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The Lombardian Gonfolite Group in central Brianza (Como and Milano Provinces, Italy): Calcareous nannofossil biostratigraphy and sedimentary record of neo-alpine tectonics

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Keywords: Southern Alps, Miocene, calcareous nannofossil biostratigraphy, foredeep turbidites, provenance, neo-alpine tectonics

ABSTRACT

The sedimentary succession cropping out in central Brianza, in an area embracing the territories of Besana Brianza, Briosco (Milan Province), Arosio and Inverigo (Como Province), is properly ascribed to the Lombardian Gonfolite Group. It consists of prevailing turbidite sandstones and marls, with conglomerate beds occurring in the central part of the section.

A precise biostratigraphic dating of the succession was obtained through the analysis of calcareous nannofossils. The occurrence of reliable index species allowed us to recognise the NN3 to NN6 nannoplankton zones (Burdigalian to Serravallian). Since in the type-areas between Varese and Como the youngest dated units of the Gonfolite Group are Burdigalian in age, the studied succession documents a more recent part in the history of the south-alpine foredeep, that might have been recorded in outcrop elsewhere in Lombardy only by the ill-dated Gurone Sandstone and Bizzozzero Mudstone (Varese area). The deformation of the studied succession seemingly requires a single event of tectonic buckling, that is reliably constrained as late Serravallian to Tortonian (late "Lombardic Phase").

Provenance signals point to roughly contemporaneous exhumation of the Pennidic nappes and active stacking of thrust sheets in the uprising Southern Alps. This phase of tectonic activity took place around the Langhian/Serravallian boundary (early "Lombardic Phase").

RIASSUNTO

La successione sedimentaria affiorante in un piccolo settore della Brianza centrale, che abbraccia il territorio dei Comuni di Besana Brianza, Briosco (Provincia di Milano), Arosio and Inverigo (Provincia di Como), mostra una chiara appartenenza al Gruppo della Gonfolite Lombarda. Essa è rappresentata da prevalenti arenarie e marne in facies torbiditica, con strati conglomeratici limitati alla parte centrale della colonna stratigrafica.

Una datazione biostratigrafica precisa della successione è stata possibile grazie all'analisi dei nannofossili calcarei. La presenza di specie-indice affidabili ci ha consentito di riconoscere le zone a nannoplancton dalla NN3 alla NN6 (Burdigaliano-Serravalliano). Poiché nelle località-tipo tra Varese e Como le unità più recenti riconosciute all'interno della Gonfolite sono burdigaliane, la successione studiata documenta uno stadio più recente nell'evoluzione dell'avanfossa sudalpina, che potrebbe essere stata registrata in altri affioramenti in Lombardia solo dalle Arenarie di Gurone e dalle Peliti di Bizzozero (Varese), unità la cui datazione rimane tuttavia poco precisa. La deformazione della successione in esame sembra compatibile con un singolo evento di piegamento, che si può ricondurre in modo convincente al Serravalliano superiore-Tortoniano (tarda "Fase Lombarda").

I segnali di provenienza indicano una sostanziale contemporaneità tra l'esumazione delle falde Penniddiche e l'impilamento attivo dei sovrascorrimenti nelle Alpi Meridionali in via di sollevamento. Questa fase di attività tettonica ebbe luogo attorno al limite Langhiano/Serravalliano ("Fase Lombarda" iniziale).

Introduction

Foredeep basins generally preserve relevant information about the evolution of collisional belts. Sedimentological, biostratigraphical and provenance studies on foredeep turbidites can greatly help to unravel the complex interplay of tectonic and magmatic processes that concurrently work to the building of a mountain belt.

Among the foredeep sediments bordering the alpine-apenninic suture, the Lombardian Gonfolite Group, exposed to the South of the South-alpine foothills, has received considerable attention in the last 20 years (Gunzenhauser 1985; Gelati et al. 1988; Bernoulli et al. 1993; Bersezio et al. 1993; Bernoulli & Gunzenhauser 2001; Carrapa & Di Giulio 2001; Fig. 1). However, many studies have discussed only superficially – if at all – the eastern end of the Gonfolite outcrop area, located in central Brianza at the triple junction among the provincial boundaries of Como, Lecco and Milano. For that area, published biostratigraphic studies date back to 50 years ago (Consonni 1953).

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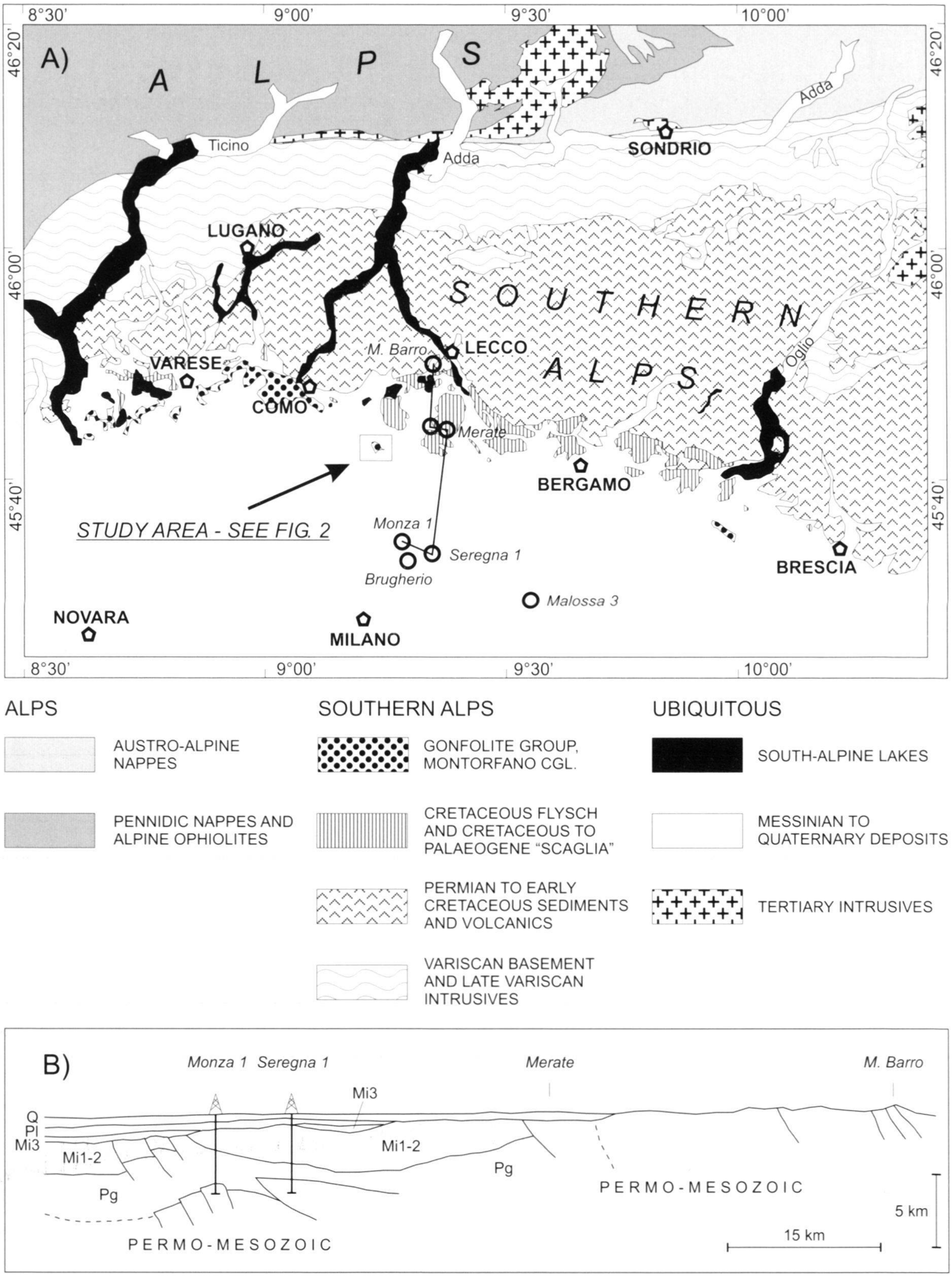


Fig. 1. A) Tectonic scheme of the western Southern Alps. Northern latitude and eastern longitude figures are reported in the frame; circles point at ENI/Agip wells (well names in italics). B) Simplified seismic section along the N-S trace in A) (redrawn after Pieri & Groppi 1981): Pg = Paleogene; Mi1-2 = Lower to Middle Miocene; Mi3 = Upper Miocene (essentially Messinian); Pl = Pliocene; Q = Quaternary.

