Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 86 (1993)

Heft: 3

Artikel: Sr-isotope-stratigraphy of the Gonfolite Lombarda Group ("South-Alpine Molasse", northern Italy) and radiometric constraints for its age of deposition

Autor: Bernoulli, Daniel / Giger, Matthias / Müller, Daniel W.

DOI: https://doi.org/10.5169/seals-167261

Eclogae geol. Helv. 86/3: 751–767 (1993)

0012-9402/93/030751-17 $ 1.50 + 0.20/0
Birkhäuser Verlag, Basel

Sr-isotope-stratigraphy of the Gonfolite Lombarda Group ("South-Alpine Molasse", northern Italy) and radiometric constraints for its age of deposition

By DANIEL BERNOULLI [1]), MATTHIAS GIGER [2]), DANIEL W. MÜLLER [3]) and URS R. F. ZIEGLER [4])

Key words: Sr-isotope-stratigraphy, radiometric dating, Gonfolite Lombarda Group, Oligo-Miocene, Southern Alps, northern Italy.

ABSTRACT

Sr isotope ratios in mollusc shells from the deep water sediments of the Oligocene Chiasso Formation and of the Oligo-Miocene Gonfolite Lombarda Group are in line with the biostratigraphically established depositional ages for the different formations. They show that Sr isotope dating can be a valuable tool also in marine depositional settings dominated by clastic input of recycled continental crustal material. Radiometric signatures in clasts of Tertiary intrusive rocks further constrain the depositional age of non-fossiliferous deep sea conglomerates (Villa Olmo Conglomerate [max. age 31.7 ± 0.5 Ma], Como Conglomerate [29.2 ± 3.2 Ma] and Lucino Conglomerate (21.0 ± 2.4 Ma]). Radiometric dating of the cooling history of pebbles (FT on apatite: 20.4 ± 2.0 Ma) derived from the Novate intrusion (≈ 26 Ma) suggest a possible correlation of the southernmost outcrops of conglomerates of the Gonfolite Lombarda Group (Castiglione Olona) with the Lucino Conglomerate. This would imply a north-vergent thrust, similar to the Monteolimpino thrust, between Castiglione Olona and Gurone.

RIASSUNTO

Il rapporto isotopico dello stronzio in gusci di molluschi provenienti da sedimenti di mare profondo appartenenti alla Formazione di Chiasso e al Gruppo Gonfolite Lombarda fornisce risultati compatibili con le età deposizionali delle differenti formazioni del Gruppo stabilite in base alla biostratigrafia. I dati indicano che il rapporto isotopico dello stronzio può essere utilizzato come strumento di datazione anche in ambienti deposizionali marini in cui sia dominante la presenza di materiale crostale continentale riciclato. Le età radiometriche misurate su clasti provenienti da rocce intrusive terziarie confermano ulteriormente l'età deposizionale dei conglomerati non fossiliferi di mare profondo (Conglomerato di Villa Olmo [età massima 31.7 ± 0.5 Ma], Conglomerati di Como [29 ± 3.2 Ma] e di Lucino [21 ± 2.4 Ma]). La datazione radiometrica della storia del raffreddamento dei clasti (FT su apatite: 20 ± 2.4 Ma) derivati dalla intrusione di Novate (≈ 26 Ma) suggerisce una correlazione dell'affioramento più meridionale di conglomerati appartenenti al Gruppo della Gonfolite Lombarda (Castiglione Olona) con i Conglomerati di Lucino. Questa correlazione implicherebbe un sovrascorrimento verso nord tra Castiglione Olona e Gurone.

[1]) Geology Institute, ETH-Zentrum, CH-8092 Zürich, Switzerland.

[2]) Muehlemattweg 21, CH-5034 Suhr, Switzerland.

[3]) Geology Institute, ETH-Zentrum, CH-8092 Zürich, now: Dr. H. Naef, Büro für angewandte Geologie, Herbrig 21, 9042 Speicher, Switzerland.

[4]) Ittigenstrasse 11, CH-3063 Ittigen, Switzerland.

Introduction

Chiasso Formation and Gonfolite Lombarda Group (together Lower Oligocene-Lower to ? Middle Miocene) represent a clastic wedge, up to three kilometers thick, infilling the deep southern foreland basin of the mid-Tertiary Alps, and were deposited during the growth of the South-Alpine fold and thrust belt. These sediments are exposed in a roughly east-west-trending narrow zone near the southern morphological boundary of the Alps between Lake Maggiore and the Brianza area (Figs. 1 and 2). Their coarse conglomerates document rapid uplift and erosion of the central Alps north of the Insubric line during the Oligocene and Early Miocene (Wagner et al. 1977, 1979, Hurford 1986, Hurford et al. 1989, Massari 1990). The main deformation along the southern border of the Southern Alps extended, however, into the Middle and Late Miocene: near Chiasso the beds of the Gonfolite are strongly tilted (> 55° to the south) and back-thrust towards the north onto the Mesozoic substrate (Monteolimpino thrust, Bernoulli et al. 1989, Bersezio et al. in press). Generally finer grained deep water sediments of the Gonfolite Group are known from the subsurface of the Po Plain where they are involved in Middle to Late Miocene decollement and thrusting (Pieri & Groppi 1981, Cassano et al. 1986, Dondi & d'Andrea 1986). Chiasso Formation and Gonfolite Lombarda

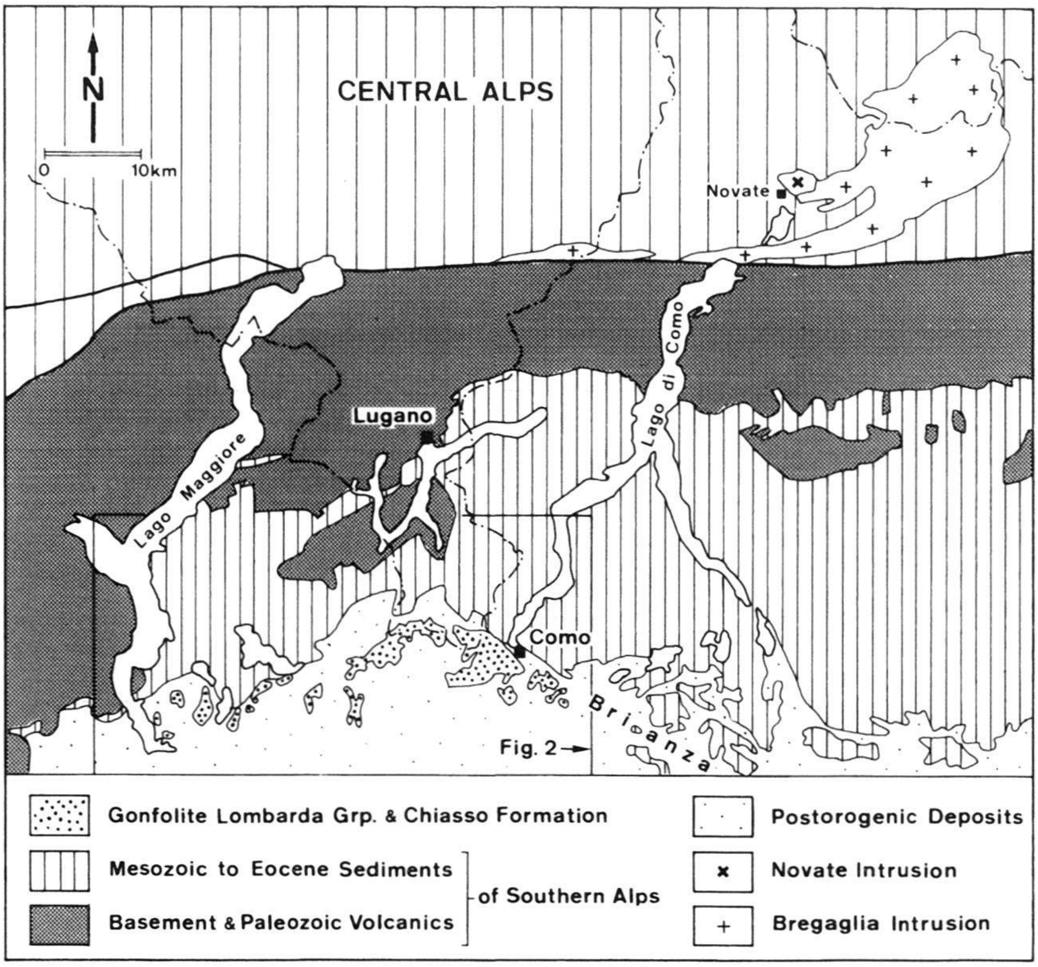

Fig. 1. Location of Gonfolite Lombarda (including the Chiasso Formation) and of late Alpine, Tertiary intrusions.

