Heavy mineral assemblages from Upper Cretaceous South- and Austroalpine flysch sequences (Northern Italy and Southern Switzerland) : source terrances and palaeotectonic implications

Autor(en): **Bernoulli, Daniel / Winkler, Wilfried**

Objekttyp: **Article**

Zeitschrift: **Eclogae Geologicae Helvetiae**

Band (Jahr): **83 (1990)**

Heft 2

PDF erstellt am: **12.07.2024**

Persistenter Link: https://doi.org/10.5169/seals-166588

Eclogae geol. Helv. 83/2: 287–310 (1990)

0012-9402/90/020287-24 $ 1.50 + 0.20/0
Birkhäuser Verlag, Basel

Heavy mineral assemblages from Upper Cretaceous South- and Austroalpine flysch sequences (Northern Italy and Southern Switzerland): source terranes and palaeotectonic implications

By DANIEL BERNOULLI and WILFRIED WINKLER[1])

ABSTRACT

The Lombardian Flysch of the Southern Alps records orogeny, uplift and erosion in the Austroalpine/South Alpine realm of the South Tethyan margin in Late Cretaceous times. The terrigenous flysch sediments overlay a deepening upward pelagic to hemipelagic sequence of Jurassic to Early Cretaceous age deposited on the submerged distal continental margin of the Apulian (Adria) promontory or microcontinent. Flysch sedimentation locally started in the Cenomanian but only became widespread from Early Turonian times onwards. After recession of the turbidite fans in the Campanian, hemipelagic and bioclastic slope sedimentation resumed in the latest Campanian to early Maastrichtian.

Pebble and lithoclast analysis of the conglomerates and sandstones in the Lombardian Flysch show that the sedimentary and basement fragments came from a passive margin sequence with a facies development identical to that of the Lombardian Zone of the southern Alps or of the Austroalpine nappes. Bottom marks, pebble imbrication in organized conglomerates and channel orientation confirm a general provenance from the North to Northeast with a deflection of the currents into a westerly direction along the basin axis. Heavy mineral data indicate two major distinct source areas.

During the early, Late Cenomanian to Turonian depositional history of the Lombardian basin, garnet and staurolite, accompanied by minor kyanite and sillimanite, indicate a main derivation of the material from (Variscan) amphibolite-grade metamorphic terranes (and overlying sediments) such as those exposed today in the Strona-Ceneri Zone of the southern Alps. During Coniacian to Early Santonian times, a different source area must have been feeding the fan system represented by the Sarnico Sandstone and the Piano di Sirone Formation. As shown by the heavy mineral assemblage which is dominated by apatite, zircon, tourmaline and rutile, the crystalline source terranes were composed of low-grade metamorphics and granitic rocks. A more northeasterly source is suggested for these sediments by a similar heavy mineral assemblage in the Turonian flysch of Val Croina and in the Insubric Flysch, as well as by the Variscan metamorphic gradient in the Southern Alps diminishing towards the East. The heavy mineral assemblage of the Sarnico Sandstone and of the Piano di Sirone Formation corresponds to that of slightly older (Turonian) Austroalpine flysch formations in the Ortler Zone and in the Samaden zone/Bernina nappe which, however, also contain chromite from obducted or accreted ophiolites exposed still further to the North. The fan progradation of the Sarnico/Sirone system obviously reflects the peak of uplift along the Austroalpine/South Penninic convergence zone. In Late Santonian/Campanian times (Bergamo Flysch) the heavy minerals again point to a high-grade metamorphic source terrane.

[1]) Department of Earth Sciences, Swiss Institute of Technology, 8092 Zürich, Switzerland.

RIASSUNTO

Il Flysch Lombardo delle Alpi meridionali è il prodotto dell'orogenesi, del sollevamento e dell'erosione del dominio austroalpino/sudalpino avvenuti nel tardo Cretaceo al margine meridionale della Tetide. I sedimenti terrigeni costituenti il Flysch giacciono al di sopra di una sequenza pelagica ed emipelagica di età Giurassico-Cretaceo medio depositatasi, in condizioni di profondità crescente, sulla parte distale sommersa del margine continentale del promontorio o microplacca apula (Adria). La sedimentazione del Flysch cominciò localmente nel Cenomaniano per diventare generalizzata soltanto a partire dal Turoniano inferiore. Nel Campaniano, con la recessione delle conoidi turbiditiche, ricomincia la sedimentazione emipelagica e bioclastica di scarpata che, dal Campaniano superiore, arriva al Eocene.

L'analisi dei ciottoli e dei litoclasti dei conglomerati e delle arenarie del Flysch Lombardo, mostra una provenienza dei clasti sedimentari e cristallini da una sequenza di margine passivo con successione di facies identica a quella del dominio lombardo delle Alpi meridionali o delle falde austroalpine. Le impronte di corrente, l'imbricazione dei ciottoli nei conglomerati e l'orientazione dei canali, indicano apporti provenienti generalmente da N, NE con una deviazione delle correnti verso Ovest lungo l'asse del bacino. I minerali pesanti indicano due distinte zone d'alimentazione.

Dalla parte bassa del Cenomaniano superiore al Turoniano, la presenza di granato, staurolite e, subordinatamente, di cianite e sillimanite, indica un alimentazione da terreni metamorfici (ercinici) in facies anfibolitica (con sovrastante copertura sedimentaria) simili a quelli esposti nella Zona Strona-Ceneri delle Alpi meridionali. Dal Coniaciano al Santoniano inferiore, un'area sorgente diversa deve aver alimentato il sistema di conoidi delle Arenarie di Sarnico e della Formazione del Piano di Sirone. In base all'associazione di minerali pesanti, dominata da apatite, zircone e rutilo, i terreni cristallini della zona di alimentazione dovevano essere costituiti da rocce metamorfiche di basso grado e da rocce granitoidi. La somiglianza con l'associazione di minerali pesanti rilevata nel Flysch della Val Croina e nel Flysch Insubrico e la generale diminuzione verso E del gradiente ercinico nelle Alpi meridionali, suggeriscono una localizzazione a NE della zona di alimentazione. L'associazione di minerali pesanti delle Arenarie di Sarnico e della Formazione del Piano di Sirone corrisponde a quella dei flysch turoniani austroalpini della zona dell'Ortler e di Samedan/falda del Bernina. Questi però, contengono anche cromite proveniente dalle ofioliti tettonicamente accrezionate od obdotte ed attualmente esposte in posizione più settentrionale. La progradazione del sistema Sarnico/Sirone è chiaramente collegata all'acme del sollevamento lungo la zona di convergenza austroalpina/sudpennidica. Nel Santoniano superiore/Campaniano, i minerali pesanti tornano ad indicare un'alimentazione da terreni metamorfici di alto grado.

Introduction

In the western Alps, Cretaceous orogenic movements are documented by widespread terrigenous flysch and melange formations and radiometrically dated high p-metamorphic mineral assemblages in continental and oceanic basement rocks. In terms of actualistic models, this subduction-related association has been interpreted as the relics of a late Early to Late Cretaceous accretionary wedge which later was involved in end-Cretaceous to Early Tertiary continental collision between Adria and Europe (PLATT 1986, MARTHALER & STAMPFLI 1989, POLINO et al. 1990). In contrast to the western Alps, the Cretaceous metamorphism in the Austroalpine realm of the eastern Alps is characterized by low-grade (Northern Calcareous Alps p.p., KRALIK et al. 1987), greenschist and amphibolite facies mineral assemblages (e.g. THÖNI 1983) reflecting normal or high geothermal gradients. Whereas the Cretaceous flysch sequences of the western Alps are invariably decolled from their substratum, those of the eastern and southern Alps often stratigraphically overlay their original substratum. A setting behind the subduction zone is generally assumed for this realm for Aptian to Late Cretaceous times (CASTELLARIN 1976, LAUBSCHER & BERNOULLI 1982, WINKLER 1988, POLINO et al. 1990).

In the Lombardian Zone of the southern Alps and in the Austroalpine nappes of southeastern Switzerland, Aptian/Albian and Upper Cretaceous flysch sediments document the early orogenic movements along the South-Tethyan active margin. These sediments generally overlay a deepening-upward pelagic to hemipelagic sedimentary sequence of Jurassic to Early Cretaceous age deposited on a submerged distal continental margin of Atlantic-type (BERNOULLI et al. 1979, WINTERER & BOSELLINI 1981). Where a stratigraphic contact between these turbiditic sequences and their original substratum is preserved it is often conformable, however, the siliciclastic content of the flysch sequences documents extensive emergent source areas of sedimentary and metamorphic terranes.

In the southern Alps, the age of the major thrusting episodes is still discussed as stratigraphic control of the deformation is only possible in border regions. Submarine unconformities and chaotic deposits in the Cenomanian of the southern Bergamasc Alps point to submarine erosion and mass-wasting, possibly in connection with minor decollement and deformation in the sedimentary cover of the southern Alps (BERSEZIO & FORNACIARI 1988). However, the bulk of siliciclastic detritus in the South Alpine flysch is derived from an emergent area situated in the present-day Orobic Zone and/or in the adjacent Austroalpine realm still further North (CASTELLARIN 1976). A pre-Late Eocene tectonic 'phase' is evident in the Adamello region where folded Mesozoic sediments and the Gallinera thrust-fault are cut by the Eocene Adamello intrusion (BRACK 1981), and a Cretaceous age cannot be excluded for these structures which also involve crystalline basement (DOGLIONI & BOSELLINI 1987).

Petrographic investigations in Cretaceous flysch sequences both in the Austroalpine nappes (Northern Calcareous Alps, DIETRICH & FRANZ 1978, GAUPP 1982, WINKLER 1988) and in the underlying South Penninic melanges (LÜDIN 1987, WINKLER 1988) show that during convergence *oceanic* and *shallow continental* crust and their sedimentary cover were uplifted and eroded. Recycling of obducted and/or subducted crust is indicated by the presence of chromite mineral grains derived from ultramafic rocks and of detrital high p/low T metamorphic minerals in flysch sequences of the external Northern Calcareous Alps and the underlying melanges (WINKLER & BERNOULLI 1986, WINKLER 1988).