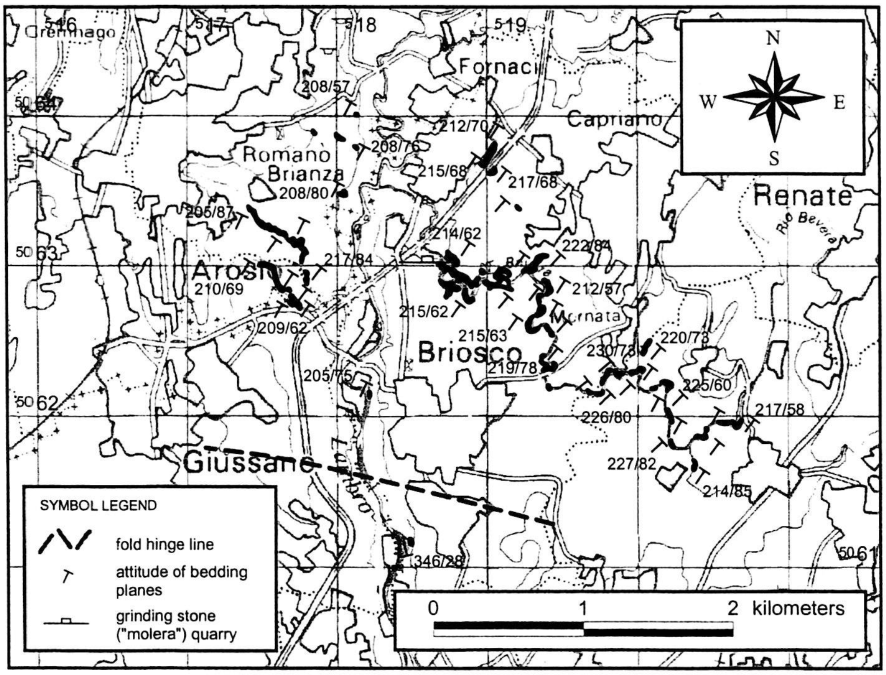


Fig. 2. Outcrop map of the study area. Gonfolite outcrops in black; attitude figures indicate azimuth/angle of dip. Gauss-Boaga coordinates for the kilometric net are provided.

New field work has been started on the district within the framework of the mapping of the new Geological Map of Italy at the 1: 50 000 scale (CARG Project, sheet 096 "Seregno": see Catenacci 1995 for an overview on the project). Aim of the present paper is:

1) to describe in sufficient detail a poorly exposed and mostly neglected district of the Gonfolite Group outcrop area;
2) to refine the biostratigraphic dating of those outcrops by analysing – for the first time in the area – the biostratigraphy of calcareous nannofossils;
3) to interpret preliminary petrographic observations on sandstones (detrital modes and geochemistry of single heavy minerals) in the scenario of the Neogene tectonic evolution of the Southern Alps.

Regional setting

Following Norian rifting and Liassic spreading of the Ligurian-Piedmont Ocean (Bertotti et al. 1993), the Southern Alps – a former remnant of the Hercynian suture at the northern end of the Adriatic microplate – became part of a short-lived passive continental margin. The first stage of subduction of the Ligurian-Piedmont Ocean is recorded, since the Cenomanian and up to the Early Maastrichtian, by the advance of submarine turbidite fans ("Cretaceous Flysch" of Lombardy: Doglioni & Bosellini 1987; Bersezio et al. 1993) fed by the erosion of accretionary prisms. Reduced tectonic activity during the Palaeocene is suggested by confined resedimentation of calcirudites within hemipelagic marls (Tabiago Formation), whereas a reprise of arc volcanism during the Middle to Late Eocene (Lutetian-Priabonian) is hinted at by large volcanic edifices cored in the Po Plain subsurface (Fantoni et al. 1999) as well as by resedimented "andesitic" crystal tuffs in marly successions from the Giudicarie area (Sciunnach & Borsato 1994); andesitic clasts found in the Upper Eocene Ternate Formation of Ticino (D. Bernoulli, pers. comm.) represent a further clue. Magmatic activity continued during the Oligocene, as documented by sparse volcaniclastic intercalations in both the South-alpine (Gallare Marls: Fantoni et al. 1999) and the "epimesoalpine" fronts (Ranzano Sandstones) of the Alpine-Apenninic system. Roughly at the same time, granitoid batholiths were intruded in both the Southern Alps (Adamello) and the Alps (Masino-Bregaglia), also as an effect of a regional tensional régime that has been interpreted as due to slab detachment (Stampfli & Marchant 1995). Since the Late Oligocene and up to the Middle Miocene, a new phase of paroxysmal tectonism, associated with thrust stacking and rapid orogenic uplift in the whole Alpine suture, is documented in the Southern Alps by the foredeep turbidites of the Lombardian Gonfolite Group: whether this tectonic climax was causally related to the coeval onset of the Apenninic Orogeny, that commenced since the Late Oligocene as a response to the opening of the Ligurian-Balearic sphenochasm, is still in debate. The Gonfolite was in turn deformed and accreted to the buried, frontal thrusts of the Southern Alps during the Middle to Late Miocene, to be unconformably overlain by the Messinian evaporites and continental clastics (Pieri & Groppi 1981; Roure et al. 1990) documenting the desiccation event in the Mediterranean Sea. Up to 9000 metres of marine hemipelagites to continental clastics represent the Pliocene to Quaternary basin fill of the Po Plain-Adriatic foredeep.