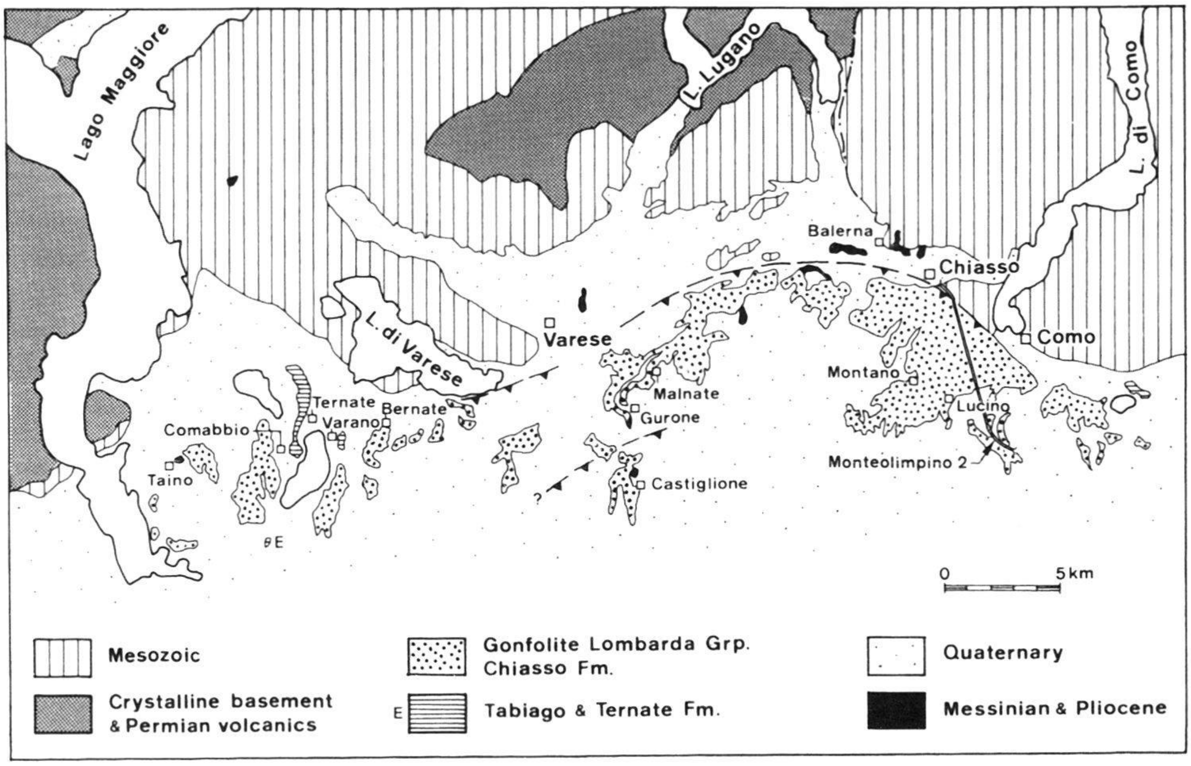

Fig. 2. Outcrop map of the Chiasso Formation and the Gonfolite Lombarda Group. After Mattirolo et al. (1932), Novarese et al. (1937) and Spicher (1980).

Group are very poor in fossils and only the sandy and argillaceous formations are dated by microfossils (Rögl et al. 1975, Gelati et al., 1988, 1991). Some chronostratigraphic constraints are obtained from radiometric and fission track cooling ages of boulders, pebbles and mineral grains from conglomerates and sandstones (Giger & Hurford 1989, Giger 1991).

In this paper we present new chronological information based on Sr-isotope ratio measurements of (still aragonitic) mollusc shells. These isotope data allow the applicability of the method in marine depositional settings dominated by clastic input of recycled continental crustal material to be tested. For comparison, fossil (primarily calcitic) shells from post-orogenic Pliocene sediments were also included in our study. New radiometric and fission track cooling ages constrain the age of the younger coarse clastic sediments of the Gonfolite Group southeast of Varese (Lucino Conglomerate near Malnate, conglomerates at Castiglione-Olona). Such data are particularly important for the upper, Miocene, part of the Gonfolite Group where biostratigraphic information is scarce.

Stratigraphy of the Chiasso Formation and the Gonfolite Lombarda Group

The Oligo-Miocene clastic wedge of the Southern Alps is represented by the Chiasso Formation and the Gonfolite Lombarda Group s.str. These sediments can be subdivided into four depositional sequences which correspond to (1) the Chiasso Formation, (2) the Como Conglomerate and its lateral equivalents, (3) the Lucino Conglomerate with its lateral equivalents and (4) the Gurone Sandstone (Figs. 3 and 4, Gelati et al. 1988, 1991).

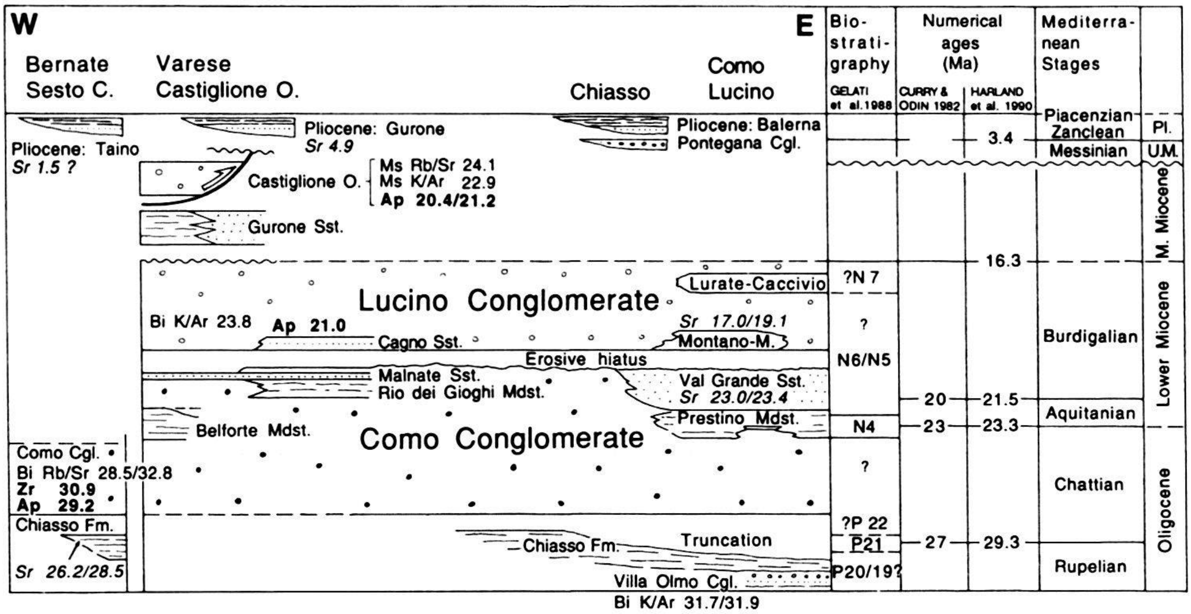

Fig. 3. Stratigraphic chart of the Chiasso Formation and the Gonfolite Lombarda Group, after Gelati et al. (1988). Planktonic foraminiferal zonation of Blow (1969). Sr isotope ages from this paper, radiometric data from Giger (1991), Giger & Hurford (1989), Oschidari (1991) and this study. Radiometric time scales from Harland et al. (1990) and Curry & Odin (1982). Ap: apatite fission track age, Bi: biotite age, Ms: muscovite age, Sr: $^{87}Sr/^{86}Sr$ age on mollusc shells, Zr: zircon fission track age in Ma.

If younger than the Gurone Sandstone, the conglomerates of Castiglione Olona would represent a fifth depositional sequence. Detailed descriptions of the stratigraphy and sedimentology of the Chiasso Formation and the Gonfolite Lombarda Group are found in Gunzenhauser (1985) and Gelati et al. (1988, 1991).