In this paper, we shall describe the heavy mineral content of Cretaceous flysch sequences in the southern Alps and in the western Austroalpine nappes of Graubünden. The sequences described here occur i) along the southern border of the southern Alps between Lago Maggiore and the town of Brescia (Lombardian Flysch, AUBOUIN et al. 1970, BICHSEL & HÄRING 1981, GELATI et al. 1982, BERSEZIO & FORNACIARI 1987), ii) in the western Trentino area (Val Croina, BONNEAU 1969, HUBER 1989) and along the Giudicarie Line (Insubric Flysch, CASTELLARIN 1976), iii) in the Upper (central) Austroalpine Ortler nappe (Val Trupchun, Graubünden, CARON et al. 1982) and iv) in the Lower Austroalpine Bernina nappe and Samaden zone (ROESLI 1944, 1945, FINGER 1978, LÜDIN 1987) (Fig. 1). These flysch sequences generally develop from hemipelagic basinal marls (Scaglia Rossa, Couches Rouges) and are either overlain by higher nappes emplaced in the Late Cretaceous (Austroalpine) or by hemipelagic deposits and small base of slope fans of latest Cretaceous to Eocene age (Southern Alps, KLEBOTH 1982, BERNOULLI et al. 1988). Whereas the Austroalpine occurrences are areally very restricted today, the Lombardian Flysch represents a lat-

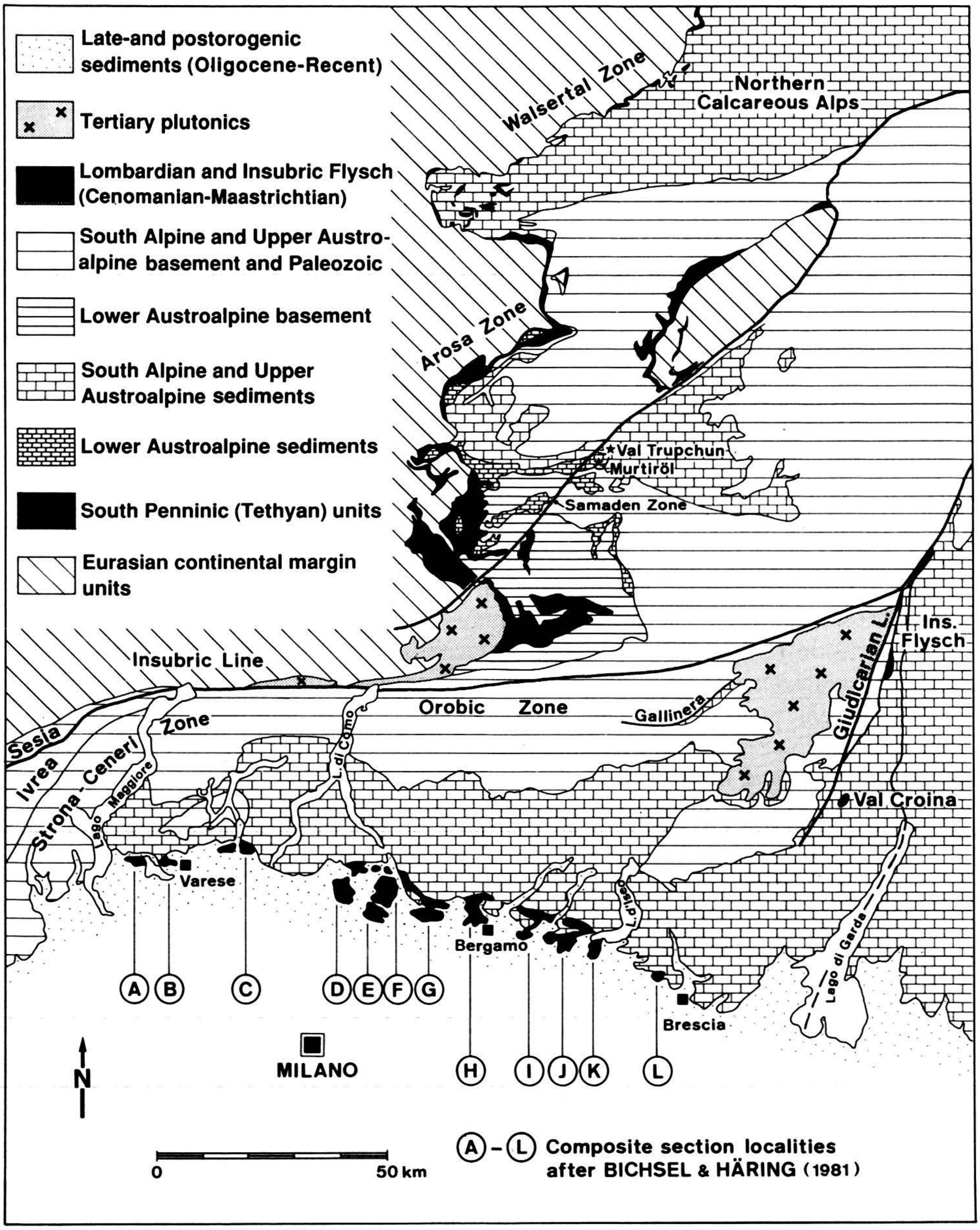

Fig. 1. Simplified geological map of the Lombardian Alps and the southwestern Austroalpine nappes, Italy and southeastern Switzerland. Letters indicate the location of the composite sections of Bichsel & Häring (1981). Geology from Spicher (1980), modified.

erally and vertically more or less continuous body of various submarine fan and basin plain deposits (Bichsel & Häring 1981, Gelati et al. 1982, Bersezio & Fornaciari 1987, 1988).

Stratigraphy

Lombardian Flysch

The stratigraphy of the *Lombardian Flysch* has been summarized by Bichsel & Häring (1981), Gelati et al. (1982) and Bersezio & Fornaciari (1987, 1988). The stratigraphical relationship between the different formations of the Lombardian Flysch are given in Figure 2.

The Lombardian Flysch occurs in a E–W-trending strip along the southern morphological border of the southern Alps (Fig. 1) the front of which is deeply buried below the Late Miocene to Recent postorogenic deposits of the Po Plain (Pieri & Groppi 1981). The sequence of the western part of the basin, between Lago Maggiore and Lago di Como, is only fragmentarily exposed and is, in its basal part (Varesotto Flysch), quite different from the sequence in the Brianza area and in the Bergamasc Alps.

Brianza and Bergamasc Alps

In the Brianza and Bergamo areas, the Lombardian Flysch reaches its greatest thickness of about 1,800 m. In the Brianza area and in the western Bergamasc Alps the terrigenous flysch sediments overlay a sequence of hemipelagic marls (Scaglia Lombarda Group, Aptian to Upper Cenomanian, for its sedimentary evolution see Arthur & Premoli Silva 1982). In this sequence, intrabasinal pelagic carbonate turbidites (Sasso della Luna Formation, Albian) occur in the Bresciano area and in the Bergamasc Alps. In general, terrigenous flysch sedimentation starts in the latest Cenomanian or earliest Turonian. However, in the Bergamasc Alps, older chaotic deposits in the Cenomanian sequence enclose a wedge of fine-grained turbiditic sandstones with a northeasterly provenance (Bersezio & Fornaciari 1988). Thin-bedded sandstone turbidites are locally intercalated in the hemipelagic Bruntino Marls (Aptian-Albian) and in the Upper Black Shale Formation (Scisti Neri Superiori, uppermost Cenomanian or lowermost Turonian, Aubouin et al. 1970).

In the Brianza and in the western Bergamasc Alps, sedimentation of the main body of terrigenous flysch sediments starts with uppermost Cenomanian or lowermost Turonian fan fringe sediments (Flysch Rosso, Sommaschio Formation) which are overlain by a thick sequence of basin plain turbidites (Pontida Formation, Turonian). In the eastern Bergamasc Alps thick-bedded sandstones and marls, the Colle Cedrina Flysch (Middle to Upper Turonian, Gelati et al. 1982), unconformably overlay the Cenomanian chaotic deposits (Bersezio & Fornaciari 1987). From the Coniacian to the Early Santonian, a system of submarine fans prograded, as suggested by a general thickening and coarsening upward trend in the Sarnico Sandstone and Piano di Sirone

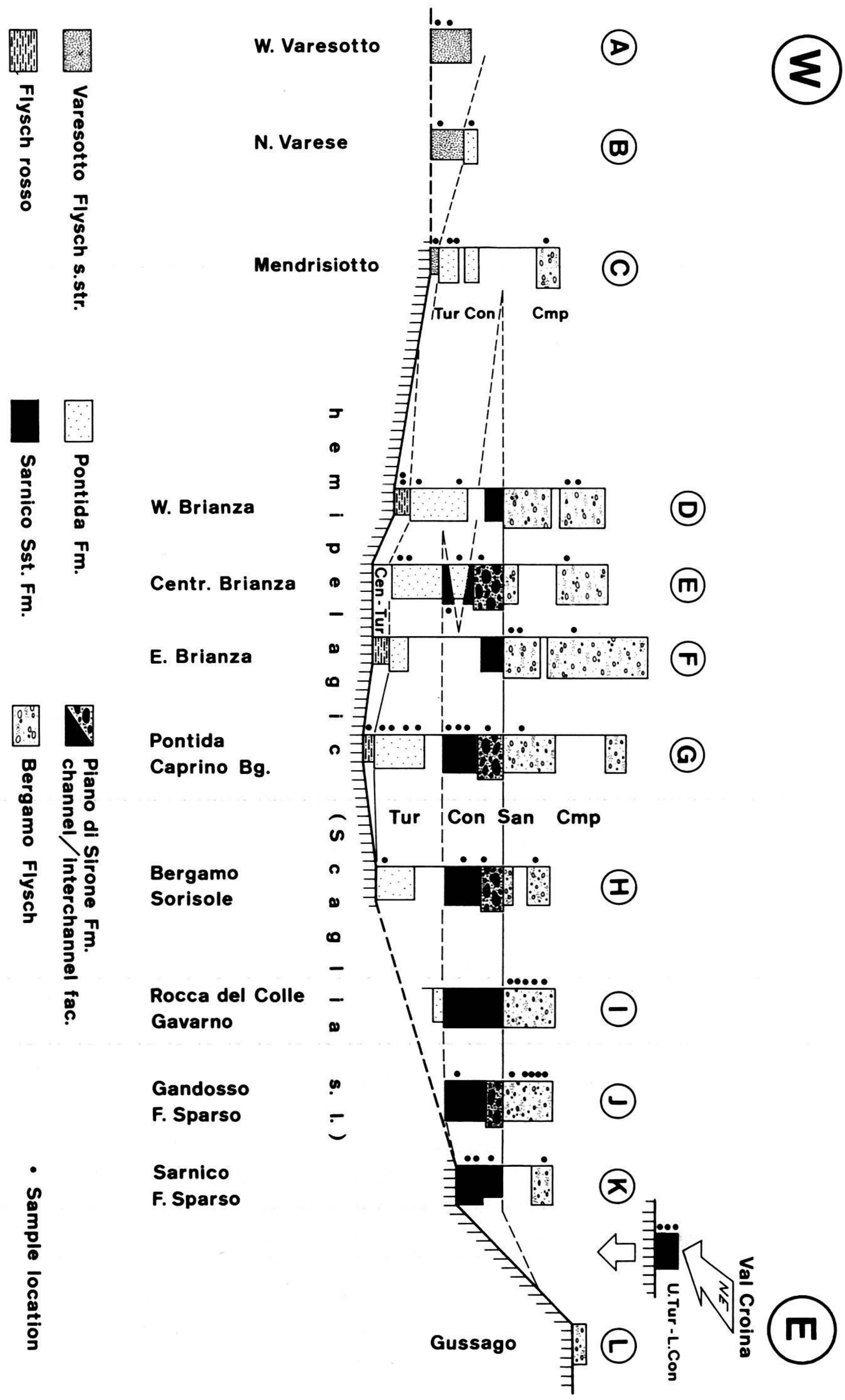

Fig. 2. Stratigraphy of the Lombardian Flysch, according to Bichsel & Häring (1981), modified. Letters refer to composite sections of Bichsel & Häring (1981).

Formation. In the Late Santonian, recession of the fan system led to deposition of outer fan deposits (Flysch di Bergamo, Pietra di Credaro) before hemipelagic and turbiditic carbonate sedimentation resumed (Piano di Brenno Formation, Tabiago Formation, KLEBOTH 1982, Ternate Formation, BERNOULLI et al. 1988). The clastic material admixed in the resediments of these small bioclastic base of slope fans of Maastrichtian to Late Eocene age seems to be of more local provenance and mostly exhumed from older sediments exposed along the basin slope or the walls of submarine valleys (BERNOULLI et al. 1988).