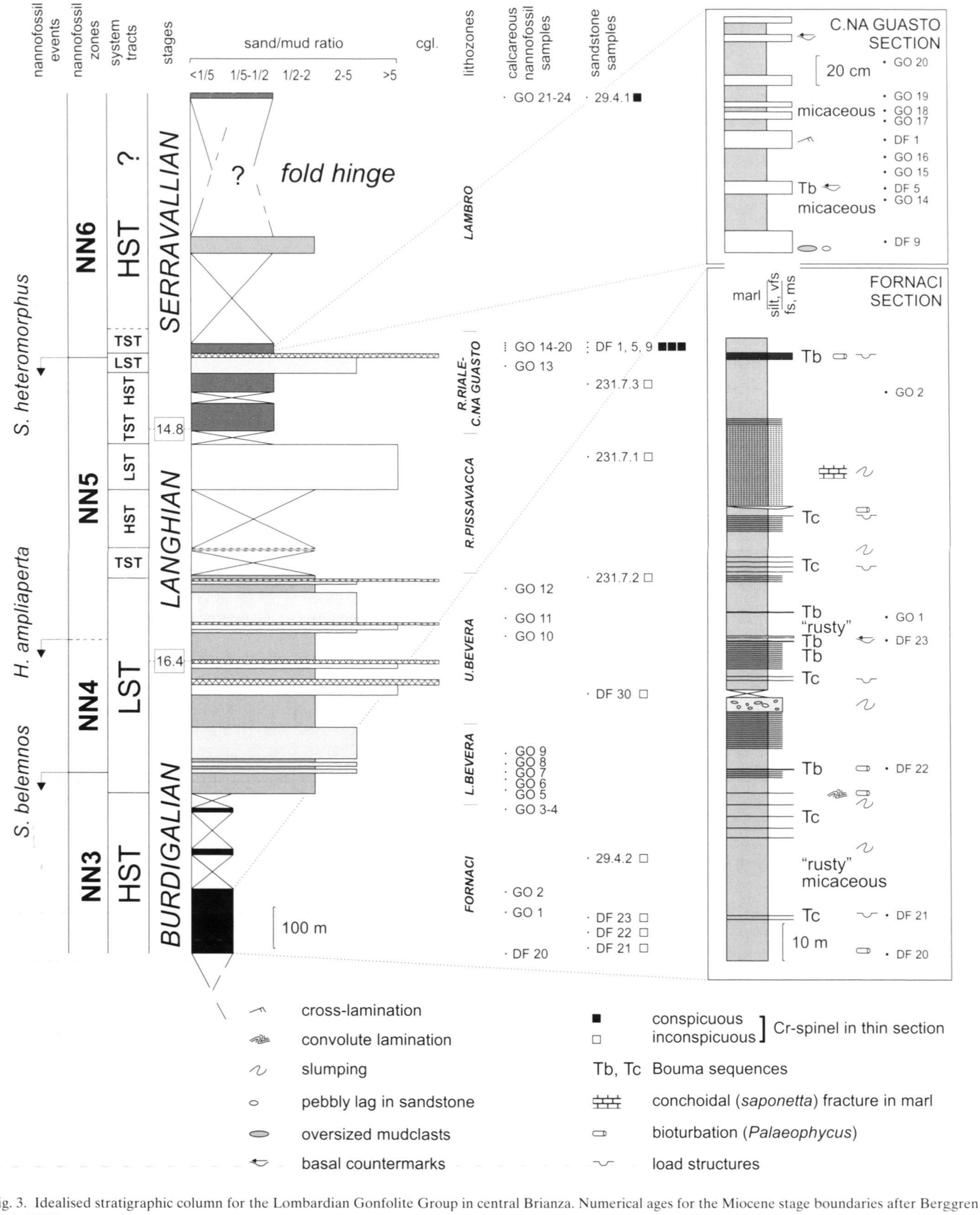


Fig. 3. Idealised stratigraphic column for the Lombardian Gonfolite Group in central Brianza. Numerical ages for the Miocene stage boundaries after Berggren et al. (1995).

Previous studies

After the pioneering monograph of Breislak (1822), several studies have briefly mentioned the steeply-dipping sandstones exposed in the area between Romanò Brianza (Inverigo, Como Province) and Naresso (Besana Brianza, Milano Province), as well as the interbedded conglomerates (see Consonni 1953 for a review). The local, informal names of "molera" (grinding stone, millstone) and "ceppo" have been used for the sandstones and the conglomerates respectively, although the latter term is misleading and more appropriate for the unconformably overlying Plio-Quaternary conglomerates.

In the official 1: 100 000 geological map of Italy (Sheet 32 "Como"), the mentioned outcrops are mapped as "Oligo-Miocene". Consonni (1953) included the whole succession into the Lombardian Gonfolite Group and proposed a late Oligocene to – more probably – earliest Miocene (Aquitanian) age based on scarce and badly preserved planktonic foraminifera. Consonni (1953) also estimated a total thickness of about 1300 m based on stratimetric calculations.

Gunzenhauser (1985) described in detail, and analysed in terms of turbidite facies and ichnofacies, the Fornaci section, correlating it to the Chiasso Formation and indirectly dating it as pre-Aquitanian.

The study area is located in a general Gonfolite map, but not investigated in detail, by Gelati et al. (1988); rather surprisingly, it is ascribed partly to the Gonfolite, partly to the Cretaceous Bergamo Flysch, in Montrasio (1990).

Field data

The sedimentary succession cropping out in central Brianza, in an area (Fig. 2) embracing the territories of Besana Brianza, Briosco (Milan Province), Arosio and Inverigo (Como Province), consists of prevailing turbidite sandstones and marls arranged in Bouma sequences. Most of the bedding planes (42 measurements) dip to the SSW (216 ± 6° N on the average) at angles averaging 69 ± 11°, and only in the southernmost part they gently turn to the NNW to form an open syncline; even within the fold, beds are invariably upright. The total thickness is difficult to evaluate due to the lack of a continuous section and to the uncertain placement of the syncline hinge, but from stratimetric calculations an assessment of at least 1800 m, and probably over 2000 m, is reasonable.

Although a continuous section lacks, the possibility of tracing along strike stratal packages characterised by homogeneous sand/mud ratio allowed us to obtain a schematic stratigraphic column (Fig. 3). From a sedimentological point of view, six informal lithozones can be distinguished, base to top:

1) *Fornaci lithozone*. Prevailing massive marls, grey in colour with thin intercalations of up to coarse-grained sandstones (Φ up to 0.5). The marly intervals are up to 15 m-thick (6 m on the average) and locally display thin, "rusty" seams seemingly due to concentrations of organic matter. Sandstones occur in both laterally continuous and lens-shaped beds, up to 10 cm-thick, displaying parallel, convolute and cross-lamination. Bioturbation (mostly represented by *Palaeophycus*, rectilinear to T-shaped flattened tubules up to 1 cm in diameter) is widespread at the top of the sandstone beds. In the Fornaci section, a single slumped bed, 4 m-thick, displays a pebbly mudstone facies: well-rounded pebbles are up to 1 cm in diameter. Slumpings, in marly to silty intervals, are widespread throughout the section.
In substantial agreement with Gunzenhauser (1985), T_{b-e} to T_{d-e} Bouma sequences are recognised. The Fornaci lithozone can be restored to a base-of-slope environment, where overbank wedges pass downslope to a basin plain setting (Normark et al. 1993). The estimated thickness is about 350 m.
2) *Lower Bevera lithozone*. Sandstones and marls, rhythmically arranged in Bouma sequences, mostly truncated at the base (T_{b-e}) or thin and incomplete (T_{ab}, T_{ace}, T_{bde}). The sand/mud ratio ranges from $^1/_2$ to 1 in the lower part, passing upwards to >>1. Massive, ungraded and structureless sandstone beds up to 1.2 m-thick also occur: they commonly display large ovoid concretions (*cogoli*), several dm-long, locally incomplete and onion-skin exfoliated. Sandstones are largely medium to coarse-grained (Φ up to 1.25–0.75); the "b" interval, 20 to 40 cm-thick, displays "thick" laminae (0.8–0.9 cm on the average). The incomplete sequences displaying the "a" interval are 20 to 30 cm-thick and are intercalated to the thickest sandstone beds. Complete Bouma sequences are comparatively rare; in their "a" intervals, normal grading is so progressive to be hardly perceived, while basal countermarks are common. A pebbly mudstone intervals, up to 2 m-thick and sealed by a T_{bc} sequence, is observed. The mudstone facies is bioturbated by *Paleophycus*. Rare conglomerate beds, 10 to 20 cm-thick, display well-rounded pebbles (maximum diameter 7 cm, modal diameter 1.5–2 cm) consisting of carbonates (80%), quartzite and metamorphic rocks (15%), and chert (5%). According to Normark et al. (1993), lobe and channel-lobe transition elements are recognised. Thickness should not exceed 200 m.
3) *Upper Bevera lithozone*. Up to coarse-grained and pebbly sandstones with intercalations of conglomerates and subordinate marls. Sandstones occur in dm-thick, both plane and lenticular beds. Amalgamation of sandstone beds, locally separated by thin and discontinuous marly intervals as a result of incomplete amalgamation, is common: the thickest amalgamated beds (> 0.8 m) are those quarried for grinding stone. Large nodular concretions (*cogoli*) are still common. Thin (< 10 cm) and incomplete Bouma sequences (T_{c-e}, T_{bce}) also occur (Fig. 4A), the "b" interval still displaying "thick" laminae; relatively thicker (30 cm) sequences may be truncated at the top (T_{ab}). Orthoconglomerates are in plane beds less than 1 m-thick, whereas pebbly sandstones are commonly thicker. Pebbles are rounded to well-rounded and are up to 35 cm in maximum