Chiasso Formation

Near Chiasso and Como, a 170 m thick sequence of silt- and mudstones (Chiasso Formation) with intercalations of thin-bedded turbidites and deep water conglomerates (Villa Olmo Conglomerate) occurs below the Gonfolite Group. Benthic foraminifera document a deeper marine, upper bathyal (600–1200 m) environment of deposition (Rögl et al. 1975); elsewhere (Bernate) intraformational unconformities and large submarine slumps suggest a slope or base of slope setting (Gunzenhauser 1985). A poor assemblage of planktonic foraminifera indicates a Late Rupelian to Early Chattian age (P 19/20 to P 21 or possibly P 22 of the zonation of Blow [1969]) in the area of Chiasso and Como (Gelati et al. 1988). West of Varese, the Chiasso Formation appears to stratigraphically overlay the bioclastic submarine fan deposits of the Upper Eocene Ternate Formation (Bernoulli et al. 1988), possibly without a major angular unconformity (Cita 1953, Villa 1955). Cita (1953) and Villa (1955) attributed an Early Oligocene age to the outcrops near Varano-Borghi (Filatoio di Varano and Cna. Boffalora, cf. Martinotti 1924) and a "middle" to Late Oligocene age to those of Bernate (Gunzenhauser 1985). However, in the Chiasso-Como area (Villa Olmo Conglomerate), the occurrence of well-rounded limestone pebbles from the Ternate Formation, already showing the typical diagenetic features of that formation, suggests subaerial truncation of the folded substrate to the north (Bernoulli et al. 1989).

Como Conglomerate and lateral equivalents

The Chiasso Formation is truncated by a major unconformity which suggests a drastic drop of relative sea-level. The overlying Como Conglomerate (uppermost Oligocene-Lower Miocene) consists of up to 1500 m thick deep water conglomerates. It probably is the result of rapid deposition in a submarine canyon system proximally incised into the slope deposits of the Chiasso Formation. Laterally, the conglomerates pass into mudstones and thin-bedded turbidites representing levee and interchannel facies (Prestino Mudstones, uppermost Chattian to Aquitanian, parts of Blow's [1969] zones N 4 and N 5, Gelati et al. 1988). Distally and upward, the Como Formation is overlain by thick-bedded sandstones (Val Grande Sandstone, Lower Miocene, $\pm$ 700 m) arranged in thickening and coarsening upward lobes (Gunzenhauser 1985). The Val Grande Sandstone contains a fauna of planktic foraminifera of Early Burdigalian age (N 5 or N 6, Gelati et al. 1988).

In the area of Varese, the upper part of the Como Conglomerate passes laterally into mudstones (Rio dei Gioghi Mudstone, Gunzenhauser 1985; Belforte Marls, Gelati et al. 1988) and turbiditic sandstones (Malnate Sandstone, Longo 1968, Gelati et al. 1988, Cagno Sandstone, Gunzenhauser 1985). Their ages and facies roughly correspond to those of the Prestino Mudstone (Belforte Mudstones, uppermost Chattian to possibly lowest Aquitanian, Gelati et al. 1988) and of the Val Grande Sandstone (Rio dei Gioghi Mudstone, Lower Burdigalian, Gelati et al. 1988).

Lucino Conglomerate and lateral equivalents

The third depositional sequence, the Lucino Conglomerate, is up to 1000 m thick and of Burdigalian and possibly also younger age. It is separated by an erosional truncation from the underlying Como and Val Grande Formations (Gelati et al. 1988). Conglomerates and pebbly sandstones grade laterally (Lucinasco Mudstones, Longo 1968, Gelati et al. 1988; Montano Member, Gunzenhauser 1985) and upward (Lurate Caccivio Mudstones, Gelati et al. 1988) into mudstones and thinner-bedded turbidites. Based on a poor foraminiferal assemblage reported by Santini (1956), Gelati et al. (1988) envisage an Aquitanian-Burdigalian (p.p.) age for the Lucinasco Mudstones. For the Lurate Caccivio Mudstones, these authors suggest a Late Burdigalian age (? Zone N 7 of Blow [1969]). Palynological results of Bernoulli and Mohr (unpublished) suggest a Middle Miocene age for at least a part of the Lucino Conglomerate. In fact, the Early Miocene age suggested by Gelati et al. (1988) is based rather on the absence of certain planktonic foraminiferal species than on actual occurrences (pers. comm. H. Thierstein 1989).

Gurone Sandstone

The Lucino Conglomerate is unconformably overlain by two other, probably heteropic formations, the Gurone Sandstone and the Bizzozzero Mudstone which represent a fourth depositional sequence (Gelati et al. 1988). The Gurone Sandstone consists of pebbly mudstones, turbiditic sandstones, mudstones, and conglomerates, representing a channel-levee complex. The Gurone Sandstone appears to pass laterally into the homogeneous Bizzozzero Mudstone. Neither formation is dated biostratigraphically, but both might be of Middle Miocene age (Gelati et al. 1991).

Conglomerates of Castiglione-Olona

South of the outcrops of the Gurone Sandstone, conglomerates crop out in the village of Castiglione-Olona (Mattirolo et al. 1932, Nangeroni 1932). They have never been described in detail and their age and stratigraphic relation to other formations of the Gonfolite Group are not obvious. They are massive, clast-supported and predominantly composed of metamorphic and rare granodiorite pebbles, and yield, according to our initial examination, no sedimentary clasts. They dip approximately 15° south and are onlapped by Pliocene marls (Nangeroni 1932, p. 80). Their southern occurrence could suggest that they are younger than the presumably Middle Miocene Gurone Formation outcropping to the north. Alternatively, the conglomerates could be part of the Lucino Conglomerate; in this case they would have been emplaced by a north-directed thrust similar to the Monteolimpino thrust (Fig. 2, cf. Bersezio et al. in press).

The sediments of the Gonfolite Lombarda Group (and the underlying Mesozoic strata) are unconformably overlain by the postorogenic Pontegana Conglomerate of probable Messinian age (Bini et al. 1978) and by Pliocene clays and argillaceous silt- and sandstones with a rich marine fauna (Corselli et al. 1985). Interestingly, the Pliocene sediments at Taino (Lago Maggiore) are reported to yield fossils also of Late Miocene age (Anfossi et al. 1983). If confirmed, these fossils are obviously reworked from an unknown source formation which, however, must have been outcropping in the South Alpine area.

Methods

Sr and Rb measurements: Seven shells of gastropods and bivalves were mechanically cleaned with a scalpel, washed in an H_2O ultrasonic bath before they were immersed in pure ethanol and dried. Then the shells as well as the dolomite sample BZG 4 were ground to a grain size of < 0.1 mm. Approximately 0.1 grams of sample material were weighed into a platinum crucible. In order to minimize leaching of Sr from non-carbonate, detrital material, the samples were dissolved in a mixture of 2 ml H_2O and 15 ml 5 M acetic acid. After 12 hours of treatment, the soluble fraction was decanted and centrifuged twice before it was brought to dryness under an infrared lamp. The purified samples were then dissolved again in 15 ml 5 M acetic acid for further handling. The dolomite sample BZG 4 was treated differently: one aliquot was completely dissolved in a 100:1 HF-$HClO_4$ mixture while the other aliquot was only partially dissolved in 2.5 N HCl with subsequent decanting and centrifuging of the resulting solution.

An aliquot of each carbonate solution was separated for the subsequent determination of the isotopic composition. To determine the Rb and Sr concentration of the soluble fraction of the samples, the rest of the solution was again split into two aliquots with the addition of highly pure ^{87}Rb and ^{84}Sr spike solutions. After drying all the aliquots were dissolved in exactly 2 ml 2.5 N HCl before loading onto Dowex 50 × 8 cation exchange columns. Samples were eluted in 2.5 N HCl and evaporated to dryness after the addition of 0.2 ml $HClO_4$. The Sr fraction was then loaded as a nitrate on a single Ta filament. Isotopic composition and concentration were determined in separate runs on a VG Sector five-collector mass spectrometer using dynamic mode with mass fractionation normalized to a $^{86}Sr/^{88}Sr$ ratio of 0.1194. The Rb fraction was loaded as a chloride on the Ta side filaments of a Ta-Re-Ta triple filament configuration. The Rb concentration was then determined on a single collector AVCO thermal ionisation mass spectrometer.

The total blank for the chemical procedure was below 5 ng/g total Sr and below 6 ng/g total Rb. Ten measurements of the Sr standard NBS SRM 987 yielded a mean $^{87}Sr/^{86}Sr$ of 0.710243 ± 45. Five measurements of the recent Mediterranean Cap d'Agde (CDA) pectinid standard of Fischer (1988) gave a mean $^{87}Sr/^{86}Sr$ ratio of 0.709168 ± 41.