The following formations have been investigated:

1. The *Flysch Rosso* (VENZO 1954, Sommaschio Formation, BERSEZIO & FORNACIARI 1987) is a relatively thin (maximum 120 m), laterally discontinous formation of reddish or green and purple marls with intercalated fine to medium-grained thin-bedded lithic sandstone turbidites (BICHSEL & HÄRING 1981). Its age is latest Cenomanian to Early Turonian (AUBOUIN et al. 1970). The passage from the underlying Scaglia Rossa or Schisti Neri Superiori into the Flysch Rosso is gradual.

2. The *Pontida Formation* (DE ROSA & RIZZINI 1967) is composed of thin- to medium-bedded turbiditic sandstones and marls of great lateral continuity. Its thickness has been estimated at 450 (BICHSEL & HÄRING 1981) to 600 m (BERSEZIO & FORNACIARI 1987). Interbedded, several m thick megaturbidites are particularly frequent in this formation. Because of its acyclic bedding pattern, BICHSEL & HÄRING (1981) suggested a basin plain environment of deposition. To the East the lateral passage into the Colle Cedrina Flysch is not exposed. The stratigraphic range of the formation and particularly the apparently diachronous upper limit are not well established, but a Turonian age is evident for its base (BICHSEL & HÄRING 1981, GELATI et al. 1982). BICHSEL & HÄRING (1981) interpreted the Pontida Formation as the distal basin plain equivalent of a prograding Sarnico Sandstone submarine fan. However, the biostratigraphic data of GELATI et al. (1982) show that the Sarnico Sandstone is not the lateral equivalent of the Pontida Formation. This is supported by the different modal compositions (BERSEZIO & FORNACIARI 1987) and heavy mineral contents of sandstones (our data) indicating that the sediments of the two formations are derived from different source areas and must be related to different distribution systems (see below).

3. The *Sarnico Sandstone Formation* (DE ALESSANDRI 1899, DE ROSA & RIZZINI 1967) consists of medium- to thick-bedded, coarse grained, partly amalgamated sandstones and conglomerates arranged in upward-thickening cycles (BICHSEL & HÄRING 1981). It has a thickness of 300 to 450 m, probably thinning to the East where it onlaps onto the Cenomanian Scaglia Rossa (GELATI et al. 1982). Palaeocurrent directions are from the East. Biostratigraphic control is poor, but from the underlying and overlying formations and from scarce nannoplankton data (BICHSEL & HÄRING 1981) a Coniacian age can be inferred. The Sarnico Sandstone represents a non-channelized mid-fan system (BICHSEL & HÄRING 1981).

4. The *Piano di Sirone Formation* (VENZO 1954) can be considered as representing a number of prograding, channelized systems of the Sarnico Sandstone fan (BICHSEL & HÄRING 1981). This is confirmed by our petrographical data which indicate the same source area for the two formations. The formation has a two-fold appearance. It partly consists of lense-shaped, mostly organized conglomerate bodies representing broad

channel fills which are embedded in thin-bedded, fine grained levee and interchannel deposits. The formation reaches a thickness of 80 to 150 m, its age is Late Coniacian to Early Santonian (VENZO 1951).

5. The *Flysch di Bergamo Formation* (GELATI & PASSERI 1967) is an irregularly, thin- to medium-bedded sequence of sandstones with interbedded marls. It is lithologically clearly distinct from the Piano di Sirone and from the Sarnico Sandstone by its much higher content in bioclastic shallow water carbonate material. The turbidite facies association points to an outer fan depositional environment (BICHSEL & HÄRING 1981). In relation to its thickness of around 1,000 m, the time span of deposition from Late Santonian to Middle/Late Campanian is rather short. The Bergamo Flysch is overlain by the hemipelagic and turbiditic carbonate sediments of the Piano di Brenno Formation (KLEBOTH 1982).

Varesotto area

Varesotto Flysch (BICHSEL & HÄRING 1981): In the Varesotto area, the hemipelagic marls of the Scaglia Rossa Formation grade upwards into a sequence of turbiditic bioclastic calcarenites and grey marls, lithic sandstones and conglomerates and intercalated micritic limestones rich in trace fossils. Large slumps and pebbly mudstones are frequent in the middle part of the formation. The upper part is again composed of lithic sandstones. The thickness is about 600 m and the age of the formation ranges from Late Cenomanian to Late Turonian-? Early Coniacian (BICHSEL & HÄRING 1981). However, the outcrops in the Mendrisiotto area and the upper part of section B (Fig. 2) show the same lithological and heavy mineral composition as the Pontida Formation and are included by us in the latter.

There is a large gap in outcrop between the Varesotto Flysch (now Pontida Formation, Section C, Fig. 2) and the next younger flysch unit, the *Coldrerio Flysch* of BICHSEL & HÄRING (1981). This formation consists of an acyclic alternation of fine to medium grained, carbonate-rich sandstones and marls and marly limestones, interpreted as basin plain deposits by BICHSEL & HÄRING (1981). Its similarity to the Bergamo Flysch has already been noticed by BICHSEL & HÄRING (1981). Indeed, its Campanian age (RUTISHAUSER in BICHSEL & HÄRING 1981) and our petrographic data (Table 2) closely relate the Coldrerio Flysch to the Bergamo Flysch in which we shall include it.

Insubric Flysch

The term *Insubric Flysch* was introduced by CASTELLARIN (1976) for the small occurrences of Upper Cretaceous flysch along the different segments of the Insubric fault system. Between Samoclevo and Rumo (Val di Sole, province of Trento), the outcrops of the Insubric Flysch are very incomplete and the sequence is tectonically repeated by imbrication along the northern segment of the Giudicarie Line. CASTELLARIN et al. (1976) thought the flysch to rest unconformably on Triassic dolomites, however, the contacts with the Mesozoic carbonates are, where exposed, tectonic (SANTINI & MARTIN 1988). The sequence comprises coarse to fine grained turbiditic calcarenites, siltstones, marls and argillaceous marls of Scaglia-type with interbedded conglomerates and pebbly mudstones. CASTELLARIN et al. (1976) give an age ranging from Turonian to Late Maastrichtian. Our own preliminary data indicate a Late Campanian to Early Maastrichtian age for Scaglia-type marls interbedded with the flysch-type sandstones and conglomerates corresponding to the middle and upper intervals of the sequence described by CASTELLARIN et al. (1976).

A 600 m thick sequence of Upper Cretaceous flysch (Formazione di Valle d'Agola) has been described by CASTELLARIN (1972) from the eastern border of the Lombardian Basin, East of M. Sabbion near Pinzolo. This formation consists of a lower, Turonian to Santonian, member of dark colored calcareous, argillaceous and siltitic hemipelagic marls with interbedded calcarenites and quartzose arenites. Intercalated rudites are obviously derived from the adjacent Trento Plateau. The upper member of Campanian to Maastrichtian age can be compared to the Piano di Brenno Formation (KLEBOTH 1982). We have not investigated this sequence.

Small relics of Cretaceous flysch are also present in the western Trentino (Val Croina, BONNEAU 1969, HUBER 1989). Here the hemipelagic marls of the Scaglia Rossa Formation gradually pass into a sequence of first dark red and bioturbated, then grayish green argillaceous marls with intercalated laminated micaceous siltstones which are interpreted as distal mud turbidites. Up-section, more carbonate-rich graded siltstones are present. The sequence is about 150 to 200 m thick, planktonic foraminifera indicate a Late Turonian to Early Coniacian age (M. CARON in HUBER 1989). Rare bottom marks indicate that sediment transport was in a southerly direction.

Ortler nappe (Upper Austroalpine)

In the Ortler nappe, no sediments younger than Turonian are found (CARON et al. 1982). Variegated shales and marly limestones of Scaglia or Couches Rouges facies and of Aptian to Middle Turonian age (Chanels Formation, DÖSSEGGER et al. 1982) overlay a Late Jurassic to Early Cretaceous pelagic sequence recording the subsidence of the Austroalpine passive margin. In the Cenomanian to Middle Turonian part of the hemipelagic sequence, thin intercalations of fine-grained turbidites are present. Samples 44 and 48 of CARON et al. (1982, Fig. 1) have been investigated by us.

Samaden zone and Bernina nappe (Lower Austroalpine)

The Samaden zone is a zone of imbricates decolled from the Austroalpine Err and Julier basement nappes (FINGER 1978). Sediments of the Bernina nappe, decolled from their substratum also occur Southeast of the River Inn in Val Varusch (God Drosa) and at Piz Murtiröl East of S-chanf (ROESLI 1927, 1944). As in the Upper Austroalpine Ortler nappe hemipelagic marls of Couches Rouges or Scaglia-type, overlying Lower Cretaceous hemipelagic shales and limestones (Aptychus Limestone and Palombini Shales) are the youngest sediments found in these Lower Austroalpine units. They also contain thin intercalations of micaceous and lithic turbiditic sandstones and are also dated as Cenomanian to Early Turonian (ROESLI 1944, FINGER 1978). The heavy mineral data discussed in this paper are from LÜDIN (1987). Sample

FORMATION	SAMPLE	LOCALITY	COORD.(TOP.MAP)	SECTION/ COMP. SECTION
Flysch Rosso	MB534	Roncaletti	759.9/067.8(CH)	30/G
	MH410,412	Pusiano	744.7/075.6(CH)	11/D
Varesotto Flysch	MH275	Breggia river	722.1/079.1(CH)	7/C
	MH157	Molino grasso	707.2/078.0(CH)	11/D
	MH244	Biandronno	700.1/075.9(CH)	2/A
	DB5422	Gropello	700.1/075.9(CH)	1/A
Pontida Fm.	MH329	Oggione railway station	747.5/075.5(CH)	19/E
	MH317	Cesana	744.7/075.6(CH)	12/D
	MH37	Olona	707.7/077.6(CH)	6/B
	MH312	Bosisio	743.1/074.5(CH)	13/D
	MH302,437	Sala al Barro	749.3/075.4(CH)	17/E
	MH212 ++	San Pietro di Stabio	716.3/079.7(CH)	39/H
	MB420,423	Roncaletti	759.9/067.8(CH)	30/G
	MB429,538	Vallone	758.9/066.2(CH)	31/G
	MB398 ++	San Pietro di Stabio	716.3/079.7(CH)	8/C
Sarnico Sst. Fm.	MB518	San Giuseppe	5059.5/571.9(I)	54/K
	MB642	Paratico	5056.4/574.3(I)	53/K
	MB408	San Pantaleone	5055.9/568.3(I)	46/J
	MB455	Castagnola	5063.0/550.7(I)	40/H
	MB399	Pratolungo	5062.3/539.6(I)	33/G
	MB406,403	Mapello	5062.3/542.6(I)	32/G
	MB426	Oggione village	748.8/073.0(CH)	18/E
Piano di Sirone Fm.	MB517	Tremellini	5060.0/571.6(I)	55/K
	MB334	Bergamo alto	5061.9/551.9(I)	41/H
	MB322	Corna	5062.6/538.6(I)	35/G
	MH223	Colle Brianza	749.8/068.5(CH)	20/E
Bergamo Flysch	MB659	Maimoni	5055.7/567.6(I)	50/J
	MB563	Bosco	5061.5/548.8(I)	42/H
	MB658	Montello	5075.5/561.5(I)	45/I
	MH407 ++	Coldrerio	720.1/078.8(CH)	10/C
	MH305,404	Costa Masnago	743.3/070.0(CH)	16/D
	MH423	Barzano	746.2/066.1(CH)	22/E
	MH364	Montevecchia 2	749.1/064.8(CH)	28/F
	MB315	Roncarro	5062.3/539.6(I)	36/G
	MH377,320	Monticello	751.7/066.7(CH)	25/F
	MB553	Credaro	5056.9/572.1(I)	56/K
	MB498,487,482	Maimoni	5055.7/567.6(I)	56/J
	MB500	Gandosso	5067.1/569.2(I)	49/J
	MB474,470,463	Montello	5075.5/561.5(I)	45/I
Val Croina Flysch	FH93,105,106	Val Cadrè, N Tirano	5085.2/629.6(I)	
Ortler Flysch	DÖ7648,7644	Val Trupchun	800.0/165.9(CH)	
Schlattain Series	PL1674	Valetta Schlattain	780.9/153.9(CH)	
God Dros Flysch	PL1651	Laviner Bügls	796.4/164.9(CH)	
Murtiröl Flysch	PL1653	Piz Murtiröl	796.6/163.8(CH)	

Table 1: List of analysed samples. Coordinates refer to Swiss (CH) and Italian (I) topographic maps. Samples indicated by ++ were assigned on petrographical grounds to other formations than by Bichsel & Häring (1981). Columnar section/composite section as in Bichsel & Häring (1981).

