formation (also called San Salvatore Dolomite in Ticino, Switzerland, and Varese province, Italy) and the related trough units of Perledo-Varenna, Lierna, Besano and Meride Formations. This geological pattern seems to be relevant for the oil fields of the Western Lombardy and east Piedmont like Gaggiano, Villa Fortuna, and Trecate (Pieri & Mattavelli, 1986; Conticini et al., 1987; Bongiorni, 1988).

The second group of potential source rocks are those deposed in the anoxic to poorly oxic troughs of the Dolomie Zonate Formation, Zorzino Limestone and Riva di Solto Shale (Late Triassic, mostly Norian), interfingering to the wide shallow carbonate complex of the Dolomia Principale Formation. Their bearing to the hydrocarbon production in the Po Basin has been already discussed by Errico et al. (1979), and by Pieri & Mattavelli (1986), dealing with the Malossa oil-field.

The Grigne Mountains at east and the Besano and M. San Giorgio belt at west, are the only areas were the Middle Triassic potential source rock complexes crop out (Fig. 1). The present study introduces a depositional model for the eastern area, whilst the Besano-M.S. Giorgio zone is still under study. Due to the great depth and to the tectonically dissected pattern (Bongiorni, 1988), the subsurface data provide a difficult picture for drawing a depositional model. These results originate from of a joint research project between AGIP Spa and Department of Earth Science of the University of Milano.

2. Geological setting.

The Grigne Mountains form a small range on the east side of Lake Como in Central Lombardy. The rocks there are well known for their Middle Triassic fauna

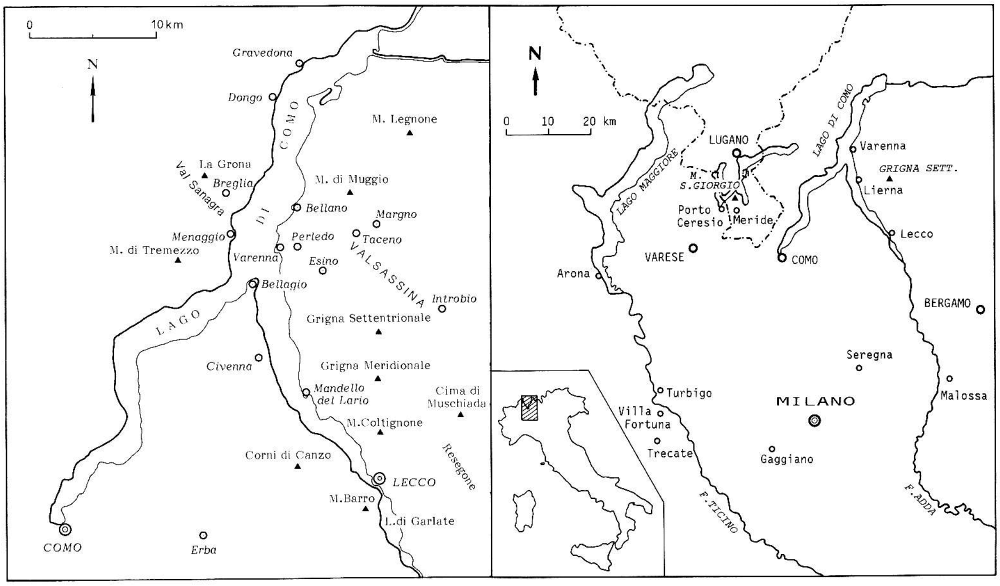

Fig. 1 - Index-map of the studied area and location of the more significant oil-fields in the near-by Po Plain.

since a century (Stoppani, 1858-60) and for their thrust sheet structure (Trümpy, 1930; De Sitter & De Sitter Koomans, 1949; Gaetani & Jadoul, 1979; Laubscher, 1985). They show also a well preserved platform/intraplatform complex, mostly developed during the Ladinian (Fig. 2).

At beginning of Middle Triassic times, the Grigne area was subdivided into an emergent area to northwest and west and a shallow bay to the southeast, with a wide terrigenous apron feeding and polluting the carbonatic bay (Gaetani et al., 1987). During Late Anisian times sea-level rose eustatically and the area was progressively submerged, so that during Ladinian times a complex carbonate platform/intraplatform pattern formed (Fig. 3).

The wide carbonate platform of the Esino Formation constitutes the backbone of three thrust sheets. However, the outcrop quality decreases from the Grigna Settentrionale, to the Grigna Meridionale, via Coltignone. In the Grigna Settentrionale the carbonate platform is about 6 km wide and interfingers to the southeast with grey nodular to platy cherty limestones (Buchenstein Formation) and volcaniclastic horizons (Pietra Verde-like) (Pasquarè & Rossi, 1969) (Fig. 3). Locally, thick volcaniclastic and siliciclastic input may follow ("Wengen" Formation). As far as the outcropping area is concerned, the carbonate platform eventually prograded over these basinal sediments.

To the northwest, the carbonate platform interfingers with dark-grey platy limestones, shaly marls and grey platy dolomitic limestones (Perledo-Varenna and Lierna Formations). Volcaniclastic input is limited. The minimal width of this intraplatform

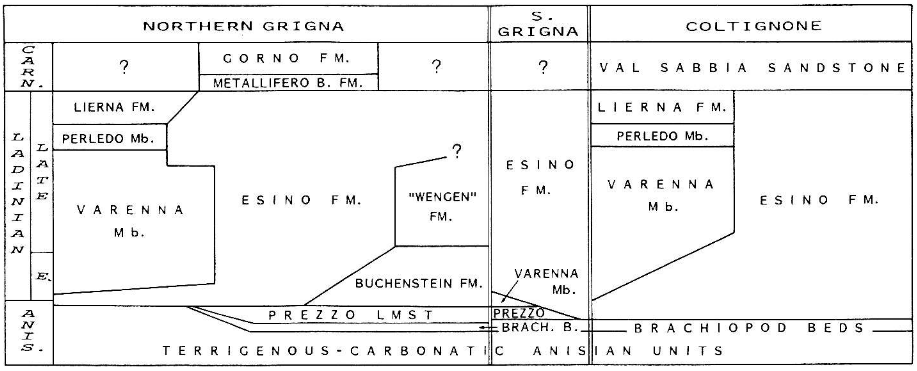

Fig. 2 - Stratigraphic scheme of the Anisian to Carnian units in the Grigne Mountains.

trough is about 7 km along the Varenna-Menaggio alignment (Fig. 3). In the Coltignone thrust sheet, the pattern has a similar orientation, but no basin deposits crop out to the south. Only slope facies may be detected in the Esino platform (Brusca et al., 1982). To the north, the platform interfingers with the basinal Perledo-Varenna and Lierna Formations, with the orientation and width of the paleogeographic elements comparable to the Grigna Settentrionale. However, tectonic fragmentation makes more difficult and interpretative the paleogeographic reconstruction. Finally, facies distribution and general paleogeographic interpretation, suggest a closure of the carbonate platforms westwards (Gaetani & Jadoul, 1987). The sediments of the anaerobic to disaerobic intraplatform troughs are obviously possible source-rocks. Both the troughs in the Grigne Mountains lie on the same side of the carbonate platform, suggesting some relationship to the general physiography. An hypothesis is that they lay leewards to the dominant winds.

3. Methods.

We have concentrated our study on the Perledo-Varenna and Lierna Formations. 12 stratigraphic sections or outcrop logs were measured, with a total thickness of about 1400 m (Fig. 4). About 600 samples were processed for sedimentology, petrography, conodont and pollen research, vitrinite reflectance, illite crystallinity index, ^{13}C and ^{18}O isotopic content, Total Organic Carbon (TOC) and Pyrolisis Rock-evaluation. All but the last three topics, are discussed in the present paper.

4. The basin succession.

The trough sequence consists of the Perledo-Varenna and Lierna Formations (Fig. 2, 5, 6). The *Perledo-Varenna Formation* has been known since more than a century for its fossil content (daonellids, Escher v. Linth, 1853; fishes and reptiles, De