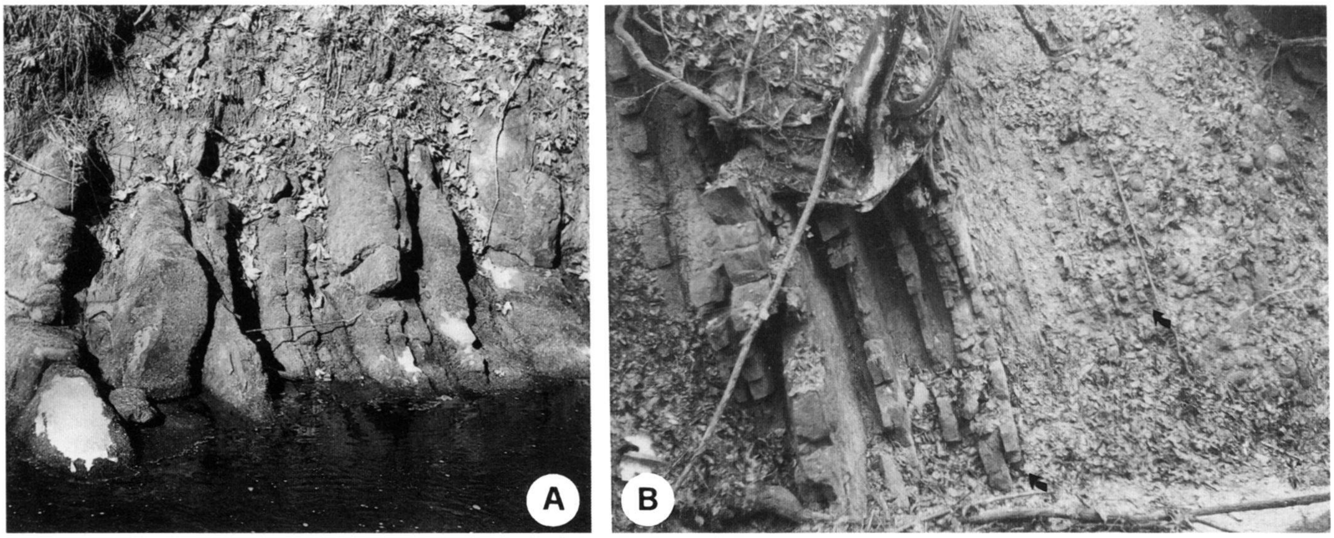


Fig. 4. Outcrop characters of the Lombardian Gonfolite Group in central Brianza. A) Typical outcrop pattern of alternating sandstones and marls in the upper Bevera lithozone; field of the photograph is about 2 m across. B) Sharp facies boundaries (arrows) in the Roggia Riale-C.na Guasto lithozone: prevailing sandstones on the left are separated from cobble conglomerates on the right by an interval of thin-bedded turbidites. Field of the photograph is nearly 4 m across.

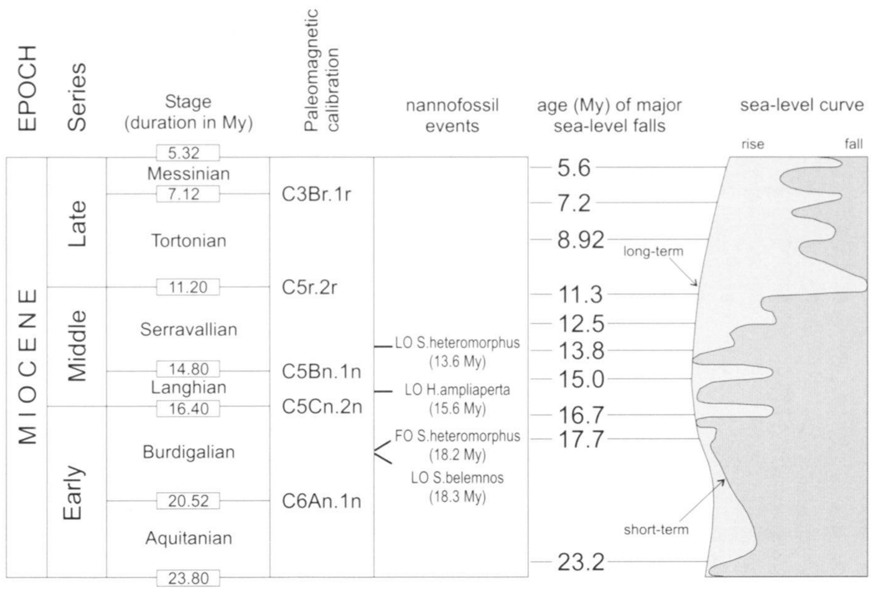
diameter (mode = 3 cm in the orthoconglomerates): they were derived from carbonates (50–60%), paragneisses, micaschists and amphibolites (20–25%), quartzite (5–15%), granitoids (0–10%), chert (0–5%), sandstones (0–5%) and volcanics to metavolcanics (0–5%). At least four negative sequences are recognised, based in complete Bouma sequences and capped by pebbly sandstones to conglomerates. This might suggest a channel-lobe transition, with cyclically prograding sandstone lobes, scoured by erosional to mixed channels. Thickness of each negative sequence averages 75 m, and thickness of the upper Bevera lithozone thus nears 300 m.

4) *Roggia Pissavacca lithozone*. After a poorly exposed interval, over 200 m-thick, homogeneous sandstones rhythmically interbedded with subordinate marls (sand/mud ratio ~ 6) crop out. Sandstones are largely medium to coarse-grained (Φ up to 1.25–0.75). Complete Bouma sequences T_{a-e}, 40 to 60 cm-thick, are common, only locally tending to amalgamation. Normal grading in the "a" interval, rich in basal countermarks, tends to be limited to the coarsest grains; convolute lamination is preserved in the "c" interval, whereas the "d" interval is thin and poorly distinguished. Since evidence for the vicinity of a channel-levee complex lacks, this lithozone is best interpreted in terms of unconfined lobe elements. The thickness of the exposed succession is about 100 m, but the underlying covered interval is probably thicker.

5) *Roggia Riale-Cascina Guasto lithozone*. Prevailing homogeneous marls in dm-thick beds, with subordinate micaceous sandstones to dolomitic siltstones interbedded in the lower part, display a major episode of deposition of coarse sandstone and conglomerates facies in the upper part, to return towards the top to micaceous, silty marls with intercalated sandstones. Sandstones are medium to fine-grained, in plane beds characterised by basal countermarks, normal grading, current ripples and only locally by pebbly lags at the base of the bed; oversized, intraformational clasts also occur. In the upper part of the lithozone (Fig. 4B), sandstones in up to 20 cm-thick beds (12 cm on the average), displaying parting lineation and ripples, and forming incomplete T_{ace} Bouma sequences with sand/mud ratio ~ 1 and bioturbated top of the "c" interval, pass upwards to a m-thick interval of thin turbidites, with sand/mud ratio ~ 1/3 and incomplete $T_{(b)-e}$ and T_{c-e} sequences, in turn overlain by a cobble conglomerate. The lower part of the conglomerate bed, about 2 m-thick, is clast-supported and contains well-rounded cobbles and boulders (maximum diameter 30 cm; modal diameter 10 cm), whereas the upper part, about 4 m-thick, is matrix-supported (maximum diameter 15 cm; modal diameter 6 cm). Intraformational clasts up to 45 cm in length are observed, and imbrication of cobbles is common in the clast-supported part. Clasts were derived from carbonates and cherty limestones, many of them displaying distinctive facies from the Mesozoic carbonate succession of the Southern Alps (Medolo, Maiolica: 80%), but also from quartzite, micaschists and paragneisses (10%), granitoid rocks (5–10%) and greenschist-facies mafic rocks ("pietre verdi": 0–1%). The spectrum of turbidite facies represented in this lithozone fits into a channel-levee complex, characterised by the lateral migration of a major distributary channel (Normark et al. 1993). The thickness of the Roggia Riale-Cascina Guasto lithozone is about 200 m.