PL 1647 is from the Schlattein Series (Finger 1978) Southeast of Piz Schlattein, sample PL 1651 from the God Drosa Series in Val Varusch and PL 1663 and 1660 are from the flysch of Piz Murtiröl (Roesli 1927, 1944).

The locations of the individual samples are indicated in Table 1.

Methods

The samples for heavy mineral analysis were prepared in the following manner: Samples of preferentially medium-grained sandstones were crushed and fragments of 1 to 4 mm diameter were dissolved in 70 °C hot, 10% acetic acid, aided by a small addition of H_2O_2. From the obtained insoluble residue the fraction 0.063–0.4 mm was sieved, from which 10 g were separated by sample splitting. The heavy minerals then were separated by centrifuge aided bromoform ($\rho = 2.9$) technique. The heavy mineral fraction was mounted in piperine and the transparent mineral grains were determined and counted (200 grains per sample, except where differently indicated, see Table 2 and Figs. 3 and 4). Numbers are frequency percentages.

Results

In the Lombardian Flysch, three major heavy mineral assemblages can be distinguished (Table 2 and Fig. 3). The most widespread association contains garnet and staurolite as the main components and subordinate amounts of kyanite and fibrous sillimanite. Compared to garnet and staurolite, mineral grains of tourmaline, zircon, rutile and other minerals of the TiO_2-group (brookite, anatase, titanite) are always only minor constituents. This heavy mineral assemblage is typical for the Flysch Rosso, the Pontida Formation and for the Bergamo Flysch. Within the Bergamo Flysch, two subgroups can possibly be distinguished by their different garnet/staurolite ratios. In a western area, the heavy mineral assemblages of the Bergamo Flysch are dominated by garnet, in an eastern one by staurolite. However, more data are needed to deduce more precise regional or stratigraphical trends. One sample from the Bergamo Flysch (MH 305, Costa Masnago) shows a somewhat unusual composition yielding 5% of chloritoid.

The prograding fan system of the Sarnico Sandstone/Piano di Sirone shows a qualitatively and quantitatively different heavy mineral assemblage. It contains major amounts of apatite, tourmaline, zircon and minerals of the TiO_2-group but only traces of garnet and staurolite. In both assemblages chromite is only a very minor constituent or completely lacking.

In the area of Varese, the Varesotto Flysch generally contains only few heavy mineral grains suggesting that only small proportions of crystalline basement rocks were exposed in the source area. This assumption is supported by thin-section observations which show that the turbidites mainly contain epiclastic and intrabasinal carbonate fragments. The heavy mineral assemblage comprises variable proportions of tourmaline, zircon, TiO_2-minerals, garnet and staurolite, and, in contrast to the rest of the Lombardian Flysch, slightly higher amounts of chromite. However, in view of the small number of grains available and the ubiquity of chromite in fine grained sandstones this observation is not significant.

East of Varese, in the Mendrisiotto, the Varesotto Flysch (MH 398, San Pietro di Stabio) and the Coldrerio Flysch (MH 407) show a heavy mineral assemblage with a strong affinity to the staurolite and garnet bearing assemblages of the Pontida Formation and Bergamo Flysch to which they are comparable also time-stratigraphically.

Our results from the Lombardian Flysch cannot be compared directly to the data of Cipriani et al. (1976) from the Sarnico Sandstone, the Pontida Formation and the Bergamo Flysch of the Bergamo area. This is partly due to the different preparation techniques applied by these authors, particularly to their treatment of the samples by HCl, causing the loss of apatite, and the finer sieve fraction investigated by them. Moreover, the position of their samples in the stratigraphic sequence in many cases is not clear. The relatively high amounts of garnet observed by these authors in part of their Sarnico Sandstone samples cannot be explained by different preparation techniques; they would sharply contrast with our results. Their sample location map (Fig. 1 in Cipriani et al. 1976) indeed suggests that part of the samples (cf. their Fig. 1 and Table 4) comes not from the Sarnico Sandstone but from other formations of the Flysch Lombardo.

Pontida Fm.

MH329	MH317	MH37	MH312	MH302	MH437 (163)	MH212	
14.3	6.6	4.8	14.7	18.1	10.4	4.2	tourmaline
1.8	2.2	4.8	1.9	9.7	4.3	1.4	zircon
6.7	16.7	3.0	5.2	16.5	8.6	4.2	rutile
26.3	8.8	6.5	6.2	4.2	10.5	5.2	br/an/ti
7.6	11.9	7.8	11.8	29.5	3.1	3.8	apatite
0.0	0.0	2.2	1.9	1.3	0.0	0.0	chromite
36.6	39.6	39.1	40.3	14.3	63.2	43.9	garnet
6.7	14.1	31.7	18.0	6.3	0.0	36.3	staurolite
0.0	0.4	0.0	0.0	0.0	0.0	1.0	kyanite
0.0	0.0	0.0	0.0	0.0	0.0	0.0	sillimanite
0.0	0.0	0.0	0.0	0.0	0.0	0.0	chloritoid

MB545	MB420	MB423	MB429	MB538	MH398	
13.3	9.7	2.1	5.9	5.5	3.4	tourmaline
3.1	1.3	0.0	1.4	0.8	0.0	zircon
4.9	5.0	2.6	2.7	2.9	1.4	rutile
9.8	15.7	0.0	5.0	8.0	0.7	br/an/ti
1.8	6.7	8.5	14.6	0.8	3.4	apatite
0.0	0.0	0.4	0.5	0.0	0.3	chromite
67.1	59.5	68.1	42.9	59.2	35.1	garnet
0.0	2.0	16.2	25.1	22.7	53.6	staurolite
0.0	0.0	2.1	0.9	0.0	2.1	kyanite
0.0	0.0	0.0	0.9	0.0	0.0	sillimanite
0.0	0.0	0.0	0.0	0.0	0.0	chloritoid

Flysch Rosso **Varesotto Flysch**

MB534	MH410	MH412	MH275 (147)	MH157 (17)	MH244 (36)	DB5422 (44)	
5.0	4.2	4.2	37.4	23.5	33.3	34.1	tourmaline
3.5	1.7	0.8	15.6	29.4	19.4	22.7	zircon
6.6	5.4	6.2	21.1	5.9	13.9	4.5	rutile
4.4	6.7	4.6	16.3	0.0	5.6	6.8	br/an/ti
0.9	8.3	2.3	6.1	0.0	2.8	0.0	apatite
0.0	0.4	0.0	1.4	17.6	5.6	4.5	chromite
71.9	54.2	56.0	2.0	5.9	11.1	20.5	garnet
6.6	18.3	25.9	0.0	17.6	8.3	6.8	staurolite
0.0	0.0	0.0	0.0	0.0	0.0	0.0	kyanite
0.0	0.0	0.0	0.0	0.0	0.0	0.0	sillimanite
0.0	0.0	0.0	0.0	0.0	0.0	0.0	chloritoid

Table 2: Normalized heavy mineral frequences in flysch samples of the Southern Alps and of the Austroalpine Ortler nappe. br/an/ti indicates total brookite, anatase and titanite.

Table 2 (continued)

Val Croina Flysch			Ortler nappe		
FH93	FH105	FH106	DO7644 (30)	DO7648	
10.7	13.8	15.0	26.7	23.9	tourmaline
16.9	15.4	11.5	46.7	47.9	zircon
24.9	31.9	34.0	6.7	12.3	rutile
26.6	6.9	17.8	6.7	1.2	br/an/ti
19.8	27.1	13.8	3.3	1.2	apatite
1.1	4.3	7.9	6.7	9.8	chromite
0.0	0.5	0.0	3.3	3.7	garnet
0.0	0.0	0.0	0.0	0.0	staurolite
0.0	0.0	0.0	0.0	0.0	kyanite
0.0	0.0	0.0	0.0	0.0	sillimanite
0.0	0.0	0.0	0.0	0.0	chloritoid

Piano di Sirone Fm.

MB517	MB334	MB322	MH223	
13.5	24.6	25.5	12.2	tourmaline
15.9	41.3	18.9	24.9	zircon
27.5	21.4	22.6	26.8	rutile
3.8	3.2	3.7	6.5	br/an/ti
36.7	4.0	25.5	25.8	apatite
1.0	3.2	2.4	1.9	chromite
1.0	2.4	1.4	1.9	garnet
0.5	0.0	0.0	0.0	staurolite
0.0	0.0	0.0	0.0	kyanite
0.0	0.0	0.0	0.0	sillimanite
0.0	0.0	0.0	0.0	chloritoid

Sarnico Sandstone Fm.