Additional $^{87}Sr/^{86}Sr$ measurements (BZG 1, BZG 5a and BZG 6a) were made using the mass spectrometer facilities at Université Libre de Bruxelles (Laboratoires Associés Géologie-Pétrologie-Géochronologie). The mean value of the Standard Reference Material SRM-987 is 0.710235. Also the recent Mediterranean CDA standard was with 0.709174 ± 24 identical with the standards measured in the Laboratory in Berne.

To enable comparison of our results with data of de Paolo & Ingram (1985), Miller et al. (1988, 1991), McKenzie et al. (1988), and Hodell et al. (1990, 1991), they have been normalized to the respective NBS SRM 987 values reported by these authors. Most of the $^{87}Sr/^{86}Sr$ ratios were corrected for the contribution from decay of ^{87}Rb since their estimated time of formation. We have used ± 0.000045 on the $^{87}Sr/^{86}Sr$ ratio as a conservative estimate for our error exceeding the intrarun precision of our measurements. This corresponds to 0.7 Ma resolution using the sea water evolution curve of McKenzie et al. (1988) which was applied to samples of Late Miocene to Early Pliocene age (4.5 to 5.5 Ma) while it corresponds to a resolution of 2.6 Ma using the curve of Miller et al. (1988) which was used for samples in the age range of 36 Ma to 24 Ma. The age of samples plotting outside these ranges were estimated using the sea water evolution curves of de Paolo & Ingram (1985), Miller et al. (1991), and Hodell et al. (1990, 1991). The carbonate data and the stratigraphic ages are listed in Tables 1 and 2.

The biotite samples KAW 2481, KAW 2485 and KAW 2486 were digested in a 100:1 HF-$HClO_4$ mixture before they were dissolved in 2.5 N HCl. Further chemical treatment and mass spectrometry did not differ from the carbonate preparation and analysis procedure. The Rb/Sr ages of the mica samples from boulders were calculated using the Rb/Sr whole rock data of Oschidari (1991) for the same samples. The Rb/Sr mica age data are presented in Table 3.

K/Ar measurements: Four mica samples separated from boulders (Table 4) were dated with the K/Ar method using the techniques described by Flisch (1986). Potassium was determined in duplicate by flame photometry, the reproducibility being better than ± 1 % for the mica analyses. Argon isotopic ratios were measured using a MM 1200 mass spectrometer in static mode, employing an enriched ^{38}Ar spike (Schumacher 1975) calibrated against both known air volumes and standard minerals. All ages have been calculated using the constants recommended by IUGS (Steiger & Jäger 1977).

Fission track ages: One zircon and four apatite samples separated from boulders in the Chiasso and Lucino Formations and from Castiglione Olona (Table 4) were dated with the fission track method using the procedures described by Gleadow (1981) and Hurford (1986a). The samples were irradiated in the HARWELL-reactors DIDO and

PLUTO. The uranium glass SRM 612 was used as a dosimeter for the apatites and the glass CN-1 for the zircon sample. For three samples the external detector method (EDM) was applied, whereas two samples were dated using the population method. The ages have been calculated using the zeta approach (Hurford & Green 1983) and age errors were assessed with conventional statistics (Green 1981). The confined track lengths of two of the apatite samples were also determined using the analytical procedures described by Gleadow et al. (1986). These track length analyses (see Table 5) demonstrate that the samples cooled relatively rapidly during uplift in the Central Alps and that, with the exception of the Como Conglomerate near Como (Giger 1991), the strata of Gonfolite Lombarda were never buried deeply enough to cause detectable annealing of fission tracks in apatites.

Sr-isotope stratigraphy

The analytical results of the Sr isotope determinations are listed in Table 1, the age calculations using the different strontium isotope seawater curves are shown in Table 2 and the results integrated in Figures 3 and 4. A gastropod (aragonite, sample BZG 6) and a bivalve (aragonite, sample BZG 6a) from the Chiasso Formation of the Filatoio di Varano (Fig. 1) yielded $^{87}Sr/^{86}Sr$ ages of 28.5 Ma and 26.2 Ma respectively, using the sea water evolution curve of Miller et al. (1988). These "middle" Oligocene ages (corresponding to the C9 and C7 chrons, respectively) are in good agreement with the results obtained using the sea water evolution curve of de Paolo & Ingram (1985). The data confirm the correlation of the outcrops of the area of Varano-Bernate with the Chiasso Formation in the area of Chiasso-Como (upper Rupelian-lower Chattian, Gelati et al. 1988) and the biostratigraphically established age of the formation in the area (Martinotti 1924, Cita 1953, Villa 1955).

The nautilid (aragonite, sample BZG 7), collected in the Val Grande Sandstone of the Monteolimpino II tunnel, yielded $^{87}Sr/^{86}Sr$ ages of 23.0 and 23.4 Ma, corresponding to the Early Miocene C6B chron, according to the curves of Hodell et al. (1991) and Miller et al. (1991), respectively. This age is only more or less in accordance with the biostrati-

Table 1. Geochemical data of mollusc shells and of dolomite from the Chiasso Formation and the Gonfolite Lombarda Group.

Sample	Description	Location	Formation	Sr (ppm)	Rb (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ (measured)	$^{87}Sr/^{86}Sr$ (Rb corr.)
BZG 1	*Ostrea* sp.	Taino	Pliocene	245	n.d.	n.d.	0.709085±5	0.709085
BZG 2	*Ostrea* sp.	Gurone	Pliocene	286.7	0.018	0.00018	0.709010±16	0.709010
BZG 3	gastropod	Montano, S Como	Lucino Fm.	919.6	3.063	0.00964	0.708563±38	0.708561
BZG 4/HF	dolomite	Montano, S Como	Lucino Fm.	928.5	31.8	0.09912	0.708812±40	0.708778
BZG 4/HCl	dolomite	Montano, S Como	Lucino Fm.	1059	13.78	0.03767	0.708413±11	0.708400
BZG 5	bivalve	Mte.Ol. 2 Tunnel	unknown	1536	1.614	0.00304	0.708889±37	0.708889
BZG 5a	bivalve	Mte.Ol. 2 Tunnel	unknown	n.d.	n.d.	--	0.708907±5	0.708907
BZG 6	gastropod	Varano	Chiasso Fm.	831.1	1.044	0.00364	0.708100±34	0.708099
BZG 6a	bivalve	Varano	Chiasso Fm.	n.d.	n.d.	--	0.708177±25	0.708177
BZG 7	nautilid	Mte. Ol. 2 Tunnel	Valgrande Fm.	887.3	1.646	0.00537	0.708309±28	0.708307

n. d. = not determined

Table 2. Obtained ages for the different fossil shells by comparison of their $^{87}Sr/^{86}Sr$ ratios to different open ocean sea water curves.

sample	$^{87}Sr/^{86}Sr$	$\delta^{87}Sr$ *	Miller et al. (1988) Ma	McKenzie et al. (1988) Ma	DePaolo & Ingram (1985) Ma	Miller et al. (1991) Ma	Hodell et al. (1990; 1991) Ma
BZG 1	0.709085	-11.7					1.5
BZG 2	0.709010	-22.3		4.85	5.0		
BZG 3	0.708561	-85.6			17.0	19.1	
BZG 4/HF	0.708778	-55.0			14.0	15.5	13.4
BZG 4/HCl	0.708400	-108.3			21.0	21.8	21.4
BZG 5	0.708889	-39.3			9.0	10.3	8.8
BZG 5a	0.708907	-36.8				8.9	8.0
BZG 6	0.708099	-150.7	28.5		28.0		
BZG 6a	0.708177	-139.7	26.2		26.0		
BZG 7	0.708307	-121.4			23.0	23.4	23.0

* $\delta^{87}Sr = [(^{87}Sr/^{86}Sr)_{sample}/(^{87}Sr/^{86}Sr)_{seawater} - 1] \times 10^5$; seawater is 0.709168 from our study

graphic attributions of Gelati et al. (1988). According to the time scales of Berggren et al. (1985) and of Harland et al. (1990) foraminiferal zone N 5 to which the Val Grande Formation is allocated by Gelati et al. (1988) begins at 21.8 and 21.5 Ma, respectively. In view of the uncertainties in the Sr-isotope time scale and of the radiometric calibration of the biozones this deviation may not be significant.