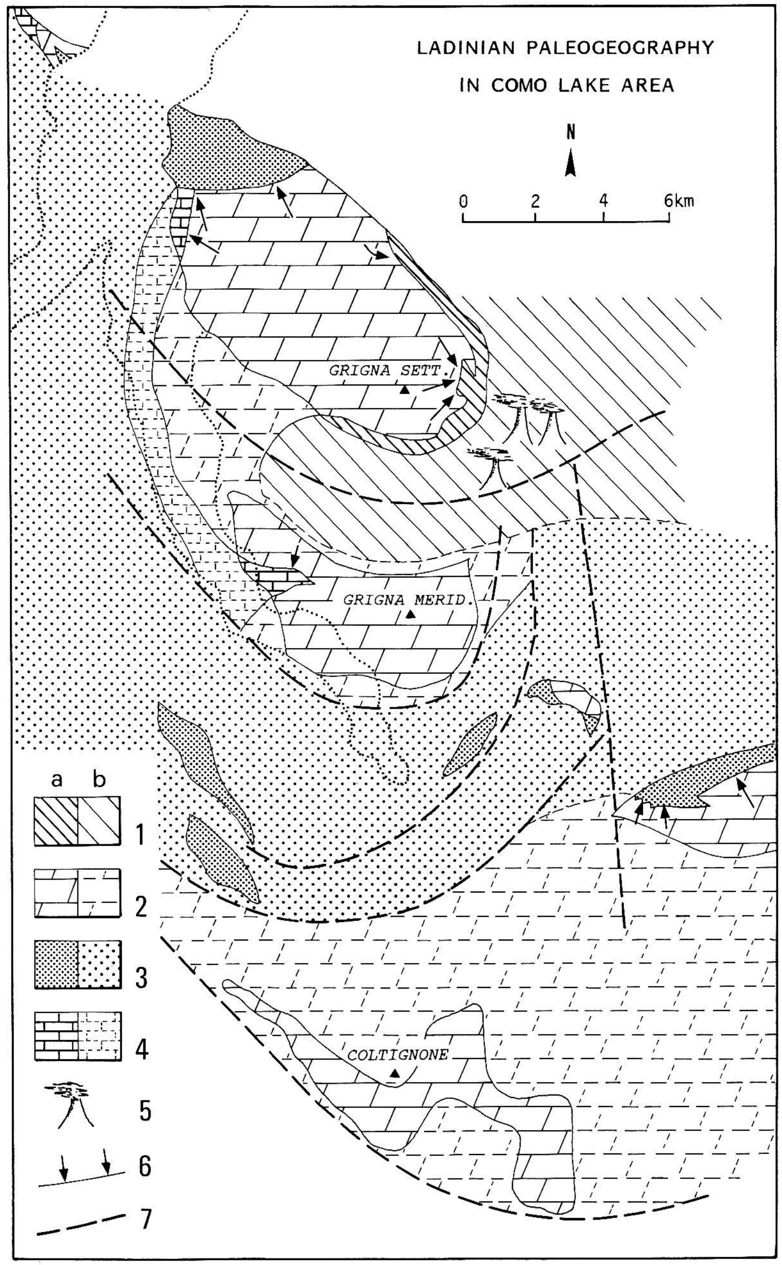

Fig. 3 - Ladinian palaeogeography in the Grigne Mountains Group. a) outcropping; b) interpreted. 1) mainly oxic intraplatform trough (Buchenstein Formation + "Wengen"); 2) carbonate platform (Esino Formation); 3) disaerobic to anaerobic intraplatform trough (Perledo-Varenna + Lierna Formations); 4) prograding belt of the carbonate platform on the Perledo-Varenna basin; 5) hypothetical position of the volcanic centres; 6) prograding direction of the carbonate platform observed on the field; 7) position of the main alpine thrusts.

Alessandri, 1910; Tintori et al., 1985) and for ornament stone quarring. This unit was described in some detail by Pasquarè & Rossi (1970). They used the double geographic name, merging the two facies: Calcare di Varenna and Scisti di Perledo originally distinguished by Stoppani (1857). We now use these two terms as Members. The

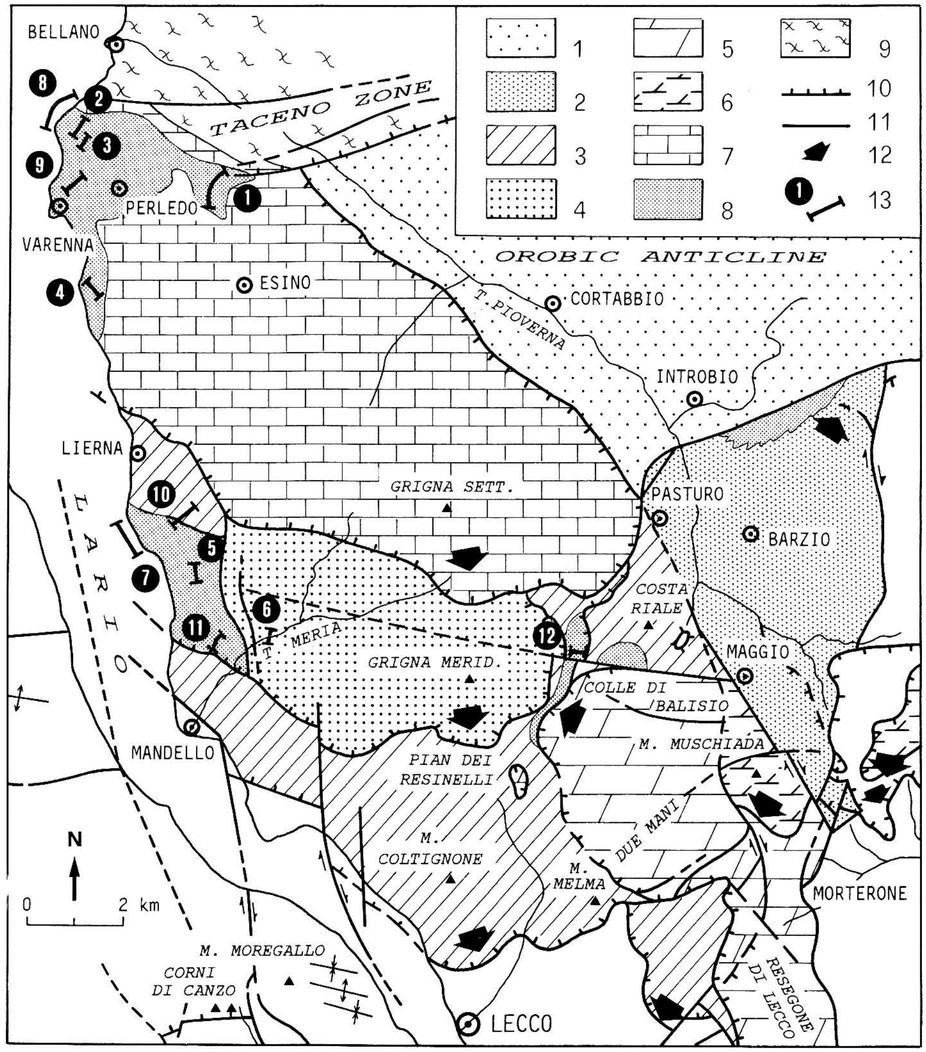

Fig. 4 - Tectonic setting of the Grigne Mountains Group and position of the stratigraphic sections. 1) basement and Permian rocks of the Orobic Anticline; 2) Middle Triassic and Carnian of the Barzio zone; 3) Coltignone Thrust Sheet; 4) Grigna Meridionale Thrust Sheet; 5 and 6) Upper Triassic rocks of the Due Mani, Resegone and Muschiada Sheets; 7) Grigna Settentrionale Thrust Sheet; 8) Perledo-Varenna Fm. outcrops in various tectonic settings; 9) crystalline basement; 10) thrusts; 11) faults; 12) sense of tectonic transport; 13) stratigraphic sections: 1 - Parlasco; 2 - Gittana; 3 - Sperone; 4 - La Gatta; 5 - Somana; 6 - Val Meria; 7 - Grumo; 8 - Morcate; 9 - Varenna; 10 - Sornico; 11 - Mandello; 12 - S. Anna. (From Jadoul & Gaetani, 1987, modified).

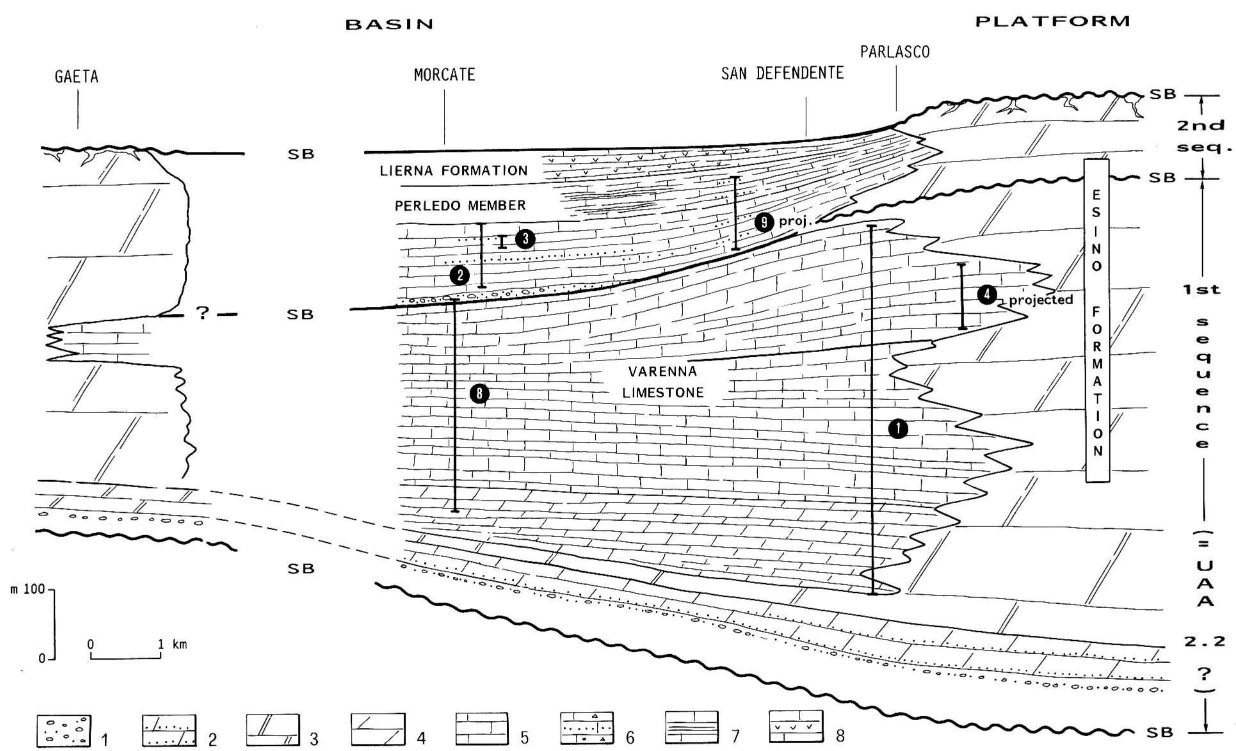

Fig. 5 - Stratigraphic scheme for the Grigna Settentrionale Thrust Sheet. 1) terrigenous and carbonate Anisian units (Bellano Fm. and Angolo Limst.); 2) Anisian peritidal dolomites; 3) carbonate platform: Esino Formation; 4) base of the Perledo-Varenna Formation, dolomitized; 5) Varenna Member; 6) coarse resedimented horizons; 7) Perledo Member; 8) Lierna Formation: SB) Inferred Sequence Boundaries. Numbers refer to the stratigraphic sections of Fig. 4.