MB518 (68)	MB642 (167)	MB480 (104)	MB455	
19.1	19.3	19.3	12.3	tourmaline
41.2	13.1	28.9	36.6	zircon
11.8	14.8	7.7	23.5	rutile
2.9	3.4	10.5	4.9	br/an/ti
20.6	44.3	1.9	18.1	apatite
0.0	2.3	8.7	0.4	chromite
0.0	1.1	15.4	4.1	garnet
0.0	1.1	0.0	0.0	staurolite
0.0	0.0	0.0	0.0	kyanite
0.0	0.0	0.0	0.0	sillimanite
0.0	0.6	0.0	0.0	chloritoid

MB399	MB406	MB403	MH426 (142)	
15.8	13.8	23.4	12.0	tourmaline
12.3	10.6	11.4	14.1	zircon
18.7	28.1	16.9	33.1	rutile
8.9	6.5	2.5	4.2	br/an/ti
38.4	35.5	42.3	27.5	apatite
3.0	0.9	0.5	2.1	chromite
3.0	3.7	3.0	6.3	garnet
0.0	0.9	0.5	0.7	staurolite
0.0	0.0	0.0	0.0	kyanite
0.0	0.0	0.0	0.0	sillimanite
0.0	0.0	0.0	0.0	chloritoid

Table 2 (continued)

Bergamo Flysch (garnet-rich assemblage)

MB659	MB563	MB658	MH407	MH305	MH304	
4.6	7.7	6.5	3.6	14.5	5.4	tourmaline
2.9	2.3	2.3	0.0	7.9	0.8	zircon
3.3	4.5	2.7	1.8	9.2	2.5	rutile
2.1	1.4	1.9	1.8	20.6	1.6	br/an/ti
19.5	4.5	17.3	4.5	15.8	5.0	apatite
0.0	0.0	0.8	0.6	0.4	0.0	chromite
41.5	67.6	35.4	45.2	18.0	64.5	garnet
25.3	12.2	28.1	41.8	6.1	19.8	staurolite
0.8	0.0	3.8	0.6	0.0	0.4	kyanite
0.0	0.0	1.2	0.0	0.0	0.0	sillimanite
0.0	0.0	0.0	0.0	7.5	0.0	chloritoid

MH423	MH364	MB315 (56)	MH377	MH320	
2.0	5.7	8.9	5.9	2.0	tourmaline
1.2	0.5	7.1	3.6	2.0	zircon
1.2	4.8	5.4	8.7	2.4	rutile
0.4	1.9	8.9	4.0	10.9	br/an/ti
2.8	26.2	3.6	36.4	36.7	apatite
0.8	0.0	0.0	0.0	0.4	chromite
67.5	44.8	41.1	35.6	42.3	garnet
16.5	16.2	23.2	5.9	2.8	staurolite
5.9	0.0	1.8	0.0	0.0	kyanite
2.0	0.0	0.0	0.0	0.0	sillimanite
0.0	0.0	0.0	0.0	0.4	chloritoid

Bergamo Flysch (staurolite-rich assemblage)

MB553	MB498	MB487	MB482	MB500	
2.4	5.3	3.3	12.0	10.7	tourmaline
1.4	0.4	0.9	2.0	0.9	zircon
2.4	4.9	4.2	6.0	3.4	rutile
2.0	0.4	4.2	7.5	7.3	br/an/ti
2.9	2.2	3.3	2.5	4.7	apatite
0.0	0.0	0.9	0.5	0.0	chromite
36.7	35.6	35.7	28.5	26.5	garnet
52.4	48.9	47.4	40.5	46.6	staurolite
0.0	1.8	0.0	0.5	0.0	kyanite
0.0	0.4	0.0	0.0	0.0	sillimanite
0.0	0.0	0.0	0.0	0.0	chloritoid

MB474	MB470	MB463	MB456	
5.1	2.8	6.6	7.9	tourmaline
0.4	1.4	1.9	0.4	zircon
6.8	2.3	4.2	5.4	rutile
3.8	2.8	6.1	8.4	br/an/ti
2.5	0.5	3.8	5.0	apatite
0.0	0.0	0.0	0.0	chromite
30.1	33.6	17.0	23.8	garnet
50.0	49.8	60.4	48.5	staurolite
0.8	5.5	0.0	0.4	kyanite
0.4	1.4	0.0	0.0	sillimanite
0.0	0.0	0.0	0.0	chloritoid

The Late Turonian to Early Coniacian flysch of Val Croina shows a heavy mineral spectrum that is qualitatively and quantitatively similar to that of the (? partly coeval) Sarnico Sandstone of the Lombardian Basin (Table 2, Fig. 3). With some variation this holds also true for the younger, Late Campanian to Early Maastrichtian flysch sandstones along the Giudicaria Line in the area between Male and Rumo. These sandstones are clearly distinct from the coeval Bergamo Flysch. Castellarin et al. (1976) report also the rare occurrence of chromite.

The Lower Austroalpine flysch sandstones in the Samaden zone and from Piz Murtiröl and God Drosa contain a trivial heavy mineral assemblage with tourmaline, zircon, rutile and other TiO_2-minerals (because of the presence of diagenetic baryte which is easily mistaken for apatite, apatite has not been counted). In contrast to the majority of the South Alpine flysch sandstones, these sandstones bear appreciable amounts of chromite. The Upper Austroalpine sandstones of the Ortler Zone are similar in composition but contain less chromite (Table 2, Fig. 4).

Interpretation of the heavy mineral assemblages

Reconstruction of the stratigraphic sequence of the source areas from pebble analysis of conglomerates of the Lombardian (Bichsel & Häring 1981) and of the Insubric Flysch (Castellarin et al. 1976) indicates that the sedimentary and basement fragments came from a passive margin sequence with a facies development identical to that of the Lombardian Zone of the Southern Alps or of the Austroalpine nappes. In present-day coordinates, the basin had an East-West extension and was bordered in the East (Trento Plateau) and South (Malossa High, see Errico et al. 1980) by submarine plateaux with pelagic sedimentation. Bottom marks in the Pontida and Sarnico Formation show a predominantly westerly, in the Bergamo Flysch a more radial southward direction of transport (Fig. 5, Bichsel & Häring 1981, Bersezio & Fornaciari 1987). In the conglomerates of the Piano di Sirone Formation and of the Insubric Flysch, pebble imbrication in organized conglomerates and channel orientation indicate provenance from the North to Northeast (Castellarin 1976, Bichsel & Häring 1981). A different source area can be established for large mass-flow deposits derived from the Garda escarpment bounding the Lombardian basin to the East (Castellarin 1972, Bernoulli et al. 1981). From the pattern of current directions (e.g. Bichsel & Häring 1981, Fig. 22, Bersezio & Fornaciari 1987, Fig. 6) and from the clastic content of the sediments it is suggested that the currents entered the basin from the North and Northeast and were deflected into a predominantly westerly direction along the basin axis. Admixed penecontemporaneously redeposited shallow water carbonate fragments and fossils in the terrigenous sandstones and conglomerates of the Lombardian Flysch show that the emergent source areas to the North were rimmed by more or less extensive carbonate shelves (Castellarin 1972, Bernoulli et al. 1987).

For the Austroalpine no data relevant for a basin analysis exist.

From heavy mineral analysis three types of basement source terranes can qualitatively be distinguished (cf. also Wildi 1985).

1. An oceanic basement, mainly composed of serpentinites and minor mafic rocks, documented by the local (and rare) presence of chromite mineral grains.

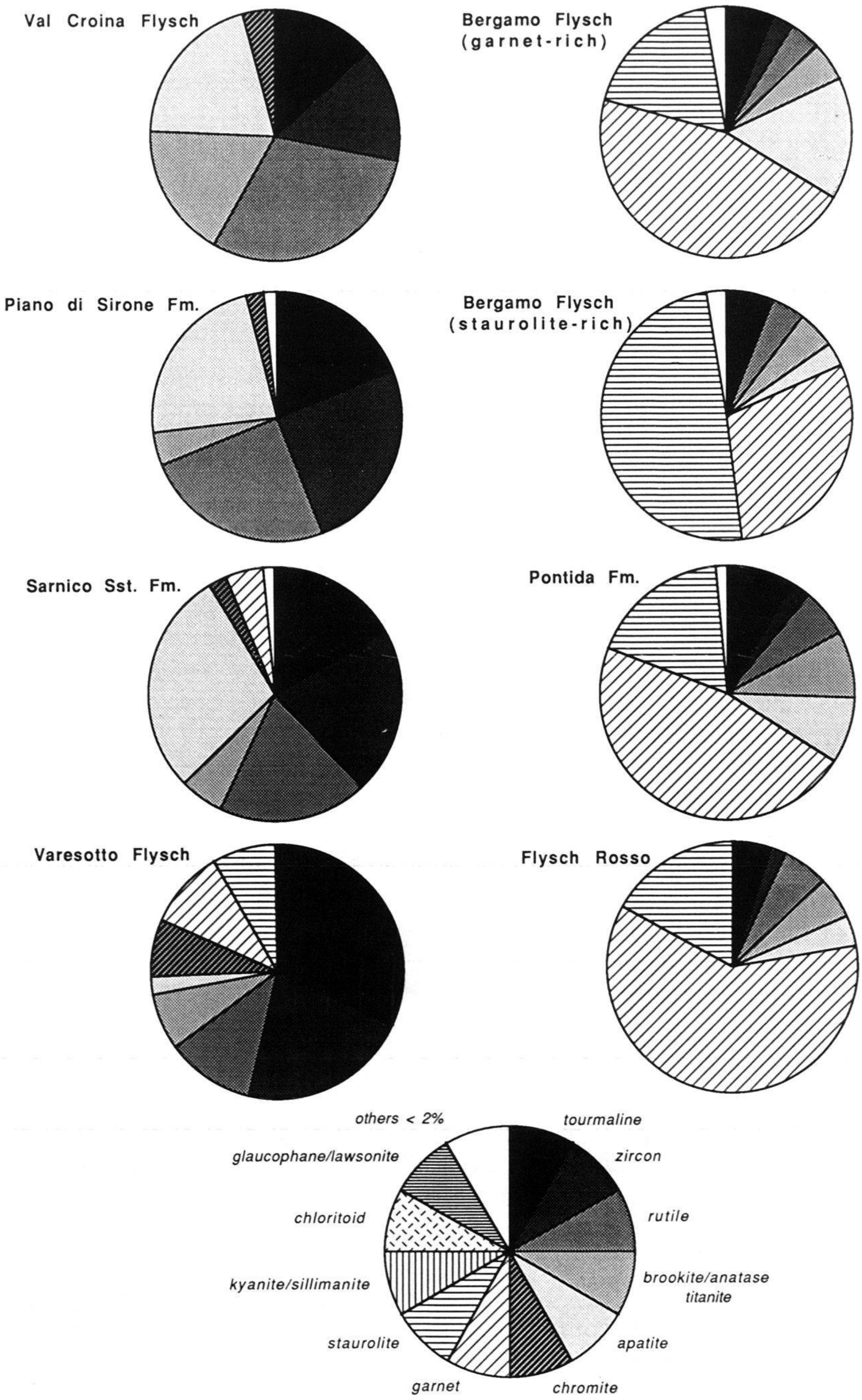

Fig. 3. Mean heavy mineral spectra of the South Alpine flysch formations. Data from the Val Croina Flysch from HUBER (1989).