A bivalve, also collected in the Monteolimpino II tunnel (aragonite, sample BZG 5) presents ambiguous results. The bivalve was thought to be derived from the Valgrande Sandstone for which an Early Miocene, Aquitanian to Early Burdigalian (N 5 or N 6) age is biostratigraphically established (Gelati et al. 1988) and confirmed by the Sr-isotope ratio of sample BZG 7. Sample BZG 5 (measured twice) yielded $^{87}Sr/^{86}Sr$ ages of 8.9 and 10.3 Ma according to the curve of Miller et al. (1991) and of 8.0 and 8.8 Ma according to that of Hodell et al. (1991). These ages clearly fall into the Late Miocene and are incompatible with the biostratigraphically established age of the Valgrande Sandstone.

At present we cannot explain this discrepancy. If real, the Late Miocene ages could signify that in the Monteolimpino II tunnel, younger, Late Miocene canyon fills are hidden which have not been recognized. Indeed, Gelati et al. (1988) interpret the presence of a deep valley encountered in the tunnel as connected with the Messinian canyon system, and the reported presence of Upper Miocene marine fossils in Pliocene deposits (Anfossi et al. 1983) could hint to the former presence of Upper Miocene marine deposits in the outcrop area of the Gonfolite Lombarda.

A gastropod (aragonite, sample BZG 3) from the Montano Member of the Lucino Formation (Coord. Swiss topogr. map 723'500/072'200) yielded a Middle Miocene $^{87}Sr/^{86}Sr$ age of 17 Ma according to the sea water evolution curve of de Paolo& Ingram (1985) and of 19.1 Ma according to that of Miller et al. (1991). This would place the lower part of the Lucino Conglomerate into the uppermost Burdigalian or near the base of the Langhian. It is therefore probable that the Lucino Formation extends into the Middle Miocene.

The dolomite level (BZG 4), found by Gunzenhauser (1985) in the Montano Member of the Lucino Formation, yielded two different $^{87}Sr/^{86}Sr$ ratios depending on the preparation technique. The average ages according to three different sea water evolution curves (De Paolo & Ingram 1985; Miller et al. 1991; Hodell et al. 1991), are 14.3 Ma for the aliquot which was dissolved in HF and 21.4 Ma for the aliquot dissolved in HCl. We assume that a contribution of detrital material containing much radiogenic Sr (e.g. micas and clay minerals) led to the younger apparent age of the HF-dissolved fractions while such contributions appear to be negligible in the partial HCl leachate which gives a rather old age of 21 Ma (Early Miocene) for the dolomite layer. It is obvious that these ages have no chronological significance. The Sr isotopic composition of this sample may represent rather a mixing composition of different sources (volcanic Sr, sea-water Sr, Sr from a Rb-enriched phase). Volcanic material is indeed present in the dolomite level, and it is probable that the dolomite was formed by the submarine alteration of volcanic ash (D. Bernoulli and B. Gunzenhauser, unpubl.) and that the $^{87}Sr/^{86}Sr$ ratio is influenced by a low $^{87}Sr/^{86}Sr$ ratio of the parent volcanic material.

The Pliocene *Ostrea* from Gurone (calcite, sample BZG 2) yielded an average age of 4.9 Ma according to the curves of McKenzie et al. (1988) and De Paolo & Ingram (1985). This is in accordance with the Zanclean (Early Pliocene) age attributed to the postorogenic Pliocene strata of Gurone by Corselli et al. (1985).

The comparison of the Sr isotopic ratio of a Pliocene *Ostrea* from Taino (calcite, BGZ 1) to the open ocean water curve of Hodell et al. (1991) yielded an exceptionally young age of 1.5 Ma which would be oldest Pleistocene. Including the resolution of the Sr isotope method of approximately $\pm$ 0.5 Ma, this sample could still be Late Pliocene in age. This age is, however, in contrast with the Early Pliocene age biostratigraphically established for this locality (Guaitani 1944, Anfossi et al. 1983). As the shell sample was detached from the sediment and thoroughly cleaned with a carbide-tipped dental drill before sampling, contamination with some clay increasing the Sr isotope ratio seems unlikely. In order to constrain a young, Late Pliocene age of the formation at Taino more measurements on different shells are obviously needed.

Radiometric constraints

In Fig. 4, the cooling paths established for the different pebbles of the conglomeratic formations (Giger & Hurford 1989, Giger 1991, new data) and our Sr-isotope data are compared with the biostratigraphic data of the different formations of the Gonfolite Lombarda Group as given by Gelati et al. (1988), calibrated according to the numeric time-scales of Curry & Odin (1982), Berggren et al. (1985) and of Harland et al. (1990).

Chiasso Formation and Villa Olmo Conglomerate

The conglomerates intercalated in the slope or base of slope deposits of the Chiasso Formation (Villa Olmo Conglomerate) contain pebbles and boulders derived from the Oligocene Bregaglia intrusive complex (Fig. 1). A tonalite pebble yielded K/Ar biotite *cooling* ages of 31.7 $\pm$ 0.5 Ma and 31.9 $\pm$ 0.4 Ma (Giger & Hurford 1989, KAW 3148, Table 4, Fig. 4) which, according to the time scales of Berggren et al. (1985, 30 Ma for the Rupelian-Chattian boundary), Haq et al. (1987, 30 Ma for the Rupelian-Chattian boundary) and Harland et al. (1990, 29.3 Ma for the Rupelian-Chattian boundary), is very near to identical to the biostratigraphically established Late Rupelian age of depo-

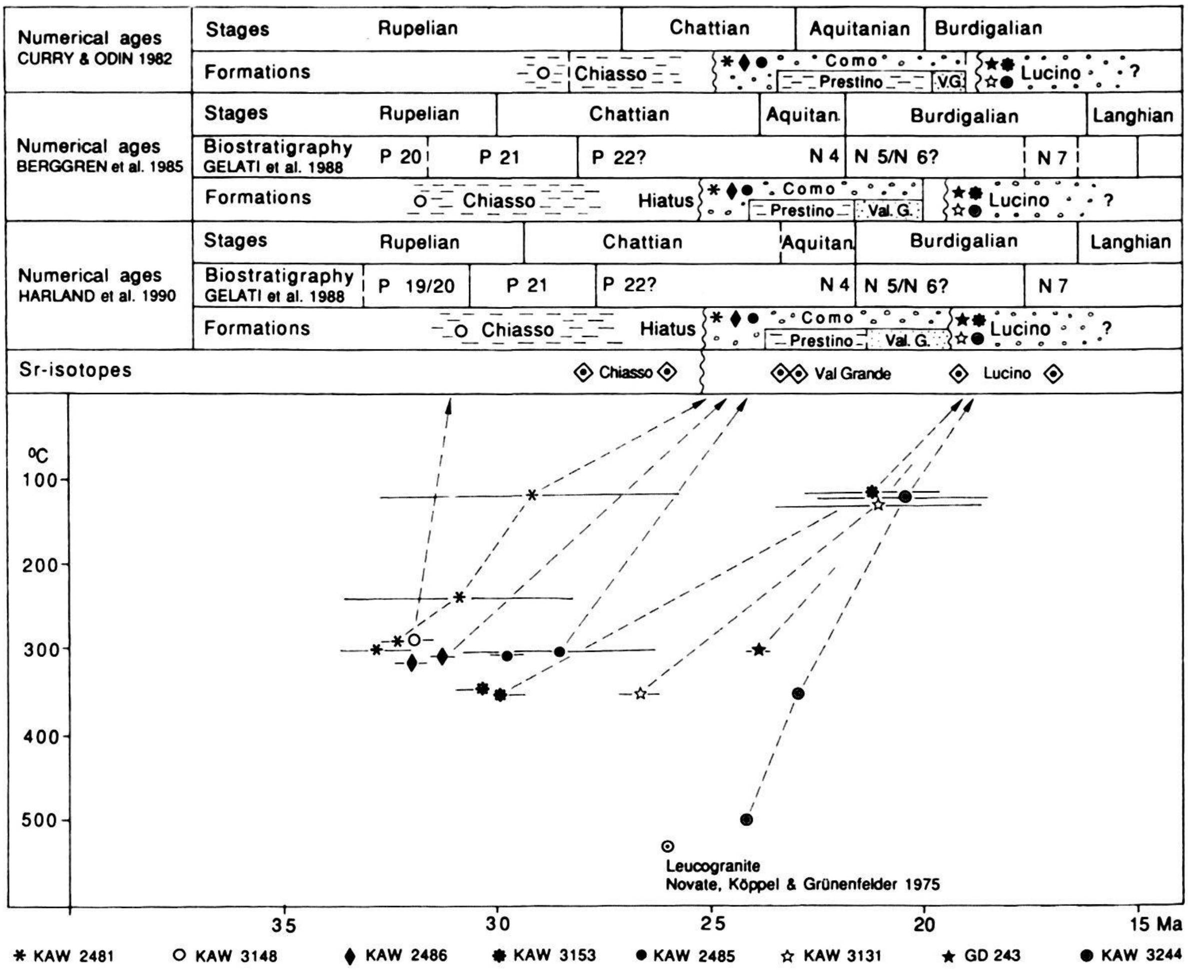

Fig. 4. Cooling path of the selected pebbles from the Villa Olmo Conglomerate and from conglomeratic formations of the Gonfolite Lombarda Group, Sr-isotope (this study) and biostratigraphic (Gelati et al. 1988) data of the different formations, compared with the numeric time-scales of Curry & Odin (1982), Berggren et al. (1985) and Harland et al. (1990).