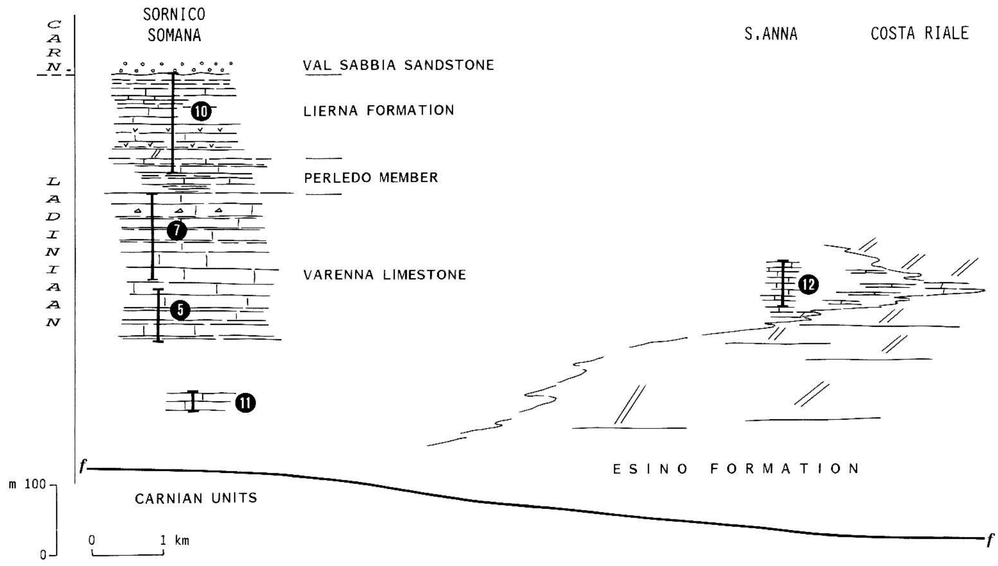

Fig. 6 - Stratigraphic scheme for the Coltignone Thrust Sheet. Note that the base of the Perledo-Varenna is not cropping out in this sheet. Numbers refer to the stratigraphic sections of Fig. 4.

Varenna Limestone Member consists of well bedded grey-dark limestones, subdivided by thin sheets of marls and dark clays (Fig. 7). The basal part is dolomitized, as well as the marginal fringe of this unit, for an average width of 500 m, where it makes transition to the carbonate platform of the Esino Formation. The maximum measured thickness is about 400 m. In the upper part, several calciruditic horizons appear, and are more frequent near the carbonate platform (Fig. 6).

The Perledo Member is much richer in thin bedded marly to shaly intercalations, which may form 10 to 50 cm sets, intercalated in the evenly laminated dark gre·ʳ limestones (Fig. 8). Most of the vertebrate fauna originates from this unit, which rarely attains 100 m thickness.

Above the Perledo-Varenna Formation we distinguish a new unit, the *Lierna Formation*, which is very poorly represented in the Grigna Settentrionale, where it was distinguished as "Marne gialline" by Gianotti and Tannoia (1988). It is much better exposed in the Lierna area, in the Coltignone Thrust Sheet. In this sheet it was previously referred to the Carnian Gorno Formation (Francani, 1971), suggesting a complicated tectonic pattern. We consider that the tectonics of the area are much simpler and that the Ladinian Lierna Formation simply lies above the Perledo Member. It consists of an alternance of grey well bedded laminated limestones and dolomites, with subordinated dark grey massive limestones, marls, and tuffitic layers. In the topmost part peritidal yellow dolomites are also present. The thickness is 130 m.

Fig. 7 - Dark grey, very finely laminated mudstones (Facies Mll) in the Perledo Member of the Perledo-Varenna Formation.

5. Facies analysis.

A total thickness of 1283 m was measured and analyzed in detail in the Perledo-Varenna Formation, and 130 m within the Lierna Formation.

5.1 Perledo-Varenna Formation.

In this unit twelve main lithofacies have been distinguished (Fig. 9-11).

1. Dark grey, finely parallel laminated mudstones and wackestones (MWl; Mll). Two end members have been designated. The first one (MWl) consists of alternating mudstone and wackestone laminae, containing scattered fossils (pelecypods, Radiolaria, ostracods) and peloids. Facies MWl occurs in beds up to 20 cm thick, often separated by very thin black shale layers. This facies represents about 14% of the measured sections in the Grigna Settentrionale Sheet and the 10% in the Coltignone Sheet. Facies MWl is inferred to represent grain-to-grain settling, in which laminae are related to periodic fluctuations in the biogenic carbonate input. Their preservation is due to unfavourable bottom conditions for life (cf. Facies E 2.2 of Pickering et al., 1986).

The second end member (Facies Mll, Fig. 7) consists of calcareous laminae (mudstone) rythmically alternating with very thin marly limestone laminae. Facies Mll occurs in sections a few cm to several m thick; individual beds are not easily detectable. This facies represents about 1.7% in the Grigna Settentrionale and 7% in the Coltignone Sheet. Depositional processes are inferred to be very similar to those of Facies MWl. Laminae are related to periodic fluctuations of biogenic and terrigenous material, within anoxic bottom conditions.

2. Dark grey, structureless mudstones and wackestones (MWm/1; MWm/2). Two end-members have been distinguished. The first one (Facies MWm/1, Fig. 8) prevails and consists of structureless mudstones and wackestones, often characterized by very thin, floating black shale clasts, up to 2 cm. This facies occurs in beds 2 cm to 25 cm thick, often separated by thin black shale layers. The wackestones contain fossils (Ostracoda, Foraminifera, etc.) and peloids. The second one (Facies MWm/2) is similar to MWm/1, occurring in thicker beds, generally 40-100 cm thick.

As a whole, Facies MWm/1 and /2 represent about 50% in the Grigna Settentrionale Sheet and 70 % in the Coltignone Sheet. They are inferred to represent relatively rapid deposition, respectively from dilute and high-concentration mud-dominated turbidity currents (cf. "disorganized turbidites" of Stow & Piper, 1984). The lime mud laden currents scoured the basin bottom and ripped up thin black shale clasts.

3. Facies Ma. We have grouped here some characteristic but sparsely represented lithofacies (about 3% in Grigna Settentrionale and 4% in the Coltignone Sheet) concerning: a) black, evenly laminated shales; b) dark grey shale-limestone rhythmites; c) dark grey, structureless or laminated marls. These lithofacies generally occurs in thin layers, a few mm to 10-12 cm thick, exceptionally reaching 50 cm in thickness. This facies group is inferred to represent grain-to-grain sedimentation. Laminae are

Fig. 8 - Dark grey, structureless mudstone-wackestones (Facies MWm/1), with floating thin black shale clasts, interbedded with mm-thick black shales or shale-limestone rhythmites (Perledo-Varenna Formation, Varenna Member).

connected to periodic fluctuation in the biogenic to terrigenous input. Structureless marls might be also related to dilute turbidity currents.

4. Grey to dark grey packstones (PC). This facies consists of packstones mainly made of fossil fragments (pelecypods, Algae, Ostracoda, Foraminifera), while locally peloids may be abundant. The packstones are often characterized by current ripple laminations or parallel laminations, and occur in beds up to 50 cm thick. This facies represent only 1-2% of the measured sections in the Grigna thrust sheets and testifies to occasionally active tractive currents on the basin bottom.

5. Grey to dark grey, normally graded packstones (PCg). These packstones are made of intraclasts and bioclasts (pelecypods, Algae, etc.) and occur in beds 10-60 cm, exceptionally 100 cm, thick. The grain size at the bed base may reach 1-2 cm. Over

the often erosional base, beds are characterized by well-developed normal grading. They show a structureless lower subdivision overlain by parallel lamination, and possibly passing up into ripple lamination.

Facies PCg is not frequent in both major thrust sheets, representing 2-3 % of the total measured thickness. It is inferred to represent deposition from high concentration turbidity currents (cf. Facies C 2.1 of Pickering et al., 1986).