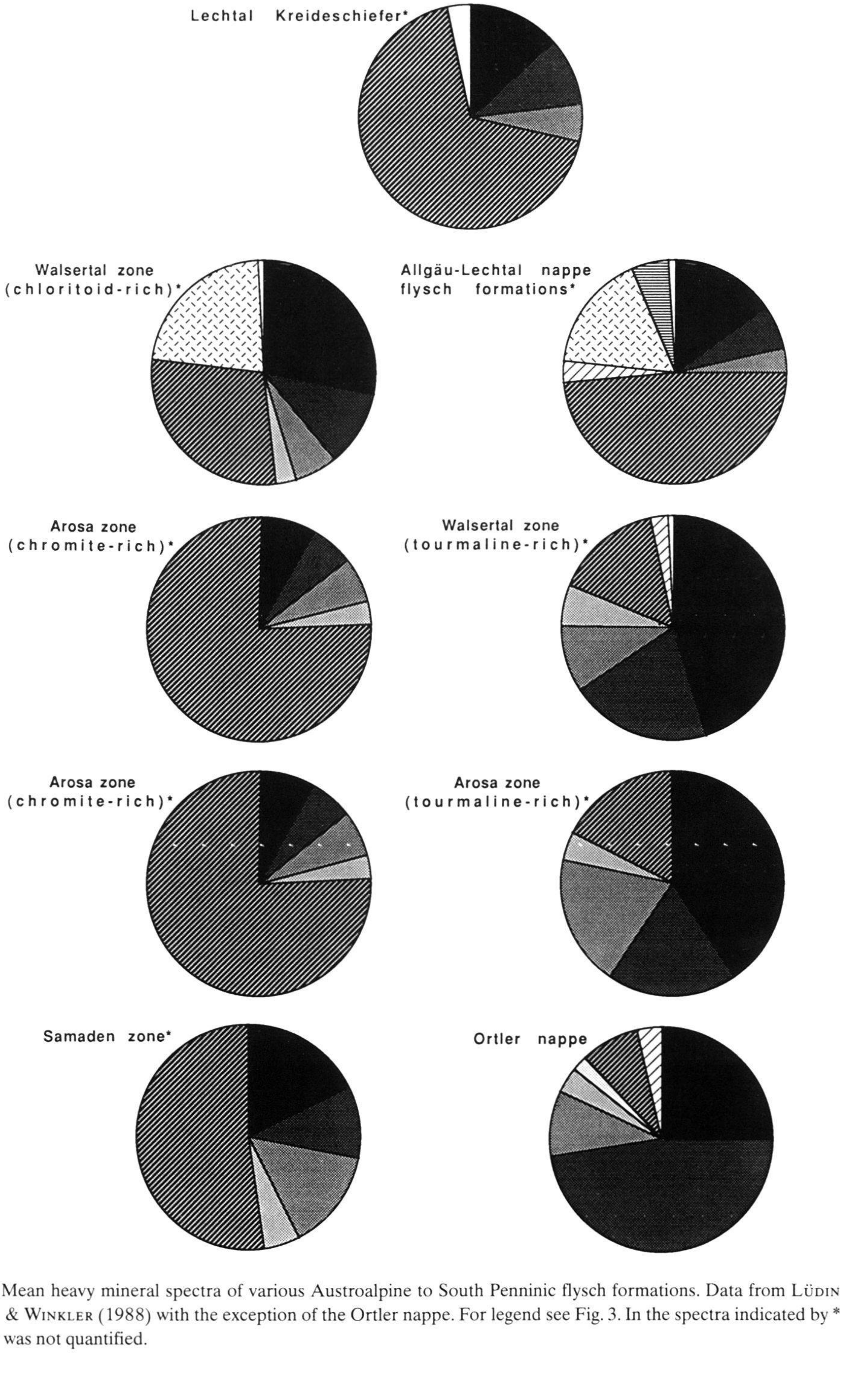

Fig. 4. Mean heavy mineral spectra of various Austroalpine to South Penninic flysch formations. Data from LÜDIN (1987) & WINKLER (1988) with the exception of the Ortler nappe. For legend see Fig. 3. In the spectra indicated by * apatite was not quantified.

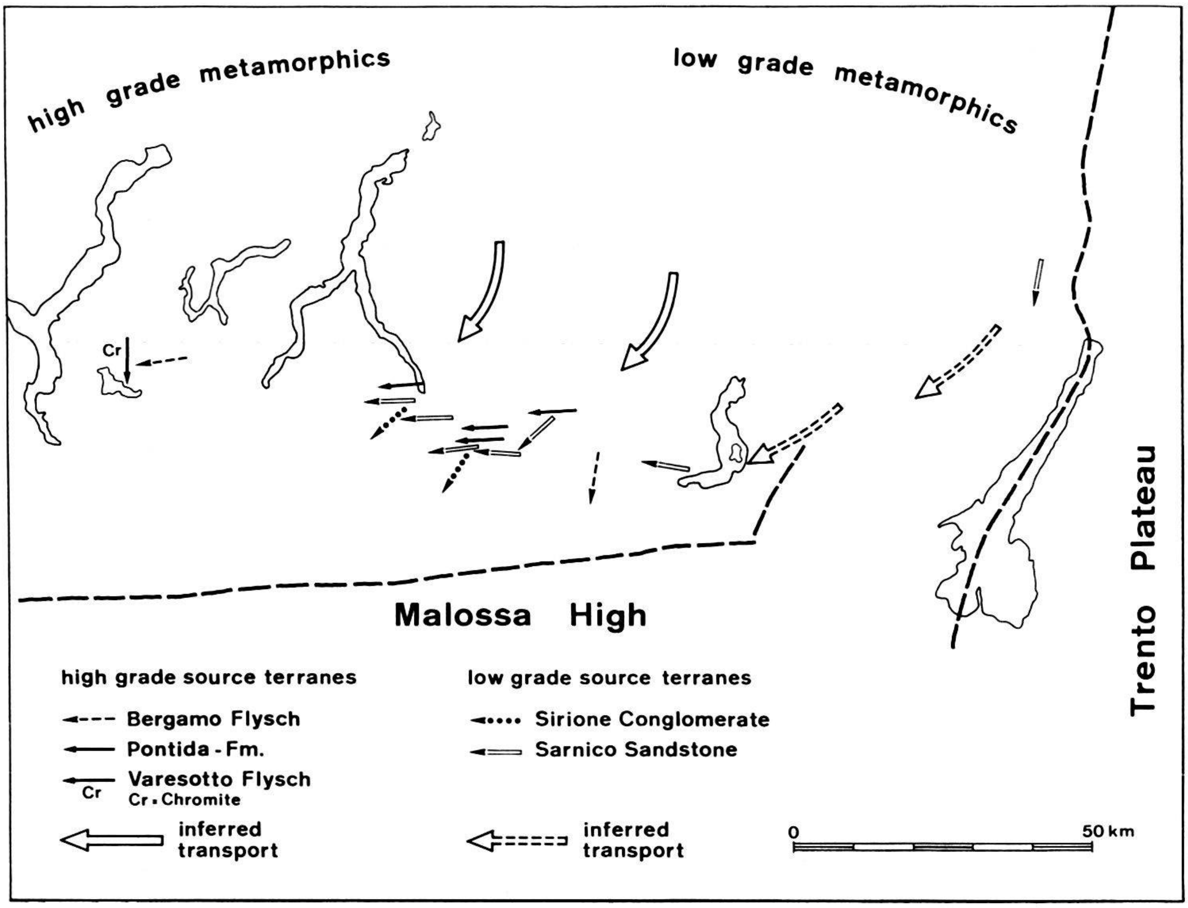

Fig. 5. Palaeogeography of the Lombardian basin from the Turonian to the Campanian. Current direction data from BICHSEL (1980) & HÄRING (1980).

2. A shallow continental crust documented by the presence of tourmaline, zircon, apatite, rutile, and other minerals of the TiO_2-group (ZTR-assemblage of WILDI 1985) derived from granitic and low-grade metamorphic gneissic terranes.

3. A deeper continental crust documented by the presence of staurolite, garnet, kyanite and sillimanite which were eroded from amphibolite or even higher grade metamorphic rocks. Microprobe (EDAX) analysis of a few garnet grains has given high almandine contents.

Obviously, the heavy minerals from the three source types have been mixed to various degrees in the source area or along transport of the sediment. Nevertheless, different distributary systems can clearly be distinguished (Fig. 5).

During the early, Late Cenomanian to Turonian depositional history of the Lombardian Flysch basin, detritus was derived mainly from sedimentary and from amphibolite-grade metamorphic terranes. This is reflected by the high garnet and staurolite contents with minor kyanite and sillimanite and small amounts of tourmaline, apatite, zircon and minerals of the TiO_2-group in the sandstone samples from the Flysch Rosso, the Varesotto Flysch and from the Pontida Formation. In the base of slope deposits of the Varesotto Flysch, small amounts of chromite are also present, pointing to an ultramafic oceanic or continental basement source. In the easternmost part of the basin, the sandstones of the Turonian Val Croina flysch show a heavy mineral assemblage typical for low-grade metamorphic source terranes. Dispersal in the now outcropping part of the basin was mainly East-West along the basin axis (Bichsel & Häring 1981) but eastsoutheasterly directions are also observed (Bersezio & Fornaciari 1987).

During Coniacian to Early Santonian times a different dispersal system must have been active feeding the prograding fan system represented by the Sarnico Sandstone and Piano di Sirone Formations. As shown by the heavy mineral assemblage the source area was dominated by low-grade metamorphic terranes (and sediments). This is confirmed by the QLF-modes of the sandstones in the Sarnico Sandstone (Bersezio & Fornaciari 1987). The data show also, that the Pontida Formation cannot be the distal equivalent of the fan deposits of the Sarnico/Piano di Sirone system. The source area of the latter system was probably more to the Northeast and its products seem to have reached mainly the eastern part of the area (e.g. the Turonian Val Croina Flysch, Figs. 2 and 3). This would be in line with Castellarin's (1976) hypothesis that during the Senonian also more northeasterly situated source terranes were active. A northeasterly low-grade metamorphic source terrane is also suggested for the Campanian-Maastrichtian Insubric Flysch. In contrast, the heavy mineral assemblages point again to high-grade metamorphic source terranes for the sandstones of the Late Santonian to Campanian Bergamo and Coldrerio Flysch formations.

The input of oceanic material in the Lombardian basin was at best very minor as shown by the limited amount of chromite present. Higher amounts of chromite are characteristic for South Penninic and Austroalpine early Late Cretaceous flysch sequences (Lüdin 1987, Winkler 1988, see also Table 2 and Fig. 4). These areas are more closely related to the actual zone of plate convergence and to possible sites of ophiolite accretion or obduction. This is particularly reflected in the heavy mineral assemblages of the Lower Austroalpine flysches which are rich in chromite.

Palaeotectonic implications

The Cretaceous flysch sequences of the Austroalpine nappes and of the southern Alps are obviously related to the Cretaceous pre-collisional orogeny along the southern margin of the Tethys. In contrast to the Cretaceous flysches of the South Penninic belt of the western Alps which are generally allocated to an accretionary wedge (Polino et al. 1990), the Cretaceous clastic sediments of the Austroalpine-South Alpine realm were probably deposited in the back of the active margin (Castellarin 1976, Laubscher & Bernoulli 1982, Winkler 1988). As shown by the different heavy mineral assemblages in the Austroalpine and in the South Alpine flysch sequences, the area must have been characterized, during the Cretaceous, by a complicated, ever changing morphology.

To restore the Cretaceous palaeotectonic situation, the effects of later, Eocene to Early Oligocene and Miocene tectonic movements must be eliminated. For our area, the main post-Cretaceous movements are the internal south-vergent thrusts of the southern Alps and the Tertiary transcurrent movements along the Insubric and the Giudicarie Line. First, kinematic inversion of the Late Miocene sinistral movements along the Giudicarie system (Laubscher 1988) would place the Insubric Flysch more to the South, to the East and Northeast of the Lombardian Basin (and the Trento Plateau still more to the South). Laubscher (1988) estimates the dextral displacement between the Late Cretaceous and the Late Miocene along the Insubric fault to be of the order of 300 km. In any case, a palinspastic restoration assuming a much smaller Tertiary lateral displacement would place the Lombardian Basin and the underlying basement (Strona-Ceneri and Orobic Zones) more to the East. Finally Miocene thrusting would have shortened the distance between the occurrences of the Lombardian Flysch and the Orobic Zone by a few tens of kilometers at least (total shortening of the Milano belt according to Laubscher [in press] would be about 100 km). Post-Cretaceous movements within the Austroalpine belt are certainly important, but can, as yet, not be assessed in a realistic way. A palinspastic restoration of the Cretaceous situation is thus still very difficult, however, a few conclusions can be drawn from the heavy mineral content of the flysch sequences.