sition (Gelati et al. 1988, P 19–20) and would imply an extremely high cooling rate for this rock prior to its erosion and a short time span between erosion and deposition. Compared with the time-scale of Haq et al. (1987) and Harland et al. (1990), the time-scale of Curry and Odin (1982, Rupelian-Chattian boundary at 27 Ma) would allow for more time for uplift, cooling, erosion and deposition of these Tertiary tonalite boulders. However, apparent discrepancies between the cooling age of the tonalite pebble and the time-scales of Berggren et al. (1985), Haq et al. (1987) and Harland et al. (1990) may originate from a still inadequate calibration of planktonic foraminiferal zones by radiometric dating.

Como Conglomerate near Comabbio and Taino

The analytical results of our new Rb-Sr age determinations on biotites separated from Tertiary tonalite boulders in the conglomerates outcropping west of Comabbio (Fig. 2) are listed in Table 3 (Samples KAW 2481, 2485 and 2486, see also Fig. 4). These

Table 3. Rb/Sr isotope data of the analysed biotites from Bregaglia tonalite boulders in the Como Conglomerate. Whole rock Rb/Sr data from Oschidari (1991), K/Ar biotite ages from Kapp (1986).

Sample	Total rocks; minerals	Location	Formation	Sr (ppm)	Rb (ppm)	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$	Age Ma	K/Ar ages Ma 1)
KAW	Total 2)	Comabbio	Como Fm.	195.76	93.81	0.709152±10	1.387		
2481	Biotite	do.	do.	5.09	476.62	0.836006±137	273.998	32.8 ± 0.9	32.3 ± 0.4 1)
KAW	Total 2)	SW Taino	Como Fm.	306.54	140.48	0.711368±10	1.326		
2485	Biotite	do.	do.	2.68	743.01	1.045897±7	827.522	28.5 ± 2.3	29.8 ± 0.4 1)
KAW	Total 2)	Sesto-	Como Fm.	267.55	65.79	0.707474±10	0.711		
2486	Biotite coarse	Calende	do.	2.02	454.55	1.005502±26	669.655	31.4 ± 1.4	32.0 ± 0.4 1)
	Biotite fine	do.	do.	2.20	454.55	0.979908±34	614.430	31.3 ± 1.4	31.8 ± 0.4 1)

References: 1) from KAPP (1986)
2) from OSCHIDARI (1991)

Table 4. K/Ar isotope data for boulders from the Villa Olmo Conglomerate and from the Gonfolite Lombarda Group.

Sample	Locality	Rock type	Mineral	Stratigraphic age of host formation	K wt %	^{40}Ar rad nl/g	^{40}Ar rad % total	K/Ar age Ma and 1σ - error
KAW 3244	Castiglione-Olona (I)	Leuco-granite	White mica	Burdigalian or younger	8.86 8.86	7.94150 1) 7.92306 1)	77.53 78.18	22.9 ± 0.3 22.9 ± 0.3
KAW 3153	Castiglione-Olona (I)	Granitic gneiss	White mica	Burdigalian or younger	8.94	10.49050	90.68	29.9 ± 0.7 2)
KAW 3153	Castiglione-Olona (I)	Granitic gneiss	Biotite	Burdigalian or younger	8.00	9.51404	95.63	30.3 ± 0.7
GD 243	Malnate (I)	Grano-diorite	Biotite	Burdigalian or younger (Lucino Fm.)	7.10	6.59615	91.97	23.8 ± 0.2
KAW 3148	Villa Olmo	Tonalite	Biotite	Late Rupelian or Early Chattian	6.98 6.96	8.67468 8.72092	90.26 88.07	31.7 ± 0.5 2) 31.9 ± 0.4 2)

1) double determination
2) from GIGER & HURFORD (1989)

biotites yield Rb/Sr ages between 28.5 ± 2.3 Ma and 32.8 ± 0.9 Ma, ages which are in good agreement with the K/Ar ages determined by Kapp (1986). Fission track ages measured on one of the samples (KAW 2481) are 30.9 ± 2.7 Ma for zircon and 29.2 ± 3.5 Ma for apatite respectively (Table 5, Fig. 4, cf. Giger 1991). For the stratigraphic considerations, apatite fission track ages were only used from the southwestern area or from the Miocene formations of the Gonfolite Lombarda Group which never were buried more than about 1 km (see track length data in Table 5). These cooling ages thus give an absolute maximum age for the deposition of the conglomerates and confirm the correlation of the outcrops with the Como Formation (Figs. 3 and 4) which yields analogous mica ages for similar boulders (Giger & Hurford 1989).

Table 5. Fission track data for boulders from the Gonfolite Lombarda Group.

Sample and locality	Mineral and no. of xx	Spontaneous ρs	Ns	Induced ρi	Ni	Ns/Ni	Irrad. No. Glass	Dosimeter ρd	Nd	p χ^2 (%)	FT Age Ma and 1σ-error
KAW 2481 Comabbio	Apatite 86 (Population)	2.755	120	14.236	620	0.193	Bern H-14 612	5.531	4308	----	29.2 ± 3.5
KAW 2481 Comabbio	Zircon 10 (EDM)	47.927	449	27.219	255	1.761	Bern H-18 CN-1	3.063	4171	≈ 95%	30.9 ± 2.7
KAW 3244 Castiglione	Apatite 100 (Population)	3.495	177	21.149	1071	0.165	Bern H-16 612	4.525	4287	----	20.4 ± 2.0
KAW 3153 Castiglione	Apatite 14 (EDM)	10.855	242	51.402	1146	0.211	Bern H-13 612	6.604	12049	≈ 90%	21.2 ± 1.6
KAW 3131 Mte. Morone	Apatite 9 (EDM)	4.143	95	19.667	451	0.211	Bern H-13 612	6.546	12049	≈ 95%	21.0 ± 2.5

Length data KAW 3153: Mean confined track length 13.9 μm. Standard deviation of distribution 1.1 μm. Number of confined tracks 76.
KAW 2481: Mean confined track length 14.7 μm. Standard deviation of distribution 1.1 μm. Number of confined tracks 25.

Notes:
i) track densities (ρ) are as measured and (x 10^5 tracks cm^{-2})
ii) population apatite ages are calculated with a zeta-SRM 612 of 273 ± 13 (1s)
iii) EDM apatite ages are calculated with a zeta-SRM 612 of 305 ± 13 (1s)
iv) EDM zircon age is calculated with a zeta-CN-1 of 115 ± 4
iv) all the EDM-samples passed a χ^2-Test and the ages were calculated with the ratio Ns/Ni

Lucino Conglomerate

K/Ar ages on biotite from Tertiary granodiorite and tonalite pebbles in the Lucino Conglomerate range from 23.8 ± 0.2 to 30.7 ± 1.2 Ma, their fission track ages on zircon from 25.7 ± 2.4 to 29.6 ± 3.5 Ma (Giger 1991), and apatite from 21.0 ± 2.5 to 24.7 ± 2.0 Ma, respectively (Table 5 and Giger 1991). These ages do not allow the age of the Lucino Conglomerate to be constrained better than by biostratigraphy or by our Sr-isotope determinations. However, the above K/Ar age of 23.8 ± 0.2 Ma on a biotite from a granodiorite pebble (GD 243, Table 4) and the Early Miocene fission track ages confirm the allocation of the conglomerates overlying the Malnate Sandstones southwest of Malnate (Coord. Swiss topogr. map 710'900/072'650) to the Lucino Conglomerate (Gelati et al. 1988).