6) *Lambro lithozone*. This interval is very poorly exposed: the

Tab. 1. Miocene chronostratigraphy and eustasy (modified after Berggren et al. 1995). The nannofossil events recognised in this study and their estimated age are shown.



few outcrops are characterised by prevailing marls and by $T_{a\text{-}c}$ Bouma sequences. Marls are intensely burrowed (mostly by *Palaeophycus*, rectilinear to T-shaped tubules over 2 cm in diameter). Sandstone beds display basal countermarks and irregular top, as well as current ripples. Although the observed facies might be consistent with both overbank wedges and distal lobes, the elemental interpretation of this lithozone is hazardous due to insufficient outcrops. Its thickness might reach up to 600 m, but just a few tens are exposed.

Calcareous nannofossil biostratigraphy

Methods. Biostratigraphic investigations were performed by means of calcareous nannofossil. This planktonic group was chosen on the basis of modest results obtained with planktonic foraminifera by Consonni (1953). This author documented a very poor foraminiferal assemblage and only 6 samples, over 80 investigated, provided some stratigraphic information.

Biostratigraphic investigations were carried out on 24 samples collected from marlstones interbedded with thick sandstone levels. Samples were prepared in smear slides using the standard technique proposed by Monechi & Thierstein (1985). Calcareous nannofossil were analysed under light microscope at 1250x magnification using the standard taxonomy as described by Perch-Nielsen (1985) and Young (1998).

The preservation of nannofloral assemblages ranges from poor to moderate and nannofossil abundance and species richness is generally low. Slight reworking is indicated by the presence of a few Cretaceous and Paleogene species. Cretaceous species mainly consist of *Watznaueria barnesae*, *Nannoconus steinmanni* and *Cretarhabdus angustiforatus*, whereas *Reticulofenestra umbilica* is the dominant species of the reworked Paleogene nannofloral assemblage.

Biostratigraphy. In this study we use the biozonation of Martini (1971) and the time-scale of Berggren et al. (1995) with a few modifications adopted by Young (1998; Tab. 1). In particular, the base of the NN3 zone is defined by the last occurrence (LO) of the *Triquetrorhabdulus carinatus* with the first occurrence (FO) of *Sphenolithus belemnos* as a secondary marker. *T. carinatus* is common only in well-preserved and open-marine sediments (Young, 1998) and it can be difficult to distinguish poorly preserved *T. carinatus* from other elongate calcite particles in samples with common detritus (Perch-Nielsen, 1985). Table 2 shows the nannofossil zones recognized and the age assignments.

The bottom (sample GO 1) of the composite section investigated is assignable to the NN3 nannofossil Zone owing to the presence of *S. belemnos* and dated as Burdigalian. This interval records high abundances of *Cyclicargolithus floridanus* and *Calcidiscus pelagicus*, whereas other species such as *Sphenolithus moriformis*, *Discoaster deflandrei*, *Helicosphaera* spp. and *Reticulofenestra* spp. are fairly rare (Tab. 2).

The base of the NN4 nannofossil Zone is defined by the LO of *S. belemnos*, which lies at the base of the lower Bevera lithozone (sample GO 6) preceeding the FOs of *Sphenolithus heteromorphus* (sample GO 7) and *Reticulofenestra pseudoumbilica* <7μm (sample GO 8), respectively. Both these FOs also occur in the lower part of the Bevera lithozone.

The LO of *Helicosphaera ampliaperta* in the middle part of the lower Bevera lithozone (sample GO 9) indicates the Langhian stage and this biostratigraphic datum is used to define the base of the NN5 nannofossil Zone. *H. ampliaperta* shows a sporadic occurence in the section investigated as well as in several other areas.

Several authors (e.g. Gartner, 1992; de Kaenel & Villa, 1996) proposed to define the base of the NN5 nannofossil Zone with the FO of *Calcidiscus premacintyrei*, but this species

Tab. 2. Range chart for the recognised calcareous nannofossil species. Preservation: P = poor, M = moderate. Occurrence: R = rare, C = common, F = frequent, FO = first occurrence, LO = last occurrence. Most relevant occurrences in bold.

Nannofossil zones (Martini, 1971)	sample	lithozone	Preservation	*R. pseudoumbilica* < 7µm	*R. pseudoumbilica* > 7µm	*R. minuta*	*R. haqii*	*H. intermedia*	*H. mediterranea*	*H. waltrans*	*H. euphratis*	*Cy. floridanus*	*C. pelagicus*	*S. moriformis*	*S. disbelemnos*	*S. dissimilis*	*D. deflandrei*	*D. druggii*	*Discoaster* sp.	rew. Paleogene species	rew. Cretaceous species	*Pontosphaera* spp.	*S. belemnos*	*H. ampliaperta*	*S. heteromorphus*	
NN 6	GO 24	Lambro	P	R	F			R				R	F	R							R					
	GO 23		P	F	F			R				F	F	R					R							
	GO 22		P	F	R	R	R					F	F	F								R				
	GO 21		P	F	F							R	F	R			R			R	R					
	GO 20	Roggia Riale - Cascina Guasto	P	F	F		R	R				R	C	R					R		R	R				
	GO 19		P	F	R	R						R	C	R			R				R					
	GO 18		M	F	R			R				R	F	F					R	R						
	GO 17		P	F	F		R	R				F	F	R								R				
	GO 16		P	F		R		R				F	C	R			R		R	R	R					
	GO 15		M	F	R			R				F	C	R												
	GO 14		P		R		R	R				R	F	R			R					R				
NN 5	GO 13		M	R		R						C	F	R					R						**R**	LO *S. heteromorphus*
	GO 12	Upper Bevera	P	R				R				R	F	R												
	GO 11		P	F		R				R		R	F	F			R			R	R	R			R	
	GO 10		P	R			R	R				C	C	F											R	
NN 4	GO 9	Lower Bevera	M	R			R	R	R			C	C	R			R		R					**R**	R	LO *H. ampliaperta*
	GO 8		P	R		R	R	R			R	R	R	R										R	R	
	GO 7		P					R			R	R	C	F	R		R	R				R		R	**R**	FO *S. heteromorphus*
NN 3	GO 6		P			R	R	R			R	F	F	F				R		R	R		**R**			LO *S. belemnos*
	GO 5		M			R		R			R	F	F	R	R	R	R	R				R	R			
	GO 4	Fornaci	P				R				R	F	F	R				R	R	R			R	R		
	GO 3		P									F	F	F		R	R	R		R	R		R	R		
	GO 2		P			R		R			R	R	F	F			F	R					R			
	GO 1		P				R					F	F	R			F	R			R		R			

has never been observed in the samples analyzed. Other secondary bioevents to define the base of the NN5 nannofossil zone, such as the LO of *Helicosphaera perch-nielseniae*, the FO of *Discoaster exilis* or the first common occurrence (FCO) of *Helicosphaera walbersdorfensis*, have not been found. In addition, only a specimen of *Helicosphaera waltrans* was identified in the investigated samples (GO 11).