6. Grey to dark grey calcareous breccias (BC). Facies BC includes rocks made of mudstone, wackestone and, locally, dolomite fragments. Grain sizes are generally from a few cm to 15 cm, but clasts up to several dm may be exceptionally present. Bioclasts are also frequent. Facies BC occurs in 20 cm to 2 m thick beds, mostly concentrated near the transition to the carbonate platform. Towards the bottom of the basin, carbonate breccias rarely exceed 1% of the total thickness.

Some different types have been observed: clast-supported, normally graded breccias; clast-supported, structureless breccias; matrix-supported breccias (grouped as F in Fig. 9 and 10). The clast-supported breccias are related to rapid sedimentation from high concentration turbidity currents or debris flows (cf. Facies A 1.1 and A 2.3 of Pickering et al., 1986). The matrix-supported breccias should derive by freezing

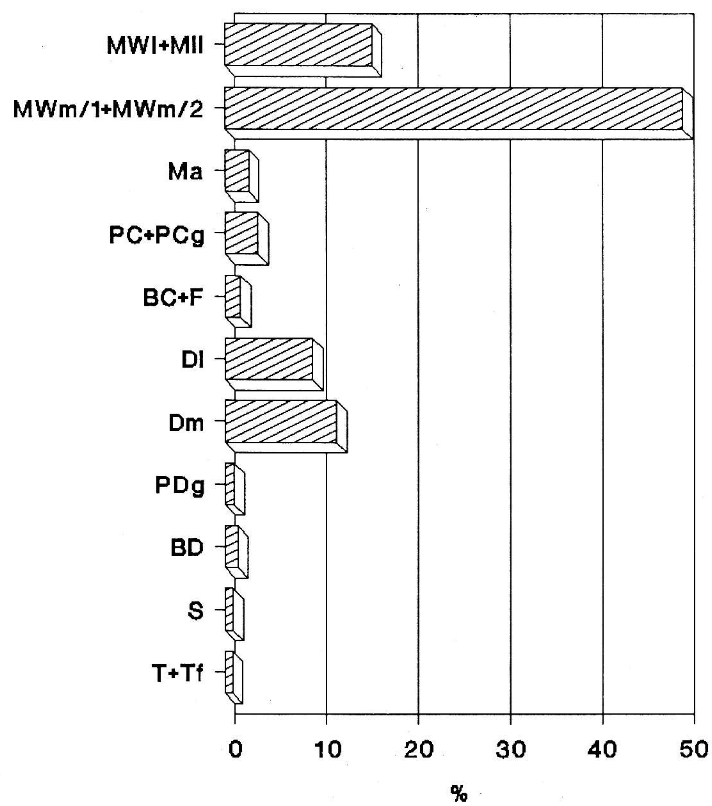

Fig. 9 - Lithofacies distribution in the Perledo-Varenna Formation in the Grigna Settentrionale Thrust Sheet. For acronyms refer to the text.

from cohesive debris flows (cf. Facies A 1.3 of Pickering et al., 1986).

7. Grey to dark grey, finely laminated dolomites (Dl). These rocks are inferred to represent a dolomitized version of Facies MWl and Mll. Facies Dl constitutes about the 10% of the measured thickness in the northern sheet, whilst it is mostly absent in the Coltignone, because the base of the unit is tectonically missing.

8. Grey to dark grey, structureless dolomites (Dm/1; Dm/2). These rocks are inferred to be a dolomitized counterpart of Facies MWm/1 and /2. They were found only in the northern sheet, where they represent about the 12% of the measured thickness.

9. Grey, normally graded dolomitic packstones (PDg). These dolomites are made of bioclasts (Algae, pelecypods, gastropods) and locally peloids. They show well-developed normal grading and occur in beds from a few cm to 45 cm thick. This facies is inferred to be the dolomitized counterpart of Facies PCg, and represents only the measured 1% in the northern sheet.

10. Grey dolomitic breccias (BD). These breccias occur in beds 15 cm to 1.8 m thick. They are inferred to represent the dolomitized analogue of Facies BC. They

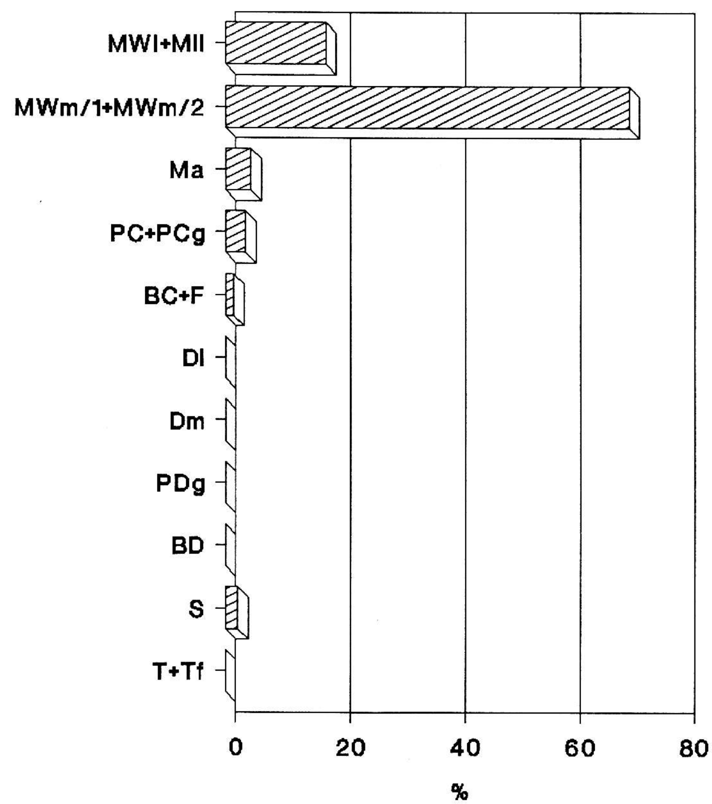

Fig. 10 - Lithofacies distribution in the Perledo-Varenna Formation in the Coltignone Thrust Sheet. For acronyms refer to the text.

represent the 1.5% of the measured sections in the Grigna Settentrionale Sheet.

11. Coherent folded/contorted strata (S). Facies S layers or horizons are rare (about 1% to the north and 2% in the Coltignone Sheet). Their thickness varies from 20 cm to 2.5 m. Facies S represents mainly gravity-induced sediment sliding and slumping; in situ, shock-induced deformation due to earthquakes is also possible (cf. Facies F 2.1 of Pickering et al., 1986).

12. Reworked (?) medium to very fine-grained tuffs (T;Tf). We have included in this group two lithofacies. The first one (Facies T) is made by medium to fine-sand sized grains (mainly feldspars; subordinately quartz; biotite is rare) and occurs in beds up to 25 cm thick. Facies T is structureless or shows parallel laminations or normal gradings. The second lithofacies (Facies Tf) is similar to the previous one, but it is very fine-grained (pelite-size); it occurs in beds 1 to 90 cm thick. As a whole these two facies are rare, less than 1% of measured thickness, and are concentrated in the north-east of the Grigna Settentrionale Sheet and in the lower middle part of the formation.

In conclusion, structureless carbonate rocks appear to be the most widespread deposits in the Perledo-Varenna Formation. The Facies MWm/1 and /2 and their dolomitic counterparts (Dm/1 and Dm/2) represent about 62% in the Grigna Settentrionale Sheet (50% + 12%) and 70 % in the Coltignone Sheet (Fig. 9 and 10). The second group is represented by the finely laminated carbonate rocks of facies MWl + Mll. Together with their dolomitic analogues (Dl) they form 26 % in the Grigna

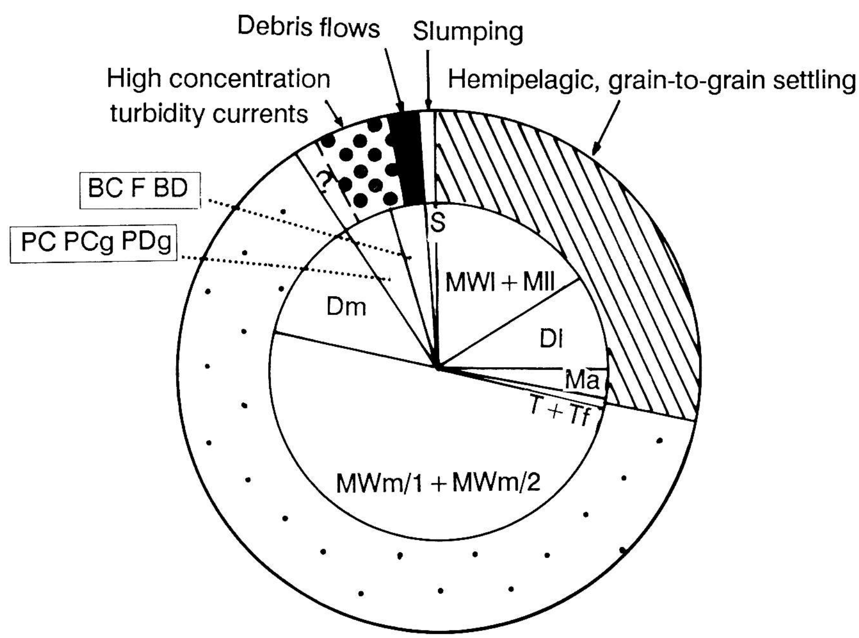

Fig. 11 - Depositional processes in the Grigna Settentrionale Thrust Sheet.