Conglomerates of Castiglione-Olona

The age and the stratigraphic relation to the formations of the Gonfolite Group are unknown for the conglomerates which crop out in the village of Castiglione-Olona (Fig. 2, Coord. Swiss topogr. map 710'850/068'275). Their facies would make a correlation with the Como or with the Lucino Conglomerate possible; on the other hand, because of their southern geographic location one could argue for a stratigraphic position high up in the Gonfolite Lombarda Group, above the probably Middle Miocene Gurone Sandstone. The age of the conglomerates can, to some extent, be constrained by the numeric maximum age of the conglomerate: A pebble of a coarse-grained, garnet-bearing leucogranite can be genetically related to garnet-bearing leucogranites of the Novate intrusion (Fig. 1). This granite intruded about 26 Ma ago according to U/Pb data of Köppel & Grünenfelder (1975). The leucogranite pebble (KAW 3244) yielded a Rb/Sr white mica age of 24.1 $\pm$ 0.3 Ma (Oschidari 1991), a K/Ar white mica age of 22.9 $\pm$ 0.3 Ma for white mica and finally an apatite fission track age of 20.4 $\pm$ 2.0 Ma (Tables 4 and 5, Fig. 4). A pre-Alpine granitic gneiss boulder (KAW 3153) gave a K/Ar white mica age of 29.9 $\pm$ 0.7 Ma (Table 4) and an apatite fission track age of 21.2 $\pm$ 1.6 Ma (Table 5, Fig. 4). These ages are only slightly younger than comparable K/Ar mica and fission track ages of pebbles from the Lucino Conglomerate. The conglomerates of Castiglione-Olona are therefore certainly not older, but possibly of the same age as the Lucino Conglomerate. Assuming a cooling trend for the leucogranite boulder similar to the cooling trends observed for some of the pebbles of the Lucino Conglomerate, a maximum sedimentation age of $\approx$ 19 Ma would result for the Castiglione-Olona conglomerates (Giger 1991); this age would still fall into the age range of the Lucino Conglomerate (Burdigalian to Langhian). From these cooling ages, as well as from their facies, it is most probable that the conglomerates of Castiglione-Olona belong to the Lucino Conglomerate and are older than the presumably Middle Miocene Gurone Formation. This would imply a north-vergent thrust north of Castiglione-Olona (Fig. 2). Such a thrust is also suggested by an outcrop of Upper Chattian mudstones, equivalent in age to the Prestino and Belforte Mudstones (upper zone P 22 to lowermost zone N 4), between the villages of Caronno and Castronno southwest of Castiglione-Olona (Bersezio et al. in press).

Conclusions

The results of our Sr isotope analysis show that Sr isotope dating on fossil material can be a valuable tool also in marine depositional settings dominated by clastic input of recycled continental crustal material: the obtained Sr isotope ratios are in relatively good accordance with the biostratigraphically established depositional ages for the different formations of the Group (Figs. 3 and 4, cf. Gelati et al. 1988). In the case of the pebbles derived from Tertiary intrusives embedded in the conglomerates of the Chiasso Formation and of the Gonfolite Lombarda, the time span comprising intrusion of the magmatic rocks, uplift and cooling to surface temperatures, erosion, transport and final deposition proved to be extremely short; in such cases radiometric signatures in lithoclasts may significantly constrain the depositional age of non-fossiliferous formations. In particular, radiometric dating of the cooling history of pebbles genetically related to the Oligocene Novate intrusion suggest a correlation of the conglomerates of Castiglione-Olona with the Burdigalian-Langhian Lucino Conglomerate. This would imply a northvergent thrust between Castiglione Olona and Gurone. This interpretation is supported by outcrops of mudstones with an Upper Chattian fauna in the area (Bersezio et al. in press).

Acknowledgements

This study was partially supported by the Swiss National Science Foundation. We thank E. Jäger and R. Gelati for much information and stimulating discussions, R. Gelati, A. J. Hurford, E. Jäger and R. Moritz for careful reviews, and U. Gerber and A. Uhr for much help in the preparation of this paper. R. Gelati kindly lent us the nautilid (sample BZG 7) from the Val Grande Formation for Sr isotope determination.

REFERENCES

ANFOSSI, G., BRAMBILLA, G. & MOSNA, S. 1983: La fauna del Pliocene di Taino (Varese). Atti Ist. Geol. Univ. Pavia 30, 83–102.

BERGGREN, W. A., KENT, D. V., FLYNN, J. J. & VAN COUVERING, J. A. 1985: Cenozoic geochronology. Geol. Soc. Amer. Bull. 96, 1407–1418.

BERNOULLI, D., BERTOTTI, G. & ZINGG, A. 1989: Northward thrusting of the Gonfolite Lombarda ("South-Alpine Molasse") onto the Mesozoic sequence of the Lombardian Alps: Implications for the deformation history of the Southern Alps. Eclogae geol. Helv. 82, 841–856.

BERNOULLI, D., HERB, R. & GRÜNIG, A. 1988: The Ternate Formation, a late Eocene bioclastic fan of the Lombardian Basin (southern Alps). Amer. Assoc. Petrol. Geol., Mediterranean Basins Conference, Nice, Sept. 25–28, 1988.

BERSEZIO, R., FORNACIARI, M., GELATI, R., NAPOLITANO, A. & VALDISTURLO, A. in press: The significance of the Upper Cretaceous to Miocene clastic wedges in the deformation history of the Lombardian Southern Alps. Géol. alp. (Grenoble).

BINI, A., CITA, M. B. & GAETANI, M. 1978: Southern Alpine lakes – hypothesis of an erosional origin related to Messinian entrenchment. Marine Geol. 27, 271–288.

BLOW, W. H. 1969: Late-middle Eocene to Recent planktonic foraminiferal biostratigraphy. In: Proceedings of the First International Conference on Planktonic Microfossils (Ed. by Brönnimann, P. & Renz, H. H.). Geneva 1967, 1, 199–241, E. J. Brill, Leiden.

CASSANO, E., ANELLI, L., FICHERA, R. & CAPPELLI, V. 1986: Pianura Padana. Interpretazione integrata di dati geofisici e geologici. 73. Congr. Soc. geol. ital., 29. sett.-4. ott. 1986, Roma.

CITA, M. B. 1953: Studi stratigrafici e micropaleontologici sulle formazioni comprese fra il Nummulitico ed il Pliocene nel territorio di Varese. Boll. Serv. geol. Ital. 75, 671–677.

CORSELLI, C., CREMASCHI, M. & VIOLANTI, D. 1985: Il canyon messiniano di Malnate (Varese): pedogenesi tardomiocenica ed ingressione marina pliocenica al margine meridionale delle Alpi. Riv. ital. Paleont. Stratigr. 91, 259–286.

CURRY, D. & ODIN, G. S. 1982: Dating of the Palaeogene. In: Numerical Dating in Stratigraphy, Part I (Ed. by Odin, G. S.), 607–630, John Wiley and Sons Ltd., Chichester.

DE PAOLO, D. J. & INGRAM, B. L. 1985: High resolution stratigraphy with strontium isotopes. Science 227, 938–941.

DONDI, L. & D'ANDREA, M. G. 1986: La Pianura Padana e Veneta dall'Oligocene superiore al Pleistocene. G. Geol. (Bologna) (3), 48, 197–225.

FISCHER, H. 1988: Isotopengeochemische Untersuchungen und Datierungen an Mineralien und Fossilien aus Sedimentgesteinen: 1. Glaukonite aus dem Jura, der Molasse und dem Helvetikum (K-Ar, Rb-Sr), 2. $^{87}Sr/^{86}Sr$-Isotopenstratigraphie an marinen und limnischen Mikro- und Makrofossilien, 3. Primärmineralien aus tertiären Bentoniten und Tuffen (U-Pb, K-Ar). Ph.D. Thesis ETH-Zürich, Nr. 8733.

FLISCH, M. 1986: K-Ar dating of Quaternary samples. In: Dating Young Sediments (Ed. by Hurford, A. J., Jäger, E. & Ten Cate, J.), 299–323, CCOP-Unesco Techn. Publ. 16, Bangkok.