The base of the Serravallian NN6 nannofossil Zone is indicated by the LO of S. *heteromorphus*, which was observed in the upper Roggia Riale-C.na Guasto lithozone (sample GO 13) predating the FO of *R. pseudoumbilica* >7µm, still from the upper Roggia Riale-C.na Guasto lithozone (sample GO 14).

The top of the section is attributed to the NN6 nannofossil zone since the FO of *Discoaster kugleri* or the LO of *C. floridanus*, indicating the base of the NN7 nannofossil Zone, have not been found.

Sandstone petrography

Methods. A petrographic screening on 11 turbidite sandstone samples was carried out. On each 25x40 mm thin section, previously stained with red alizarine to distinguish calcite from dolomite, 300 points were counted; QFL detrital modes were recalculated from the point-counting data following the Gazzi-Dickinson method (carbonate lithics included in the L pole), while the NCE-CE-NCI-CI modes were calculated after Zuffa (1985). Grain size and sorting, semiquantitatively evaluated following the method described in Sciunnach (1996), were statistically correlated to compositional data. SEM-EDS microprobe analyses were carried out on selected grains in polished thin sections (kV = 20.0, nA = 300–350, livetime = 50 seconds, international standards and metallic cobalt for calibration).

Modal data on the sandstone framework. The studied samples mostly fall in the field of feldspathic litharenites after Folk (1974); lithic arkoses are limited to the Fornaci lithozone, whereas sedimentary litharenites occasionally occur in the Roggia Riale-C.na Guasto lithozone. Grain size ranges from fine to coarse (Φ = 2.50–0.50); sorting is generally moderate.

Among the main constituents, quartz is both monocrystalline and polycrystalline, with a highly variable C/Q ratio (0.07–0.44), mainly as a response to grain size variations (Pearson's correlation coefficient of C/Q vs. grain size = -0.84, sign. lev. < 1%). Nearly identical values (0.22–0.24) of the C/Q ratio are obtained from sandstones of comparable, fine grain size (Φ = 2.50), sampled from consecutive turbidite beds. Bipyramidal, embayed quartz of volcanic origin was never detected with confidence, whereas polycrystalline quartz commonly displays elongated crystals with sutured boundaries and parallel inclusions of tiny mica flakes, pointing to a metamorphic origin.

Feldspars are represented by plagioclase, commonly twinned and less commonly zoned (untwinned, poikilitic albite also occurs), and by alkalifedlspars: perthitic orthoclase, chessboard-albite and microcline (the latter is rare in the upper two lithozones). The P/F ratio is highly variable around an average of 0.5.

Volcanic rock fragments are widespread although not abundant (1–5% of rock volume): they display a variety of structures, felsitic and vitric rock fragments (probably derived from acidic volcanics) prevailing over microlithic rock fragments (probably intermediate to basic in composition) also due to higher mineralogical stability in the sedimentary environment. Subvolcanic and granitoid rock fragments are common, although the abundance of the latter is controlled by grain size (correl. coeff. = - 0.81, sign. lev. < 1%). Orthogneissic rock fragments are also more abundant in coarser-grained samples (correl. coeff. = - 0.71, sign. lev. < 2%), but their abundance slightly decreases upsection (correl. coeff. = - 0.53, sign.

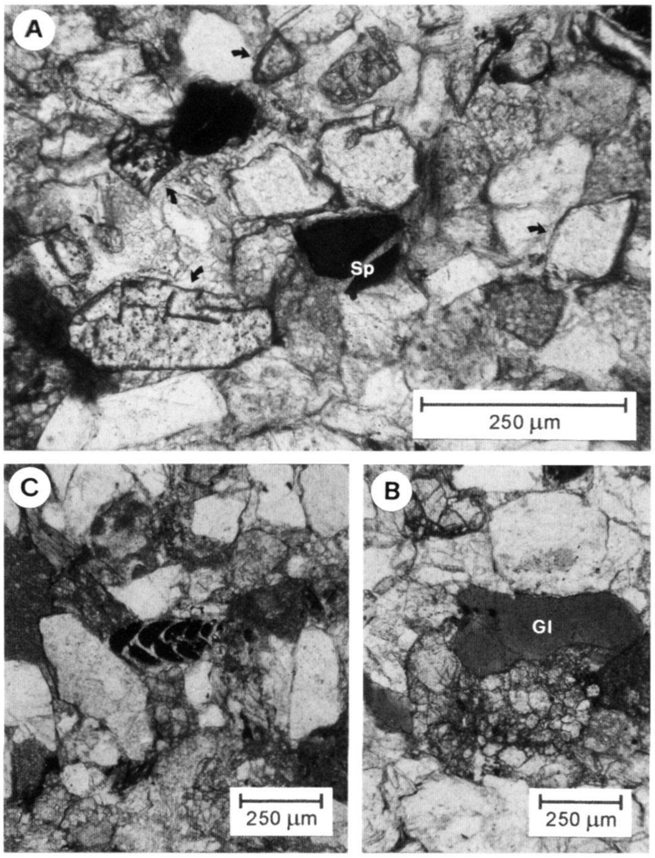


Fig. 5. Heavy minerals (A) and intrabasinal grains (B-C) in the Gonfolite sandstones of central Brianza. A) Sample DF 1 – detail on a lamina enriched in heavy minerals: garnet (arrows) and chromian spinel (Sp). B) Sample DF 9 – glaucony pellet (Gl). C) Sample DF 9 – reworked benthic foraminifer (*Brizalina* sp.), with broken test and chambers filled by an oxidised matrix. All photos are in plane polarised light.

Tab. 3. Compositional parameters helpful for distinguishing petrofacies and petrologic intervals within the studied succession. Q, L, V/L after Dickinson (1970); CE, DE after Zuffa (1985).

	Q	L	V/L	CE + DE
upper	28-39	41-55	5-9%	25-36
intermediate	35-41	35-42	13-16%	18-20
lower	39-61	16-39	13-31%	4-15

lev. < 10%): metasedimentary lithics (slate, phyllite, chloritic schist, garnet micaschist) are instead widespread, averaging 6% of rock volume with low standard deviation all over the section, independent of grain size. Among sedimentary lithics, pelite and chert fragments are widespread in low number from base to top of the succession: we have counted as cherty lithics also isolated, deeply-recrystallised and undeformed radiolarians, their tests filled by chalcedony ± haematitic clay. Limestone (CE) and dolostone (DE) extrabasinal fragments are instead abundant and record a further, gradual increase upsection (correl. coeff. of CE + DE vs. stratigraphy = 0.89, sign. lev. < 0.1%).

Pseudomorphs, grown at the expense of framework grains (Schmidt & McDonald 1979) and pseudo-interstitial pseudomatrix (Dickinson 1970) also occur, never exceeding 2.5% of rock volume. Heavy minerals (3–8% of rock volume) are represented mostly by detrital phyllosilicates (white mica; brown, green and "leached" biotite; chlorite) along with subordinate garnet (Fig. 5A), sphene, epidote, tourmaline, amphibole, zircon, rutile, apatite, pyroxenes, brown to green spinel (Fig. 5A), allanite, monazite, xenotime and kyanite; among opaque minerals, titanomagnetite and ilmenite were identified.

Non-carbonate intrabasinal grains (NCI) are mostly represented by rare glauconite pellets (K_20 up to 6%; Fig. 5B) that tend to decrease in abundance upsection (correl. coeff. = - 0.56, sign. lev. < 10%); even rarer carbonate intrabasinal grains (CI) consist of shelly fragments, abraded foraminifer tests (Fig. 5C), echinoid plates and micritic intraclasts.

Primary pores were filled by muddy matrix and syntaxial cements, whereas residual and secondary pores were largely filled by sparry calcite and subordinate framboidal pyrite. Minimum calcite content is recorded in sandstones lacking CI, pointing to CI dissolution as a possibly important source for authigenic calcite.