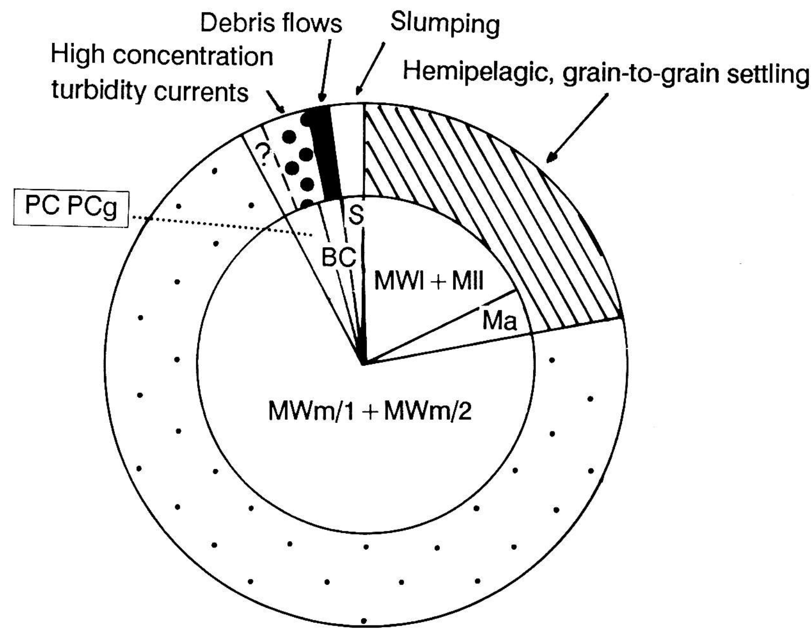

Fig. 12 - Depositional processes in the Coltignone Trust Sheet.

Settentrionale Sheet (16% + 10%) and 17 % in the Coltignone Sheet, where no dolomitic counterpart were measured. All the other lithofacies are subordinate, with individual percentages always below 5%. Calcarenitic to calciruditic facies, counted together, do not exceed 8% in the Grigna Settentrionale and 5% in the Coltignone Sheet.

As far as depositional process are concerned (Fig. 11 and 12), dilute turbidity currents were responsible for the 62% to 70% of the total measured thickness. Only 5-7 % was deposited under high concentration turbidity currents and debris flows. Another 22 to 28% are related to grain-to-grain hemipelagic settling. Slump and pyroclastic horizons represent the remaining deposits, which could have formed either as hemipelagites or as re-sediments.

5.2 The Lierna Formation.

The lithofacies of the Lierna Formation are similar to those of the Perledo-Varenna Formation, but with different occurrence percentages. Facies MWl and Mll represent about 50 % of the measured thickness, with dominance of the MWl facies. Facies MWm/1 and /2, and their partly dolomitized counterparts, represent here only 23%, whilst they were the majority in the Varenna Member. Facies T + Tf are more abundant, reaching the 3 %, testifying to the increasing volcanic activity towards the top of the stratigraphic interval here considered. This volcanic influence is even larger if we take in the account also Facies Ma + MaD. These consist of dark grey, locally dolomitic marls and clays in thick beds with thin interlayered cm-thick dolomitic beds. These facies reach 18% of the measured thickness and clay analyses suggests that part of the clay might be of volcanic origin. Finally, in the top, a facies of dolomitic mudstones and wackestones (MWD) consists of grey-yellowish dolomites, slightly brecciated and with clay films, in 10 to 50 cm-thick beds. They represent about 5% of the total measured thickness.

The Lierna Formation is inferred to represent a progressive shoaling in the basin, ending with subtidal to supratidal setting of dolomites. Depositional processes were now dominated by grain-to-grain deposition, with only 1/4 of the total thickness deposed under diluted turbidity currents. Also coarser sediments are noteably absent. The increasing pyroclastic material is in agreement with the latest Ladinian-Carnian evolution of the Central Lombardy area (Garzanti & Jadoul, 1985; Garzanti, 1986).

6. Age.

Fossil content is scanty, but sufficient to obtain a Ladinian age for the intraplatform sediments here considered (biostratigraphic classification according to Krystyn, 1983).

Near the base of the unit, in the Parlasco section, the conodonts *Gondolella trammeri*, *G. constricta*, *G.* cf. *longa*, followed a few decimeters higher by *G. bakalovi* and *Metapolygnatus* cf. *truempyi* have been found (identifications by A. Nicora, Milano). They indicate an upper Early Ladinian age. Moreover, 132 m from the base of the unit in the Morcate section the conodont *Metapolygnatus hungaricus* and the bivalve *Daonella moussoni* have been collected. Similar assemblages have been found above Regoledo. They testify to the Archelaus Zone of the Late Ladinian. Finally, in the upper part of the Lierna Formation, in the Sornico section, the palynomorphs *Ovalipollis pseudoalatus, Staurosaccites quadrifidus,* cf. *Triadispora plicata, Rimaesporites* sp., *Falcisporites* sp., *Alisporites* sp., have been isolated by E. Trincianti (AGIP SGEL). They suggest a Ladinian age.

7. The platform succession.

The Perledo-Varenna and Lierna Formations grade laterally into a carbonate platform unit called the Esino Formation. Named over a century (Hauer, 1858; Stoppani, 1858-60), it forms a huge composite carbonate body, about 1000 m thick in the southeast of Grigna Settentrionale, but only 500 m in the area of Pizzi di Parlasco. Several lithozones may be outlined. Basal peritidal stratified dolomites represent the transgressive set on the terrigenous shallow bay, the tidal flat and the alluvial plain. A huge body of massive or unbedded light grey limestones, often dolomitized, forms about 70-80 % of the total thickness. Where not dolomitized, they consist of biogenic packstones and grainstones, locally mudstones. Fossil content may be abundant, with major components made by algal crusts and envelopes, by blue-green Algae tufts as *Cladogirvanella* sp., by the microproblematic *Tubiphytes obscurus*, and subordinately by pelecypods, corals, and sponges, amongst which *Dyctiocoelia manon* may be recorded. Porifera and Scleractinia, however, form only small bafflestone patches, the main body consisting mostly of carbonatic skeletal sands. This first part ends with an emergence surface with palaeokarst, which is better exposed on the southern rim of the Grigna Settentrionale carbonate buildup.

A new carbonate lithozone occurs in the upper part of the Esino Formation, usually no thicker than 200-300 m. To the south, a massive lithofacies is observed, deeply dissected by large solution phenomena and precipitation of carbonate cements (Jadoul & Frisia, 1988; Frisia et al., 1989). The carbonate platform shows a well preserved interfingering with the basinal "Wengen" volcaniclastic sediments at southeast towards the Valsassina, with clinoforms dipping up to 20-25°.

To the northwest, from Bocchetta di Prada onwards, a stratified unit crops out, in two facies. A fully dolomitized facies is present near the transition to the trough, with an extension of 1-2 km. In the area of M. Pilastro-Cainallo, a still calcareous sequence crops out, showing a typical peritidal carbonate sequence, with algal laminae microfacies and skeletal sand microfacies, organized in m-thick cyclothems. From this stratified unit come most of the described ammonites (Mojsisovics, 1882; Rossi Ronchetti, 1960) which give the Late Ladinian age of the unit. At the top, repeated emergence phenomena are well exposed along the Agueglio-Cainallo road (Gaetani & Jadoul, 1986; Gaetani et al., 1987).

The Coltignone Thrust Sheet has a similar evolution, but is much more dolomitized and the lateral transition to the Perledo-Varenna and Lierna Formations is heavily tectonized. Also in the Piani Resinelli area, the unit ends with a very thick section of peritidal-supratidal cycles, in which well developed tepee structures may observed. The Grigna Meridionale Sheet shows instead an incomplete set of the Esino Formation, missing the top. Moreover, it is fully dolomitized.

8. Sequence stratigraphy.

Two depositional sequences may be recognized in the Upper Anisian-Ladinian rocks of the Grigne Mountains (Fig. 2, 5). The first has a much wider extent. Its basal unconformity may be identified in the topmost part of the Bellano Formation (Gaetani, 1982; Gaetani et al., 1987) and traced through the topmost part of the Angolo Limestone. At its base, the sequence contains a sublitharenitic/quartzarenitic body, partially eroding a substrate of marine and transitional carbonates. The Transgressive System Tracts should be represented by the Prezzo Limestone, by the basal lithofacies of the Esino Formation and by the transition tidal flat/basal dolomitized facies of the Perledo-Varenna Formation. The High Stand should be reached during the deposition of the Varenna Limestone Member, of the bulk of the massive Esino

Formation and by the Buchenstein Formation. This first sequence might end in the intraplatform basin with a discontinuity situated at the base of a carbonate breccia horizon, well exposed around Morcate and Varenna. The emersion facies on the carbonate platform identify the end of this first sequence.