GELATI, R., NAPOLITANO, A. & VALDISTURLO, A. 1988: La "Gonfolite Lombarda": stratigrafia e significato nell'evoluzione del margine sudalpino. Riv. ital. Paleont. Stratigr. 94, 285–332.

– 1991: Results of studies on the Meso-Cenozoic succession in the Monte Olimpino 2 tunnel. The tectono-sedimentary significance of the "Gonfolite Lombarda". Riv. ital. Paleont. Stratigr. 97, 565–598.

GIGER, M. 1991: Geologische und petrographische Studien an Geröllen und Sedimenten der Gonfolite Lombarda Gruppe (Südschweiz und Norditalien) und ihr Vergleich mit dem alpinen Hinterland. PhD Thesis, Univ. Bern.

GIGER, M. & HURFORD, A. J. 1989: Tertiary intrusives of the Central Alps: Their Tertiary uplift, erosion, redeposition and burial in the south-alpine foreland. Eclogae geol. Helv. 82, 857–866.

GLEADOW, A. J. W. 1981: Fission track dating: what are the real alternatives? Nuclear Tracks 5, 3–14.

GLEADOW, A. J. W., DUDDY, I. R., GREEN, P. F. & LOVERING, J. F. 1986: Confined fission track length in apatite – a diagnostic tool for thermal history analysis. Contr. Mineral. Petrol. 94, 405–415.

GREEN, P. F. 1981: A new look at statistics in fission track dating. Nuclear Tracks 5, 77–86.

GUAITANI, F. 1944: Revisione della fauna dei lembi pliocenici delle Prealpi Lombarde. Riv. ital. Paleont. Stratigr. 50, 1–29.

GUNZENHAUSER, B. A. 1985: Zur Sedimentologie und Paläogeographie der oligo-miocaenen Gonfolite Lombarda zwischen Lago Maggiore und der Brianza. Beitr. geol. Karte Schweiz 159.

HAQ, B. U., HARDENBOL, J. & VAIL, P. R. 1987: Chronology of fluctuating sea levels since the Triassic. Science 235, 1156–1167.

HARLAND, W. B., ARMSTRONG, R. L., COX, A. V., CRAIG, L. E., SMITH, A. G. & SMITH, D. G. 1990: A Geologic Time Scale 1989. Cambridge University Press.

HODELL, D. A., MEAD, G. A. & MUELLER, P. A. 1990: Variation in the strontium isotopic composition of seawater (8 Ma to present): Implications for chemical weathering rates and dissolved fluxes to the oceans. Chem. Geol. 80, 291–307.

HODELL, D. A., MUELLER, P. A. & GARRIDO, J. R. 1991: Variations in the strontium isotopic composition of seawater during the Neogene. Geology 19, 24–27.

HURFORD, A. J. 1986: Cooling and uplift patterns in the Lepontine Alps, South Central Switzerland and an age of vertical movement on the Insubric fault line. Contr. Mineral. Petrol. 92, 413–427.

– 1986a: Application of the fission track dating method to young sediments: principles, methodology and examples. In: Dating Young Sediments (Ed. by Hurford, A. J., Jäger, E. & Ten Cate, J.). CCOP-Unesco Techn. Publ. 16, 199–233, Bangkok.

HURFORD, A. J. & GREEN, P. F. 1983: The zeta age calibration of fission track dating. Isotope Geosc. 1, 285–317.

HURFORD, A. J., FLISCH, E. & JÄGER, E. 1989: Unravelling the thermo-tectonic evolution of the Alpes: a contribution from fission track analysis and mica dating. In: Alpine Tectonics (Ed. by Coward, M. P., Dietrich, D. & Park, R. G.). Geol. Soc. (London) Spec. Publ. 45, 369–398.

KAPP, C. 1986: Petrographisch-geologische Untersuchungen im Gebiet zwischen dem Lago Maggiore und Varese. Unpubl. Diploma Thesis, Univ. Bern.

KÖPPEL, V. & GRÜNENFELDER, M. 1975: Concordant U-Pb ages of monacite and xenotime from the Central Alps and the timing of the high temperature metamorphism, a preliminary report. Schweiz. mineral. petrogr. Mitt. 70, 129–132.

LONGO, V. 1968: Geologie und Stratigraphie des Gebietes zwischen Chiasso und Varese. Mitt. geol. Inst. ETH u. Univ. Zürich, N. Ser. 86.

MARTINOTTI, A. 1924: Foraminiferi della Molassa di Varano (Varesotto). Atti Soc. ital. Sci. nat. (Milano) 82, 317–354.

MASSARI, F. 1990: The foredeeps of the northern Adriatic margin: evidence of diachroneity in deformation of the Southern Alps. Riv. ital. Paleont. Stratigr. 96, 351–380.

MATTIROLO, E., NOVARESE, V., TARICCO, M., PULLÈ, G., FOSSA MANCINI, E. & CATALISANO, S. 1932: Carta Geologica d'Italia, 1:100000, Foglio 31 Varese. Servizio Geologico d'Italia, Roma.

MCKENZIE, J. A., HODELL, D. A., MUELLER, P. A. & MUELLER, D. W. 1988: Application of strontium isotopes to late Miocene-early Pliocene stratigraphy. Geology 16, 1022–1025.

MILLER, K. G., FEIGENSON, M. D., KENT, D. V. & OLSSON, R. K. 1988: Oligocene stable isotope ($^{87}Sr/^{86}Sr$, $\delta^{18}O$, $\delta^{13}C$) standard section, Deep Sea Drilling Project Site 522: Paleoceanography 3, 223–233.

MILLER, K. G., FEIGENSON, M. G., WRIGHT, J. D. & CLEMENT, B. M. 1991: Miocene isotope reference section, Deep Sea Drilling Project Site 608: An evaluation of isotope and biostratigraphic resolution. Paleoceanography 6, 33–52.

NANGERONI, L. G. 1932: Carta geognostico-geologica della provincia di Varese con uno studio su la geologia, le rocce e le forme del terreno della regione varesina. R. Ist. Techn., Varese.

NOVARESE, V., STELLA, A., REPOSSI, E., MERLA, G. & REDINI, E. 1937: Carta Geologica d'Italia, 1:100000, Foglio 32 Como. Servizio Geologico d'Italia, Roma.

OSCHIDARI, H. 1991: Geochemie und Isotopengeochemie an tertiären Bergeller Plutoniten aus der Südalpinen Molasse und dem alpinen Hinterland. PhD Thesis, Univ. Bern.

PIERI, M. & GROPPI, G. 1981: Subsurface geological structure of the Po Plain. Progetto Finalizzato Geodinamico/Sottoprogetto "Modello Strutturale". Pubbl. Cons. Naz. Ric. 414.

RÖGL, F., CITA, M. B., MÜLLER, C. & HOCHULI, P. 1975: Biochronology of conglomerate bearing Molasse sediments near Como (Italy). Riv. ital. Paleont. Stratigr. 81, 57–88.

SANTINI, L. 1956: Studio stratigrafico e micropaleontologico delle formazioni marnoso-arenacee della Gonfolite di Como. Riv. ital. Paleont. Stratigr. 62, 239–264.

SCHUMACHER, E. 1975: Herstellung von > 99.9997% ^{38}Ar für die 40K-40Ar-Geochronologie. Chimia 29, 441–442.

SPICHER, A. 1980: Geologische Karte der Schweiz, 1:500000, 2nd edition. Schweiz. Geol. Komm., Bern.

STEIGER, R. H. & JÄGER, E. 1977: Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology. Earth planet. Sci. Lett. 36, 359–362.

VILLA, F. 1955: Studi stratigrafici sul terziario sudalpino lombardo. Nota IV. Gli affioramenti terziari a sud del lago di Varese. Riv. ital. Paleont. Stratigr. 66, 66–93.

WAGNER, G. A., REIMER, G. M. & JÄGER, E. 1977: Cooling ages derived by apatite fission-track, mica Rb-Sr and K-Ar dating: The uplift and cooling history of the Central Alps. Mem. Ist. Geol. Mineral. Univ. Padova 30.

WAGNER, G. A., MILLER, D. S. & JÄGER, E. 1979: Fission track ages on apatite of Bergell rocks from Central Alps and Bergell boulders in Oligocene sediments. Earth planet. Sci. Lett. 45, 355–360.

Manuscript received 25 February 1993
Revision accepted 3 August 1993