The abundance of chromite in the Austroalpine flysch sequences points to local, southward obduction of oceanic crust and lithosphere onto the southern continental margin (Laubscher 1970, Winkler 1988) or to the emergence of an accretionary wedge exposing ultramafic ophiolites (e.g. Winkler & Bernoulli 1986). As shown by the occurrence of chromite mineral grains already in Early Cretaceous deposits of the Northern Calcareous Alps, the emplacement of ophiolites must have taken place during an early stage of convergence (Winkler 1988). This mineral also occurs in the Aptian-Albian flysch of the Lienz Dolomites (Faupl 1976) and in younger flysch sequences of the Austroalpine arc system, in particular in the Turonian to Coniacian flysch sediments of the Simme nappe s.str. (Flück 1973, Homewood 1983, Wicht 1984), in the central Austroalpine Ortler Zone and in the Lower Austroalpine Err-Bernina nappe (our data).

Chromite is very rare or absent in the Lombardian Flysch. Slightly higher amounts of this mineral in the Varesotto Flysch show that a limited input of chromite occurred in the west of the Lombardian Basin. This chromite is not necessarily derived from ophiolitic terranes. Chromite occurs in the ultramafic rocks of the Ivrea Zone (Vogt 1962), in rare ultramafic intercalations of the Strona-Ceneri Zone (Spicher 1940) and in similar peridotites of the Austroalpine realm (personal communication by G.V. dal Piaz, 1990). Obviously the basin was largely sheltered from the influx of ophiolitic detritus in contrast to the Austroalpine flysch basins. This could be due to a topographical barrier, in particular an emergent area between the two basins. The former location of such an emergent barrier, however, can only be surmised by circumstantial evidence.

A source area for the siliciclastic material of the Lombardian Flysch, situated in the present-day southern Alps, in particular in the Orobic Zone, has been assumed by earlier workers (Insubric Ridge of Elter et al. 1966, Massari & Medizza 1973). The heavy mineral contents of the Lombardian Flysch indicates a high-grade metamorphic source terrain for the Late Cenomanian to Turonian flysch sequences. Such a high-grade terrain is present today in the Strona-Ceneri Zone between the lower Sesia valley and Lake Como and might have extended in Late Cretaceous times further to the North. As Permian volcanics and clastic sediments directly overlay these Variscan and older high-grade metamorphic rocks (Zingg 1983), their exposure would not have been preceded by the erosion of Variscan low-grade metamorphic sequences but could be more or less simultaneous with the erosion of the overlying Mesozoic sediments. Indeed, as results from illite crystallinity and vitrinite reflectivity measurements in the Carboniferous sediments at Manno (STADLER et al. 1976), the sedimentary cover of the Strona-Ceneri Zone was never very thick and could have been eroded at an early stage of the Cretaceous orogeny. Variscan high-grade terranes yielding garnet, staurolite, kyanite and sillimanite are also exposed in the Tonale Zone North of the Insubric Line and in adjacent Austroalpine units, however, as, to judge from their Cretaceous metamorphic overprint (THÖNI 1983), these units were covered by higher tectonic units in the Late Cretaceous, they are not potential source areas for the Lombardian Flysch.

Later, during the Coniacian and Early Santonian, the more deeply buried low-grade metamorphic terranes of the area North and Northeast of the Bergamasc Alps could have delivered the heavy mineral assemblages of the Sarnico Sandstone and of the Piano di Sirone conglomerates. Bergamo Flysch and Coldrerio Flysch are dominated again by heavy mineral assemblages derived from high-grade source terranes.

Late Cretaceous thrusting is suggested for the Lower Austroalpine Err-Bernina nappe and the Ortler Zone where no Cretaceous sediments younger than Turonian are preserved. Radiometric cooling ages in nearby areas, particularly in the underlying Platta nappe (110-70 Ma, DEUTSCH 1983) further document the early closure of the sedimentary basins. The presence of Turonian (92-89 Ma) sediments in the Ortler Zone, however, is not easily reconciled with the postulated tectonic events at 100 to 85 Ma and the cooling ages around 80 Ma established by THÖNI (1983) in the nearby Sesvenna-Engadine Dolomites nappe. In the Canavese Zone which is considered to represent part of the distal South-Tethyan margin, Late Cretaceous low-grade metamorphism (prehnite-pumpellyite-actinolite facies according to BIINO & COMPAGNONI 1989), most probably related to burial by overthrusted units, possibly the Ivrea-Strona-Ceneri basement, is documented in the area of Ivrea by K-Ar ages of illites between 72 and 60 Ma (ZINGG et al. 1976).

The post- or Late Turonian (pre-Gosau, OBERHAUSER 1973) closure of the last lower and central Austroalpine basins, however, is closely followed by the Coniacian-Early Santonian progradation of the Sarnico-Sirone fan. In turn, the occurrence of redeposited shallow water fossils such as rudists and actaeonellids in the Sirone conglomerate (DE ALESSANDRI 1899) suggests a connection with the shallow water areas of the early Gosau deposits of the southern Austroalpine realm (MASSARI & MEDIZZA 1973).

Late Cretaceous thrusting is thus established for the Lower and Upper Austroalpine, the westernmost area of the southern Alps, i.e. the Canavese Zone s.str. and is likely for the Orobic Zone or the area to the North of it. Pre-Late Eocene thrusting is prooven for the latter in the Adamello area (BRACK 1981) and DOGLIONI & BOSELLINI (1987) have suggested a Late Cretaceous age for this event. This, however, does not exclude Late Eocene movements to the South (BERNOULLI et al. 1988).

CASTELLARIN (1976) has proposed a model for the relation between source and depositional areas of the Lombardian Flysch. Assuming a water depth of about 2,000 m for the inner fan deposits of the Lombardian Basin (e.g. Piano di Sirone) in Late Cretaceous times and a basin slope of about 3°, one can calculate a minimum distance of 45 km to the shoreline. If we accept a post-Cretaceous shortening of a few tens of kilometers between the Orobic Zone and the outcrop area of the Lombardian

Flysch, the source area of the Lombardian Flysch could be situated in the Orobic Zone and its western prolongation. In this case, the heavy mineral assemblages in the Lombardian Flysch would reflect the Variscan metamorphic gradient observed today in the Southern Alps: amphibolite and higher-grades in a western source area of the Varesotto Flysch and the Pontida Formation, low-grade and granitic source terranes (? Gneiss Chiari) in the eastern source areas of the Sarnico Sandstone, Piano di Sirone and Insubric Flysch formations. However, whether the Gallinera thrust in the Adamello area (Cassinis & Castellarin 1988) is a Cretaceous thrust or not, can only be decided with radiometric age determinations of the fault rocks or by establishing the cooling history North and South of the thrust by fission track dating.

Acknowledgments

We thank M. Bichsel, R. Dössegger, M. Häring, F. Huber, and P. Lüdin for the release of samples and A. Castellarin, C. Doglioni, H. Laubscher and G.V. dal Piaz for stimulating discussions. The study was financially supported by the Swiss National Science Foundation (Grants 2.083-0.83 and 4.903-0.85.20). A. Castellarin, C. Doglioni and W. Wildi critically reviewed the manuscript.

REFERENCES

Arthur, M.A., & Premoli Silva I. 1982: Development of widespread organic carbon-rich strata in the Mediterranean Tethys. In: Nature and origin of Cretaceous carbon-rich facies (Ed. by Schlanger, S.O., & Cita, M.B.), 7–54, Academic Press, London.

Aubouin, J., Sigal, J., Berland, J.P., Blanchet, R., Bonneau, M., Cadet, J.-P., Guillot, P.-L., Lacour, A., Piat, B., & Vicente, J.-C. 1970: Sur un bassin de flysch: stratigraphie et paléogéographie des flyschs crétacées de la Lombardie (versant sud des Alpes orientales, Italie). Bull. Soc. géol. France (7), 12/4, 612–658.

Bernoulli, D., Beckmann, J.P., Bolli, H.M., & Gunzenhauser, B.A. 1987: Upper Cretaceous deep-water sediments near Prella (Southern Alps, Mendrisiotto, Switzerland). Mem. Sci. geol. (Padova) 39, 49–71.

Bernoulli, D., Bichsel, M., Bolli, H.M., Häring, M.O., Hochuli, P.A., & Kleboth, P. 1981: The Missaglia Megabed, a catastrophic deposit in the Upper Cretaceous Bergamo Flysch, northern Italy. Eclogae geol. Helv. 74/2, 421–442.

Bernoulli, D., Caron, C., Homewood, P., Kälin, O., & van Stuijvenberg, J. 1979: Evolution of continental margins in the Alps. Schweiz. mineral. petrogr. Mitt. 59/1+2, 165–170.

Bernoulli, D., Herb, R., & Grünig, A. 1988: The Ternate Formation, a Late Eocene bioclastic submarine fan of the Lombardian Basin (Southern Alps). Abstract, Amer. Assoc. Petrol. Geol., Mediterranean Basins Conf. Nice, Sept. 25–28, 1988.

Bersezio, R., & Fornaciari, M. 1987: Cretaceous sequences in the Lombardy Basin: stratigraphic outline between the Lakes of Lecco and Iseo. Mem. Soc. geol. ital. 40, 187–197.

— 1988: Geometria e caratteri stratigrafici della Sequenza Cenomaniana nell'Bacino Lombardo (Alpi Meridionali). Riv. ital. Paleont. Strat. 94, 425–454.

Bichsel, M. 1980: Zur Sedimentologie des lombardischen Oberkreideflyschs zwischen Lecco und Brescia. Ph. D. Thesis Univ. Basel.

Bichsel, M., & Häring, M. 1981: Facies evolution of Late Cretaceous Flysch in Lombardy (northern Italy). Eclogae geol. Helv. 74/2, 383–420.

Biino, C., & Compagnoni, R. 1989: The Canavese Zone between the Serra d'Ivrea and the Dora Baltea River (Western Alps). Eclogae geol. Helv. 82/2, 413–427.

Bonneau, M. 1969: Contribution à l'étude géologique de la Judicarie, au nord-ouest du lac de Garde (Alpes méridionale, province de Trente, Italie). Bull. Soc. géol. France (7), 11/6, 816–829.

Brack, P. 1981: Structures in the southwestern border of the Adamello intrusion (Alpi bresciane). Schweiz. mineral. petrogr. Mitt. 61/1, 37–50.

CARON, M., DÖSSEGGER, R., STEIGER, R., & TRÜMPY, R. 1982: Das Alter der jüngsten Sedimente der Ortler-Decke (Oberostalpin) in der Val Trupchun (Schweizerischer Nationalpark, Graubünden). Eclogae geol. Helv. 75/1, 159-169.

CASSINIS, G., & CASTELLARIN, A. 1988: Il significato delle linee della Gallinera e delle Giudicarie sud nella geologia dell'Adamello e zone circonstanti. Atti tic. Sci. Terra 31, 446–462.