The second sequence is much shorter and has a Low Stand corresponding to the carbonate breccias, intermingled in the topmost Varenna Limestone, whilst the Transgressive and High Stand System Tracts may be traced within the Perledo Member and the Lierna Formation. On the carbonate platform, the peritidal cycles of the Esino area and the slope deposits of the Valsassina side sequence belong to this. The final regression is testified by the wide emergence and the dissolution/cement precipitation phenomena recorded in the top of the Esino Formation, either on the massive, or on the stratified parts.

The single depositional sequence from Late Anisian to Late Ladinian (sequence UAA-2.2 of Haq et al., 1988) is here subdivided in two parts. A secondary cycle may be identified in the latest Ladinian, before the wider and larger sea-level fall. Such a two-fold subdivision may be present in other areas in Central Lombardy (Assereto et al., 1977; Jadoul & Frisia, 1988; Frisia et al., 1989). These two unconformity surfaces, especially the topmost one, may represent excellent stratigraphic plays.

9. Diagenesis.

The Illite Cristallinity Index (IK), according to the experimental conditions of Kübler (1968), was measured on 117 suitable samples, derived from the three thrust sheets. However, due to the very reduced extension of the Perledo-Varenna Formation in the Grigna Meridionale Sheet, significant comparisons may be only drawn for the two major sheets (Fig. 13, 14, 15). Most samples from the northern sheet have IK indexes between 4 and 7, thus well into the anchimetamorphism or deep diagenesis field. A few lie between 2.5 and 4. The Grigna Meridionale and Coltignone samples have more scattered IK values, with the bulk between 5.5 and 11. They fall into the diagenesis/deep diagenesis field. As a rough estimate, the two sets of rocks have suffered different heating levels, increasing from south to north (Fig. 13).

A similar pattern is shown by maturity estimates from optical analysis on organic matter by means of Vitrinite Reflectance (Ro). This analysis was performed on a Leitz Ortoplan MPV III Microscope System (reflected light, oil immersion), following the standard procedures suggested by Robinson (1969), Durand & Nicaise (1980), and MacKowsky (1982) for kerogen isolation. A minimum of 20-25 reflectance values were required for each sample to be statistically reliable. Fig. 14 illustrates the Ro regional pattern, on the base of 22 suitable samples collected in the three thrust sheets. In the northern sheet the average Ro is between 1.86% and 3.7%, whilst in the southern sheets, the average Ro lies between 1.72% and 1.97%. Thus in the southern sheets rocks remained within the wet-gas and condensates facies, whilst organic metamorphism was reached in the northern sheet.

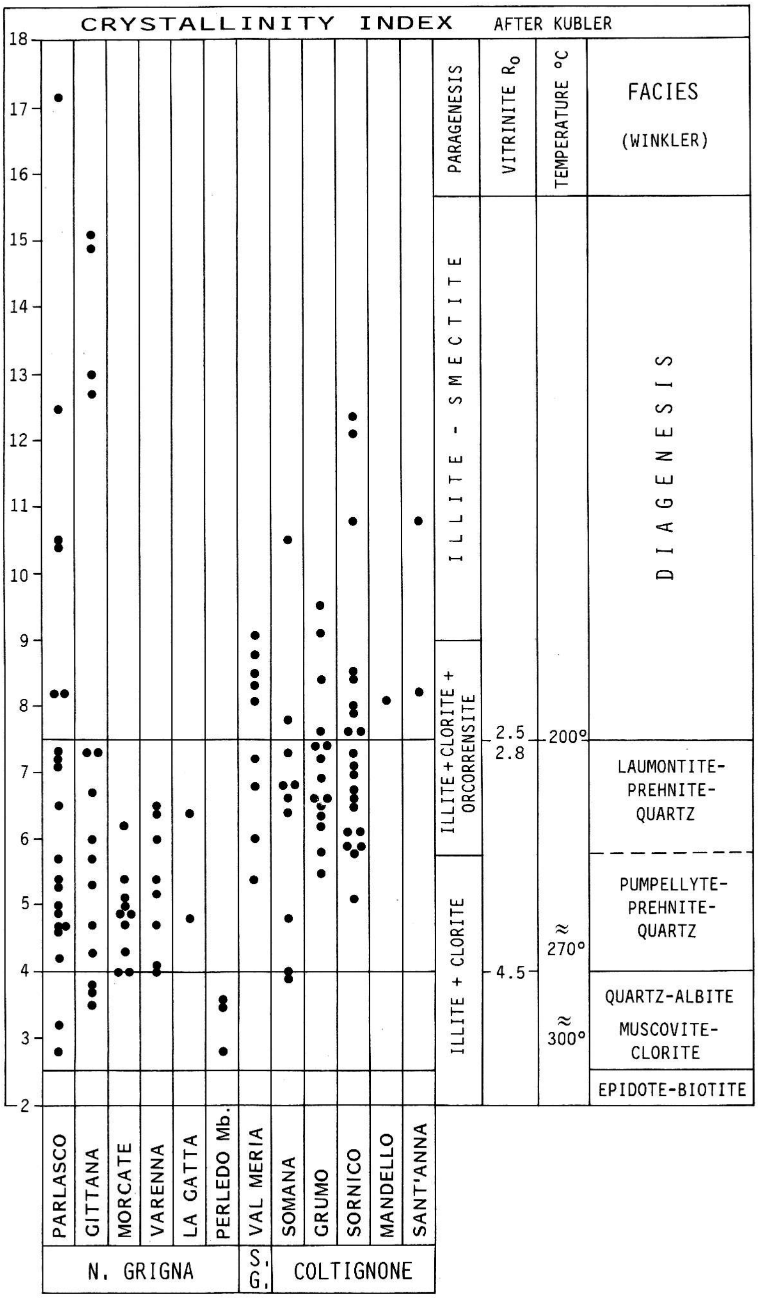

Fig. 13 - IK - Illite Crystallinity Index (Kübler Index) distribution in the three thrust sheets of the Grigne Mountains.

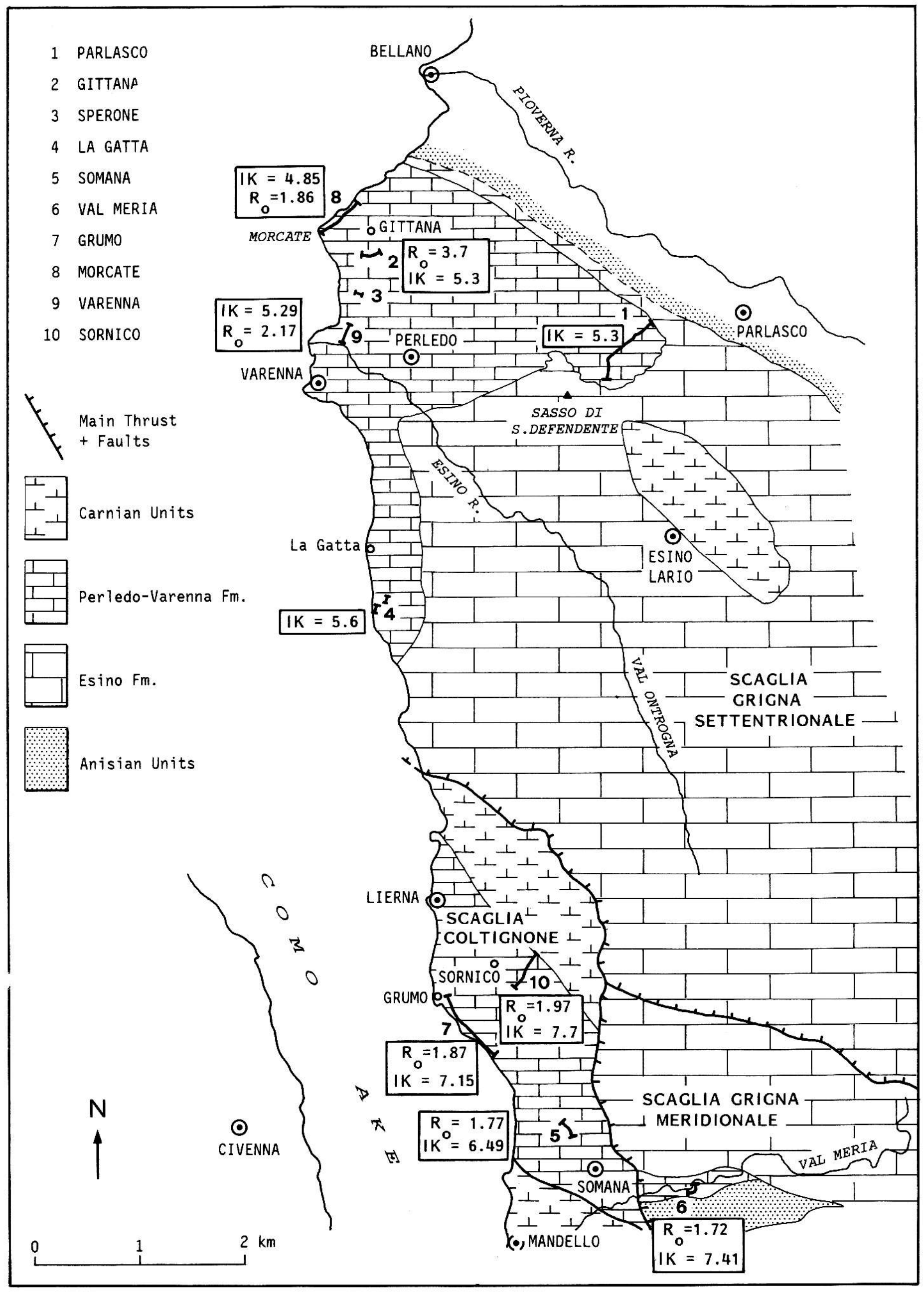

Fig. 14 - Distribution of average values for IK and Ro% in the stratigraphic sections.