Petrologic intervals and provenance. Vertical evolution of detrital modes, evaluated on parameters not basically dependent on grain size, allowed us to recognise three distinct petrologic intervals in the studied succession: a lower petrologic interval (samples DF 21 to 29.4.2), characterised by higher quartz content and V/L ratio, passes transitionally through an intermediate petrologic interval (DF 30 to 231.7.1) to an upper petrologic interval (DF 9 to 29.4.1), characterised by higher lithic content and especially by higher CE + DE (Tab. 3). These compositions, still comparable to those described in Carrapa & Di Giulio (2001) as far as the Fornaci lithozone is considered, are progressively shifted towards the L+CE pole of the ternary plot as a result of increasing contribution from the Mesozoic sedimentary succession of the Southern Alps to the foredeep basin (Fig. 6): such a provenance is strongly indicated also by the abundance of carbonate pebbles in all the conglomerate beds. Even if the CE are not computed as lithics, most samples fall in the "recycled orogen" provenance field of Dickinson (1985).

Geochemistry of detrital Cr-spinel. Detrital chromian spinels were found in fine- to medium-grained sandstones from the Roggia Riale-C.na Guasto and Lambro lithozones: they occur as angular to subrounded grains, 90 to 240 µm in length (165 µm on the average), ranging in colour from coffe-brown to amber red and, exceptionally, bottle green (the latter colour is associated to the lowest value of Cr#). Geochemical analyses revealed a Cr_2O_3 content mostly of 23–33%, corresponding to a Cr# generally ranging between 0.29 and 0.39. After normalisation of microprobe data, the examined Cr-spinels can be classified as a solid solution of the end-members magnetite (28–47%), Mg-ferrite (21–37%), chromite (7–24%)

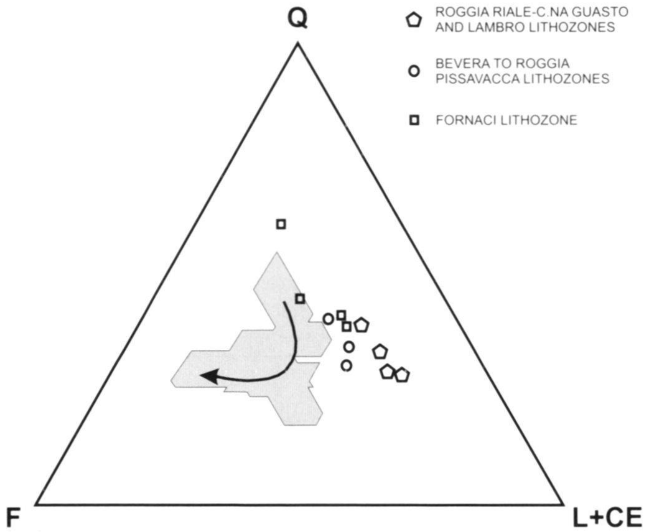


Fig. 6. Triangular plot for the bulk framework composition of the analysed sandstone samples. Detrital modes and compositional trend of older Gonfolite sandstones (shaded area and arrow) after Carrapa & Di Giulio (2001) are displayed for comparison.

and Mg-chromite (6–19%); other end-members, like spinel (1–4%) and hercynite (1–4%) are subordinate, while Jacobsite, Mn-chromite, ulvöspinel and Zn-spinel are negligible.Typical inverse correlations of Cr vs. Al and Mg vs. Fe are recognised. Rim alteration results in a strong Al loss, a relevant Mg loss and a slight impoverishment in Cr, partially compensated by enrichments in Si, Fe, Ti, Mn and Ca. Composition of the analysed spinels best fits with provenance from alpine-type ophiolite complexes (Fig. 7).

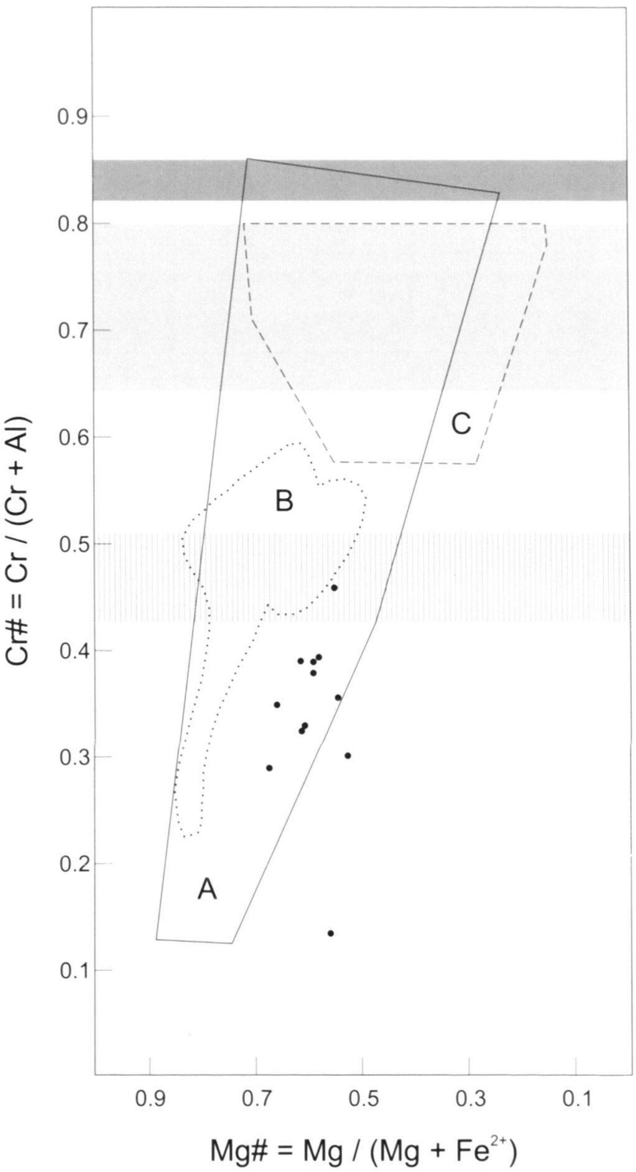


Fig. 7. Mg# vs. Cr# plot for the analysed detrital chromian spinels. A) (solid line) = field of spinels from alpine-type ophiolite complexes after Hamlyn & Bonatti (1980); B) (dotted line) = field of spinel from Atlantic MORB after Sigurdsson & Schilling (1976) and Jaques (1980); C) (dashed line) = field of spinels from stratiform intrusions after Hamlyn & Bonatti (1980). Shaded areas indicate the Cr# ranges for spinels from the Ladinian-Carnian succession of the Southern Alps after Garzanti & Sciunnach (1997): dark grey = Carnian S.Giovanni Bianco Fm., light grey = Ladinian Wengen Fm., vertically striped = Carnian Val Nozza basaltic flow.

Discussion

Structural setting. A few structural observations can be made on this poorly-exposed district. The remarkably constant strike (126 ± 6° N on the average) and dip (69 ± 11° on the average) of the bedding planes, the negligible evidence for faulting even in large outcrops, the invariably upright polarity of beds even in the folded southern part, and the progressive younger age towards the south allowed us to interpret the studied succession as a substantially even limb of a large syncline, in spite of scarce outcrops.

The syncline geometry of the southern end of the district matches the local geometry of Miocene strata as inferred from the available seismic sections (Pieri & Groppi 1981; Fig. 1).

The main phase of folding of the studied Gonfolite succession can be biostratigraphically constrained as not older than the late Serravallian (probably Zone NN7 or younger), and seismically as not younger than the unconformably overlying Messinian. Thus, a largely Tortonian age (late "Lombardic phase" of Schumacher et al. 1996) seems to best fit the time constraints.