CASTELLARIN, A. 1972: Evoluzione paleotettonica sinsedimentaria del limite tra «piattaforma veneta» e «bacino lombardo» a nord di Riva del Garda. G. Geol. (Bologna) (2) 38/1, 11–212.

CASTELLARIN, A. 1976: Ipotesi paleogeografica sul bacino del Flysch sudalpino cretacico. Boll. Soc. geol. ital. 95/3-4, 501–511.

CASTELLARIN, A., MORTEN, L., & BARGOSSI, G.M. 1976: Conglomerati di conoide sottomarina nel Flysch insubrico di Malè e Rumo (Trento). Boll. Soc. geol. ital. 95/3-4, 513–515.

CIPRIANI, N., MAGALDI, D., & MALESANI, P. 1976: Studio mineralogico-petrografico delle Arenarie di Sarnico (Prealpi Bergamasche) e correlazioni con la Pietraforte (Toscana). Ateneo parmense, acta nat. 12/3, 285–309.

DE ALESSANDRI, G. 1899: Osservazioni geologiche sul Cretacico e sull'Eocene della Lombardia. Atti Soc. ital. Sci. nat. Mus. civ. Storia nat. 38/3, 253–320.

DE ROSA, E., & RIZZINI, A. 1967: Prealpi flysch near Bergamo. In: ANGELUCCI, A. et al.: Sedimentological characteristics of some Italian turbidites. Geol. romana, 6, 356–362.

DEUTSCH, A. 1983: Datierungen an Alkaliamphibolen und Stilpnomelan aus der südlichen Platta-Decke (Graubünden). Eclogae geol. Helv. 76/2, 295–308.

DIETRICH, V., & FRANZ, U. 1978: Ophiolith-Detritus in den santonen Gosau-Schichten (Nördliche Kalkalpen). Geotekt. Forsch. 50/1-2, 85–109.

DOGLIONI, C., & BOSELLINI, A. 1987: Eoalpine and mesoalpine tectonics in the Southern Alps. Geol. Rdsch. 76/3, 735–754.

DÖSSEGGER, R., FURRER, H., & MÜLLER, W.H. 1982: Die Sedimentserien der Engadiner Dolomiten und ihre lithostratigraphische Gliederung (Teil 2). Eclogae geol. Helv. 75/2, 303–330.

ELTER, G., ELTER, P., STURANI, C., & WEIDMANN, M. 1966: Sur la prolongation du domaine ligure de l'Apennin dans le Montferrat et les Alpes et sur l'origine de la nappe de la Simme s.l. des Préalpes romandes et chablaisiennes. Arch. Sci. (Genève) 19/3, 279–377.

ERRICO, G., GROPPI, G., SAVELLI, S., & VAGHI, G.C. 1980: Malossa Field, a deep discovery in the Po Valley, Italy. In: Giant oil and gas fields of the decade 1968–1978 (Ed. by HALBOUTY, M.T.) Mem. Amer. Assoc. Petrol. Geol. 30, 525–538.

FAUPL, P. 1976: Sedimentologische Studien im Kreideflysch der Lienzer Dolomiten. Anz. math.-natw. Kl. Österr. Akad. Wiss., 1976/9, 131–134.

FINGER, W. 1978: Die Zone von Samaden (Unterostalpine Decken, Graubünden) und ihre jurassischen Brekzien. Mitt. geol. Inst. E.T.H. Univ. Zürich, N.F. 224.

FLÜCK, W. 1973: Die Flysche der praealpinen Decken im Simmental und Saanental. Beitr. geol. Karte Schweiz, N.F. 146.

GAUPP, R.H. 1982: Sedimentationsgeschichte und Paläotektonik der kalkalpinen Mittelkreide (Allgäu, Tirol, Vorarlberg). Zitteliana 8, 33–72.

— 1983: Die paläogeographische Bedeutung der Konglomerate in den Losensteiner Schichten (Alb, Nördliche Kalkalpen). Zitteliana 10, 155–171.

GELATI, R., & PASSERI, L. 1967: Il Flysch di Bergamo, nuova formazione cretacica delle Prealpi Lombarde. Riv. ital. Paleont. Stratigr. 73/3, 835–850.

GELATI, R., CASCONE, A., & PAGGI, L. 1982: Le unità stratigrafiche aptiano-maastrichtiane delle Prealpi Bergamasche. Riv. ital. Paleont. Stratigr. 88/1, 75–112.

HÄRING, M.O. 1980: Zur Sedimentologie des Lombardischen Oberkreideflysches zwischen dem Lago Maggiore und Lecco. Ph. D. Thesis Univ. Basel.

HOMEWOOD, P. 1983: Palaeogeography of Alpine Flysch. Palaeogeogr. Palaeoclimatol. Palaeoecol. 44/2, 169–184.

HUBER, F. 1989: Zur Geologie der Val di Croina (Val di Ledro, Trentino meridionale, Italia). Diploma Thesis Univ. Basel, unpubl.

KLEBOTH, P. 1982: Stratigraphie und Sedimentologie der höheren Unterkreide und des Alttertiärs der Brianza (Provinz Como, Italien). Mem. Sci. geol. (Padova) 35, 213–292.

KRALIK, M., KRUMM, H., & SCHRAMM, J.M. 1987: Low-grade and very low-grade metamorphism in the Northern Calcareous Alps and in the Greywacke zone: Illite-crystallinity data and isotopic ages. In: Geodynamics of the Eastern Alps (Ed. by FLÜGEL, H.W., & FAUPL, P.), 164–178, Franz Deuticke, Vienna.

LAUBSCHER, H. 1970: Bewegung und Wärme in der alpinen Orogenese. Schweiz. mineral. petrogr. Mitt. 50/3, 565–596.

Laubscher, H. 1988: Material balance in Alpine orogeny. Bull. Geol. Soc. Amer. 100/9, 1313–1328.

Laubscher, H. in press: The problem of the deep structure of the Southern Alps: 3-D material balance considerations and regional consequences. Tectonophysics.

Laubscher, H.P., & Bernoulli, D. 1982: History and deformation of the Alps. In: Mountain Building Processes (Ed. by Hsü, K.J.), 169–180, Academic Press, London.

Lüdin, P. 1987: Flysche und tektonische Melanges im südpenninisch/unterostalpinen Grenzbereich (Arosa-Zone; Mittelbünden und Rätikon, Schweiz). Doctoral Thesis University of Basel.

Marthaler, M., & Stampfli, G. 1989: Les schistes lustrés à ophiolites de la nappe du Tsaté: un ancien prisme d'accrétion issu de la marge active apulienne. Schweiz. mineral. petrogr. Mitt. 69/2, 211–216.

Massari, F., & Medizza, F. 1973: Stratigrafia e paleogeografia del Campaniano-Maastrichtiano nelle Alpi meridionali. Mem. Ist. Geol. Mineral. Univ. Padova 28, 1–63.

Oberhauser, R. 1973: Stratigraphisch-Paläontologische Hinweise zum Ablauf tektonischer Ereignisse in den Ostalpen während der Kreidezeit. Geol. Rdsch. 62/1, 96–106.

Pieri, M., & Groppi, G. 1981: Subsurface geological structure of the Po Plain. Progetto Finalizzato Geodinamico/ Sottoprogetto «Modello Strutturale». Pubbl. Cons. naz. Ric. 414.

Platt, J.P. 1986: Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. Bull. Geol. Soc. Amer. 97/9, 1037–1053.

Polino, R., dal Piaz, G.V., & Gosso, G. 1990: Tectonic erosion at the Adria margin and accretionary processes for the Cretaceous orogeny of the Alps. In: Deep Structure of the Alps (Ed. by Roure, F., Heitzmann, P., & Polino, R.). Mém. Soc. géol. France, 156, Mém. Soc. géol. Suisse 1, vol. spec. Soc. geol. ital. 1.

Roesli, F. 1927: Beitrag zur Geologie des Murtiröl bei Zuoz. Dissertation Univ. Bern.

— 1944: Fazielle und tektonische Zusammenhänge zwischen Oberengadin und Mittelbünden. Eclogae geol. Helv. 37/2, 355–383.

— 1945: Sedimentäre Zone von Samaden (Samaden Kt. Graubünden). Eclogae geol. Helv. 38/2, 329–336.

Santini, L., & Martin, S. 1988: Basamento australpino e coperture sudalpine nella zona di Samoclevo (Val di Sole, Trentino occidentale. Mem. Sci. geol. (Padova) 40, 275–284.

Spicher, A. 1940: Geologie und Petrographie des oberen Val d'Isone. Schweiz. mineral. petrogr. Mitt. 20, 17–100.

— 1980: Geologische Karte der Schweiz, 1:500 000. 2nd edition, Schweiz. Geol. Komm., Bern.

Stadler, G., Teichmüller, M., & Teichmüller, R. 1976: Zur geothermischen Geschichte des Karbons von Manno bei Lugano und des «Karbons» von Falletti (Sesia-Zone der Westalpen). N. Jb. Geol. Paläont. Abh. 152/2, 177–198.

Thöni, M. 1983: The thermal climax of the early Alpine metamorphism in the Austroalpine thrust sheet. Mem. Sci. geol. (Padova) 36, 211–238.

Venzo, S. 1951: Ammoniti e vegetali albiano-cenomaniani nel Flysch del Bergamasco occidentale. Condizioni stratigrafiche e tettoniche della serie barremiano-turoniana. Atti Soc. ital. Sci. nat. 40, 175–244.

— 1954: Stratigrafia e tettonica del Flysch (Cretacico-Eocene) del Bergamasco e della Brianza orientale. Mem. descr. Carta geol. Ital. 31.

Vogt, P. 1962: Geologisch-petrographische Untersuchungen im Peridotitstock von Finero. Schweiz. mineral. petrogr. Mitt. 42/1, 59–125.

Wicht, J.-M. 1984: Le flysch de la nappe de la Simme dans les Préalpes romandes. Thèse Univ. Fribourg.

Wildi, W. 1985: Heavy mineral distribution and dispersal pattern in penninic and ligurian flysch basins (Alps, northern Apennines). G. Geol. (Bologna) (3), 47/1–2, 77–99.

Winkler, W. 1988: Mid- to Early Late Cretaceous flysch and melange formations in the Western part of the Eastern Alps. Palaeotectonic implications. Jb. geol. Bundes-Anst. (Wien) 131/2, 341–389.

Winkler, W., & Bernoulli, D. 1986: Detrital high pressure/low temperature minerals in a Late Turonian flysch sequence of the eastern Alps (western Austria). Geology 14/7, 598–601.

Winterer, E.L., & Bosellini, A. 1981: Subsidence and sedimentation on Jurassic passive continental margin. Bull. Amer. Assoc. Petroleum Geol. 65/3, 394–421.

Zingg, A. 1983: The Ivrea and Strona-Ceneri Zones (Southern Alps, Ticino and N-Italy) – a review. Schweiz. mineral. petrogr. Mitt. 63/2+3, 361–392.

Zingg, A., Hunziker, J.C., Frey, M., & Ahrendt, H. 1976: Age and degree of metamorphism of the Canavese zone and of the sedimentary cover of the Sesia zone. Schweiz. mineral. petrogr. Mitt. 56/2, 361–375.

Manuscript received 22 December 1989
Revision accepted 20 February 1990