The Conodont Alteration Index (CAI) (Epstein et al., 1977; Rejebian et al., 1987) was measured only on a few samples of the Grigna Settentrionale sheet, where the value is between 4-5 (Fig. 15). The burial temperature suggested by the conodonts of about 300° C in the Grigna Settentrionale agrees with the picture delineated by IK and Ro.

Isotope homogeneization was also detected in the vadose cements within the Esino Formation (Frisia et al., 1989), suggesting a late, strong, diagenetic overprinting, probably connected with the Alpine Orogenesis.

Lower values for the IK were found by Dunoyer De Segonzac and Bernoulli (1976) in the Upper Triassic rocks of Generoso Trough, west of the Grigne Mountains. Other samples collected south of the Grona fault in Anisian rocks (our data) and on the Corni di Canzo paleohigh in the Zu Limestone (Rhaetian) (Tesfaye, 1989) indicate similar lower burial values.

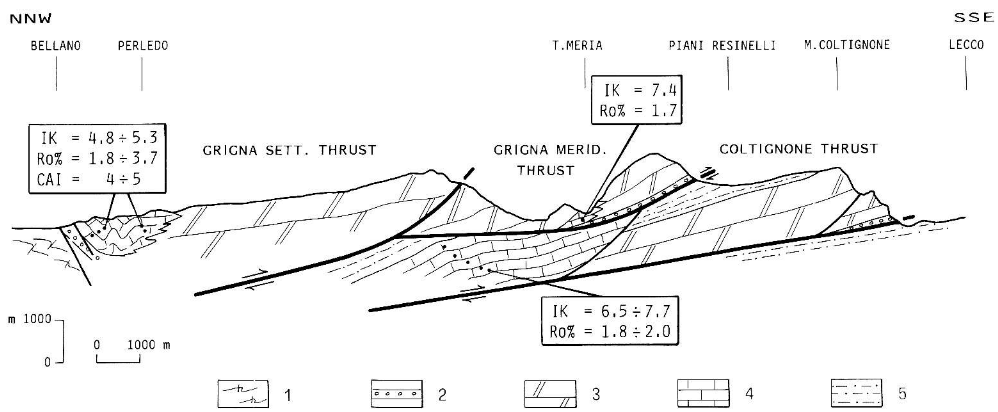

Fig. 15 - Structural scheme of the three thrust sheets with distribution of average IK, Ro% and CAI values. 1) crystalline basement; 2) Permian to Anisian terrigenous rocks; 3) carbonate platform (Esino Formation); 4) basinal rocks (Perledo-Varenna and Lierna Formations); 5) mixed terrigenous-carbonate units of Carnian age.

9.1 Discussion.

The burial temperatures of Perledo-Varenna and Lierna rocks give insight into the diagenesis and deformation history of the Grigne Mountains platform/intraplatform complex. The south to north trend of increasing temperature contrasts with the lower values observed in the west, at different stratigraphic levels. This is more striking because the Generoso Trough received a much heavier sediment burden during Mesozoic times (Bernoulli, 1964; Gaetani, 1975; Gaetani & Jadoul, 1987) than the Grigne Mountains. These latter would act more as a paleohigh during the Jurassic (as suggested by the resedimented earliest Jurassic breccias in the Civenna area) and thus with a much more reduced sediment burden. It is also difficult to account the increasing heating observed from south to north in the Grigna sheets on the basis of depositional changes, because the Late Triassic/Early Jurassic structural trends would imply no major subsidence changes in a north/south direction (Gaetani & Jadoul, 1987). In any case, more burden should expected to the south, due to the Carnian volcaniclastic prism (Garzanti & Jadoul, 1985).

No indication has been detected of a plutonic body below the Grigna Settentrionale, to account for the anchimetamorphic anomaly. A "from below stove model" could be also supposed in connection with the Triassic-Jurassic extension on the Adria passive margin, eventually resulting in the opening of the Ligurian-Piedmont Jurassic Ocean and in a shallowing of warmer astenosphere. Evidence of this heating from below are presently under study by Siletto et al. (pers. comm., 1990) in crystalline rocks, north of the Grigne Mountains. However, to account for the observed difference, several tens of km shortening should be hypotethized, larger than usually considered.

Consequently we are inclined to consider the Northern Grigna heat anomaly as due to thrust sheet tectonics. The sheets deriving from the south to north underthrusting, are now under exhumation and erosion. Time and tectonic overburding (another thrust sheet including basement rocks ?) could account, in our opinion, for the heating anomaly.

This south to north increasing trend of the diagenesis fits with the general pattern of the organic maturity in the subsurface equivalent rocks of the Po Plain. There, also at 5000 m depth, organic matter is often still immature (Chiaramonte & Novelli, 1985; Pieri & Mattavelli, 1986; Bongiorni, 1988).

Conclusions.

The Ladinian carbonate platform/intraplatform system of the Grigne Mountains indicates the existence of troughs in which sedimentation occurred mostly under anaerobic to disaerobic conditions, allowing organic matter burial. The carbonate sediments are thought to derive from the neighbouring carbonate platform, which acted as a "carbonate factory". Different depositional processes may account for the transport to the basin. For the Perledo-Varenna Formation the most important were dilute turbidity currents. They possibly originated from storm events which stirred up carbonate muds from the adjoining platform.

Waters loaded with suspended carbonate particles might be carried beyond the platform margin and plunge downslope as dilute turbidity currents. Shale intraclasts might be ripped up from previously sedimented black shales laminae. Rarely, high concentration turbidity currents and debris flows were triggered by slides involving platform margins and slope. Hemipelagic, grain-to-grain settling took place under generally anoxic bottom conditions, as testified by the well preserved laminations. The benthic organisms locally found in these deposits derived from the neighbouring carbonate platform. No direct evidence for the water depth in the basins has been found. The Buchenstein basin should have been deeper and the slope to the platform, especially in latest Ladinian times, steeper than the Perledo-Varenna / Lierna basin. This is indicated by the frequent and locally huge carbonatic megabreccia bodies and by the clinoforms found on the Valsassina side (Gaetani et al., 1987). Huge megabreccias are not present in the Perledo-Varenna Formation. Taking in account 1) the coarse breccia lenticular body cropping out near Morcate (Varenna) and its distance from the coeval platform margin (3000 m minimum) and 2) a possible average slope of 3, 4, 5 degrees respectively, possible water depths of 160, 210 and 260 m may be calculated for the deposition of the upper part of the Varenna Member. During the Perledo Member and the Lierna Formation, water depth should be even less deep. This would also indicate that the depth of the sills closing the basin and causing water stratification, were probably only a few tens of meters.

In conclusion, this is a possible scenario to be encountered in the subsurface source rocks-reservoirs complexes of the neighbouring Po Plain.

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REFERENCES

Assereto R., Jadoul F. & Omenetto P. (1977) - Stratigrafia e metallogenesi del settore occidentale del distretto a Pb, Zn, fluorite e barite di Gorno (Alpi Bergamasche). *Riv. It. Paleont. Strat.*, v. 83, n. 3, pp. 395-532, 69 fig., Milano.

Bernoulli D. (1964) - Zür Geologie des M. Generoso (Lombardische Alpen). *Mater. Carta Geol. Svizzera*, v. 118, pp. 1-134, 2 pl., 51 fig., Bern.

Bongiorni D. (1988) - La ricerca di idrocarburi negli alti strutturali mesozoici della Pianura Padana: l'esempio di Gaggiano. *Atti Tic. Sc. Terra*, v. 31, pp. 125-141, Pavia.

Brusca C., Gaetani M., Jadoul F. & Viel G. (1982) - Paleogeografia ladino-carnica e metallogenesi del Sudalpino. *Mem. Soc. Geol. It.*, v. 22 (1981), pp. 65-82, Roma.

Chiaramonte M.A. & Novelli L. (1985) - Organic matter maturity in northern Italy: some determinant agents. (Abst.) *Proceedings 12th Intern. Meeting Organic Geochemistry.*

Conticini F., De Scalzi C., Mazzei R. & Salvador L. (1987) - Seismic prospecting combined with core and log analysis to define the internal structure of a reservoir. *12th World Petroleum Congr.*, pp. 1-13, Houston.

De Alessandri G. (1910) - Studi sui Pesci triassici della Lombardia. *Mem. Soc. It. Sc. Nat.*, v. 7, pp. 1-145, 9 pl., Milano.

De Sitter L. U. & De Sitter Koomans C.M. (1949) - The Geology of the Bergamasc Alps, Lombardia, Italy. *Leid. Geol. Mededel.*, v. 14 B, pp. 1-257, 2 geol. maps, Leiden.