Sedimentary evolution. At the scale of the studied succession, six lithozones – widely varying in exposure quality and continuity – and up to four 3rd order stratigraphic sequences can be recognised (Fig. 3). The coarser-grained episodes might be interpreted as Lowstand System Tracts (LST), in particular as basin floor-fans to slope fans; alternatively, they might simply represent the result of lateral migration of the channel-levee complex. The absence of large outcrops prevents any three-dimensional geometrical reconstruction of the ancient fan, and the possibility of choosing with confidence between the two options.

Taking into account their duration (about 1 My), the lack of prominent unconformities, and the possible control by short-term sea-level changes, the described lithozones can be regarded as "turbidite systems" following the classification of Mutti & Normark (1987). If the integrated time-scale of Berggren et al. (1995) is adopted, accumulation rates nearing 300 m/My are calculated.

Correlations. To draw correlations for the studied succession within the available stratigraphic framework for the Lombardian Gonfolite Group is a hard task. The most continuous part of the succession is the Fornaci section, biostratigraphically dated as Burdigalian (Zone NN3). No evidence is found in that section for the latest Aquitanian to mid-Burdigalian event, represented over much of the Mediterranean area by stratigraphic gaps, volcaniclastic deposits and a generalised bloom of the siliceous plankton: the Fornaci section might be thus interpreted as post-dating that event and to be entirely late Burdigalian in age. Such an age would suggest correlation of the Fornaci lithozone with the Lurate Caccivio Pelites (Gelati et al. 1988), whereas the overlying, sandier facies (lower and upper Bevera lithozones) might correspond – at least in part – to the Lucino Conglomerate, the age of which has been tentatively extended to the early Langhian in Bernoulli et al. (1993).

To our knowledge, the Langhian to Serravallian time interval has not been biostratigraphically documented to date anywhere in the Gonfolite outcrop area. Gelati et al. (1988) described two informal lithostratigraphic units from the Varese area (Gurone Sandstone and Bizzozzero Mudstone); as those units lack determinable planktonic foraminifera, they were tentatively constrained as post-Burdigalian and pre-Messinian based on stratigraphic position. Much of the central Brianza succession, from the Roggia Pissavacca lithozone upwards, should be at least in part time-equivalent to the Gurone Sandstone and Bizzozzero Mudstone, but a detailed correlation is hampered by exceedingly discontinuous exposure in both districts and – to date – by the lack of biostratigraphic data based on calcareous nannoplankton from the Varese outcrops.

Depth constraints. The P/B ratio is generally < 1 all over the Gonfolite Group (Consonni 1953; Rögl et al. 1975), but this does not necessarily reflect shallow depth as turbidity currents reworked benthic foraminifera from the shelf. Reworking of glaucony pellets suggests deposition deeper than the shelf break (Odin & Fullagan 1988). The *Palaeophycus* trace fossils can be regarded as domichnia (Bromley 1990); such ichnites are distributed over depths ranging from 300 to 2000 m (Ekdale et al. 1984). The Chattian-Aquitanian part of the Gonfolite Group in the Como-Chiasso type area is restored to the upper bathyal zone, at an indicative depth range of 500–1000 m (Rögl et al. 1975). Based on palaeoecological analysis on benthic foraminifera and molluscan-echinoid assemblages, Gelati et al. (1988) proposed depth ranges at 500–1300 m and 400–2000 m, respectively, for the whole Gonfolite Group. Although several turbidite units from the Alpine-Apenninic foredeeps are being reconsidered and interpreted as shelfal successions deposited by hyperpycnal flows generated under catastrophic flood conditions (Mutti et al. 1996; Artoni et al. 1999), there seems to be sufficient palaeontologic, ichnologic and lithologic evidence to restore the deposition of the Lombardian Gonfolite Group to bathyal settings.

Sedimentary evidence for Alpine uplift. Provenance signals recorded by the Gonfolite foredeep turbidites document the Burdigalian to Serravallian evolution of the Alpine source areas: the Oligocene-Aquitanian part of the same Group was in fact deposited in fairly similar environments and is unlikely to have experienced a significantly different diagenetic evolution. Increasing detritus derived from the carbonate nappes of the uprising Southern Alps is recorded since the Langhian and, even more dramatically, starting at Serravallian times. Contemporaneous appearance of conspicuous detrital Cr-spinel from Alpine-type ophiolites would be consistent with exhumation and initial unroofing of the Pennidic nappes, that crossed the brittle-ductile transition around 18–20 My (Heitzmann 1987) and might have well reached the surface some My later.

Alternative explanations for these provenance signals are less likely. The increase of carbonate clasts in the upper part of the section might be due to increasingly arid (or cold) climate in the sedimentary environment (Folk 1974): actually, much independent stratigraphic evidence points to a globally more arid and colder climate since the mid-Miocene, but it is unlikely that a climatic shift alone was able to triplicate the average CE + DE content from base to top of the succession. Detrital Cr-spinels might have been recycled – at least in part – from Ladinian to Carnian volcaniclastics of the Southern Alps (Buchenstein and Wengen Formations, Val Sabbia Sandstones: Garzanti & Sciunnach 1997), but these grains are very rare even in those Triassic formations, and the volume of those formations is in turn small compared to the metamorphic to sedimentary succession of the Southern Alps, so their recycling in the Gonfolite Group should be negligible. Moreover, analysed Cr-spinels from the Ladinian-Carnian succession yielded commonly higher values of Cr# with respect to those found in the Gonfolite.

Provenance from Alpine-type ophiolitic nappes is instead favoured by the geochemistry of the Cr-spinels (Fig. 7) and the occurrence, in the conglomerates of the Roggia Riale – C.na Guasto lithozone, of pebbles consisting of metagabbro. Unroofing of the Pennindic nappes in the Alps was thus seemingly paralleled by migration of thrust stacking in the Southern Alps, where carbonate nappes (notably Ladinian and Norian dolomitic platforms, as well as Jurassic to Early Cretaceous basinal limestones) were in turn structurally and topographically uplifted. In addition, E-W extension between the Lepontine Dome and the Tauern Window during the Miocene

(Mancktelow 1985; Merle et al. 1989) might have caused river captures, forcing the drainage pattern towards the "antecedent" style that – with the notable exception of the Adda River course north of Lake Como – still prevails at present.

As to the timing of tectonic events, a major provenance shift started at Langhian times, consistent with a climax in tectonic activity (early "Lombardic phase" of Schumacher et al. 1996). Continuing convergence would have accreted the foredeep turbidites themselves to the frontal, buried thrust of the South-alpine range, mostly during the Tortonian (late "Lombardic phase" of Schumacher et al. 1996).

Conclusions

The following general conclusions can be drawn about the Lombardian Gonfolite succession cropping out in central Brianza:

1) a net of sparse outcrops can be restored to a buried homocline, steeply-dipping to the South and at least 1800 m-thick. Polarity is invariably upright, even in the southern sector, where tight folds are developed;
2) the age of the succession spans the Burdigalian (Zone NN3) to the Serravallian (Zone NN6), generally younger than assessed for the Lombardian Gonfolite Group in the type-areas between Como and Varese. Ages are established on the youngest index species of calcareous nannofossils found in the marly intervals, allowing us to correct older ages based on reworked planktonic foraminifera;
3) provenance signals are recorded by the evolution of sandstone composition from base to top. A basal petrofacies, dominated by lithic arkoses relatively rich in microcline and orthogneissic rock fragments, passes gradually at first, and then more abruptly around 14 Ma, to feldspathic litharenites fed mainly by the carbonate succession of the Southern Alps. Contemporaneous appearance of detrital Cr-spinel from Alpine ophiolites suggests exhumation of the Pennidic Nappes in the Central Alps, and a major reorganisation of the hydrographic net, possibly tectonically-controlled by the overthrusting of carbonate nappes in the Southern Alps.

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