Dunoyer de Segonzac G. & Bernoulli D. (1976) - Diagenèse et métamorphism des argiles dans le Rhétien Sud-alpin et Austro-alpin (Lombardie et Grisons). *Bull. Soc. Géol. France*, s. 7, v. 18, pp. 1283-1293, Paris.

Durand B. & Nicaise G. (1980) - Procedures for kerogen isolation. Kerogen, chapt. 2, pp. 35-52, Technip, Paris.

Epstein A.G., Epstein J.B. & Harris L.D. (1977) - Conodont Color Alteration - an Index to Organic Metamorphism. *Geol. Surv. Prof. Pap.*, v. 995, pp. 1-27, 20 fig., Washington.

Errico G., Groppi G., Savelli S. & Vaghi G. C. (1979) - Malossa field, deep discovery in Po Valley. In Giant Oil and Gas Fields of the decade 1968-1978. *Amer. Assoc. Petrol. Geol. Mem.*, v. 30, pp. 525-538, Tulsa.

Escher v. der Linth H. (1853) - Lagerung und Alter des Schrattenkalkes; Reihenfolge der Formationen in Voralberg und im Bergamaskischen. *N. Jahrb. Miner., Geol. Palaeont.*, 1853, pp. 165-168.

Francani V. (1971) - Osservazioni sulla geomorfologia e l'idrologia del gruppo delle Grigne. *Geol. Tecnica*, v. 18, pp. 71-101, 6 fig., 1 geol. map, Milano.

Frisia Bruni S., Jadoul F. & Weissert H. (1989) - Evinosponges in the Triassic Esino Limestone (Southern Alps): documentation of early lithification and late diagenetic overprint. *Sedimentol.*, v. 36, pp. 685-699, 9 fig., Oxford.

Gaetani M. (1975) - Jurassic stratigraphy of Southern Alps: a review. In Squyers C. (Ed.) - Geology of Italy. *Earth Sc. Soc. Lybian Arab. Rep.*, pp. 377-402, Tripoli.

Gaetani M. (1982) - Elementi stratigrafici e strutturali della galleria Bellano-Varenna (nuova SS 36) (Como). *Riv. It. Paleont. Strat.*, v. 88, n. 1, pp. 1-10, 2 fig., Milano.

Gaetani M. & Jadoul F. (1979) - The structure of the Bergamasc Alps. *Rend. Acc. Naz. Lincei, Cl. Sc. Mat. Fis. Nat.*, s. 8, v. 66, n. 5, pp. 411-416, 1 fig., Roma.

Gaetani M. & Jadoul F. (1986) - Escursione N. 1, Stop 1.5: Alpe di Agueglio. La successione ladinico sommitale-carnica della Grigna Settentrionale. *Guida all'escursione*, Conv. Geol. Lariana, Varenna.

Gaetani M. & Jadoul F. (1987) - Controllo ancestrale sui principali lineamenti strutturali delle Prealpi Lombarde Centrali. *Rend. Soc. Geol. It.*, v. 10, pp. 21-24, 1 fig., Roma.

Gaetani M., Gianotti R., Jadoul F., Ciarapica G., Cirilli S., Lualdi A., Passeri L., Pellegrini M. & Tannoia G. (1987) - Carbonifero superiore, Permiano e Triassico nell'area Lariana. *Mem. Soc. Geol. It.*, v. 32 (1986), pp. 5-48, 3 pl., 18 fig., Roma.

Garzanti E. (1986) - Source rock versus sedimentary control on the mineralogy of deltaic volcanic arenites (Upper Triassic, Northern Italy). *Journ. Sedim. Petrol.*, v. 56, n. 2, pp. 267-275, 5 fig., Tulsa.

Garzanti E. & Jadoul F. (1985) - Stratigrafia e paleogeografia del Carnico lombardo (Sondaggio S. Gallo, Valle Brembana). *Riv. It. Paleont. Strat.*, v. 91, n. 3, pp. 295-320, 7 fig., Milano.

Gianotti R. & Tannoia G. (1988) - Elementi per una revisione stratigrafico-paleontologica del Trias medio-superiore della regione compresa tra il Lario ed il Ceresio. *Atti Tic. Sc. Terra*, v. 31, pp. 434-445, 3 fig., Pavia.

Haq B.U., Hardenbol J. & Vail P. (1988) - Mesozoic and Cenozoic Chronostratigraphy and Eustatic Cycles. *Soc. Econ. Paleont. Min., Spec. Publ.*, v. 42, pp. 48-70, 15 fig., Tulsa.

Hauer F.R. (1858) - Erläuterungen zu einer geologischen Uebersichts-Karte der Schichtgebirge der Lombardei. *Jb. K. K. Geol. Reichsanst.*, v. 9, pp. 445-496, 1 geol. map, Wien.

Jadoul F. & Gaetani M. (1987) - L'assetto strutturale del settore lariano centro-meridionale. *Mem. Soc. Geol. It.*, v. 32 (1986), pp. 123-132, 3 fig., Roma.

Jadoul F. & Frisia S. (1988) - Le Evinosponge: ipotesi genetiche di cementi calcitici nella piattaforma ladinica delle Prealpi Lombarde (Alpi Meridionali). *Riv. It. Paleont. Strat.*, v. 94, n. 1, pp. 81-103, 11 fig., Milano.

Krystyn L. (1983) - Das Epidaurus-Profil (Griechenland) - ein Beitraeg zur Conodonten Standardzonierung des Tethyalen Ladin und Unterkarn. *Schrift. Erdw. Komm. Oesterr. Akad. Wiss.*, v. B5, pp. 231-258, 2 fig., Wien.

Kuebler X. (1968) - Evaluation quantitative du métamorphisme par la cristallinité de l'illite. *Bull. Centre Rech. Pau*, v. 2, pp. 385-397, Pau.

Laubscher H. P. (1985) - Large-scale, thin-skinned thrusting in the Southern Alps: Kinematic models. *Geol. Soc. Amer. Bull.*, v. 96, pp. 710-718, 8 fig., Boulder.

MacKowsky M. (1982) - Stach's textbook of Coal Petrology. Methods and tools examinations. Pp. 296-299, Borntraeger, Berlin.

Mojsisovics E. v. (1882) - Die Cephalopoden der Mediterranen Trias-Provinz. *Abh. K. K. Geol. Reichsanst.*, v. 10, pp. 1-322, 94 pl., Wien.

Pasquarè G. & Rossi P.M. (1969) - Stratigrafia degli orizzonti piroclastici medio-triassici del gruppo delle Grigne (Prealpi Lombarde). *Riv. It. Paleont. Strat.*, v. 75, n. 1, pp. 1-83, Milano.

Pasquarè G. & Rossi P.M. (1970) - Calcare di Perledo-Varenna. *St. Illustr. Carta Geol. Italia, Formazioni geologiche*, v. 4, pp. 43-55, 3 fig., Roma.

Pickering K., Stow D., Watson M. & Hiscott R. (1986) - Deep-water Facies, Processes and models: A Review and Classification Scheme for Modern and Ancient Sediments. *Earth-Sc. Rev.*, v. 23, pp. 75-174, Amsterdam.

Pieri M. & Mattavelli L. (1986) - Geologic Framework of Italian Petroleum Resources. *Amer. Assoc. Petrol. Geol. Bull.*, v. 70, pp. 103-130, Tulsa.

Rejebian V. A., Harris A. G. & Huebner J. S. (1987) - Conodont color and textural alteration: An index to regional metamorphism, contact metamorphism and hydrothermal alteration. *Geol. Soc. Amer. Bull.*, v. 99, pp. 471-479, Boulder.

Robinson W. E. (1969) - Isolation procedures for kerogens and associated soluble organic materials. In Organic geochemistry, pp. 181-193.

Rossi Ronchetti C. (1960) - Il Trias in Lombardia (Studi geologici e paleontologici). II. Cefalopodi ladinici del Gruppo delle Grigne. *Riv. It. Paleont. Strat.*, v. 66, n. 1, pp. 1-64, 8 pl., Milano.

Stoppani A. (1857) - Studi geologici e paleontologici sulla Lombardia. V. of 461 pp., 4 pl., Milano.

Stoppani A. (1858-60) - Les pétrifications d'Esino, ou déscription des fossiles appartenant au depôt supérieur des environs d'Esino en Lombardie. *Paléont. Lombarde*, v. 1, pp. 1-151, 3 pl., Milano.

Stow D.A.V. & Piper D.J.S. (1984) - Deep-water fine-grained sediments: facies models. In Stow D.A.V. & Piper D.J.S. (Eds.) - Fine Grained Sediments: Processes and Facies. *Geol. Soc. London, Spec. Publ.*, n. 15, pp. 611-645, London.

Tesfaye L. (1989) - Sedimentologia, analisi delle microfacies e diagenesi del Calcare di Zu nella Lombardia centrale. *Ph. D. Thesis*, Milano.

Tintori A., Muscio G. & Nardon S. (1985) - The Triassic fossil fishes localities in Italy. *Riv. It. Paleont. Strat.*, v. 91, n. 2, pp. 197-210, 3 fig., Milano.

Trümpy E. (1930) - Beitrag zur Geologie der Grignagruppe am Comersee (Lombardei). *Ecl. Geol. Helv.*, v. 23, n. 2, pp. 379-487, 3 pl., 3 fig., 1 geol. map, Basel.