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Mid- to Early Late Cretaceous Flysch and Melange Formations in the Western Part of the Eastern Alps. Palaeotectonic Implications.

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With 20 Figures and 9 Tables

Vorarlberg
Allgäu
Liechtenstein
Graubünden
Eastern Alps
Flysch
Stratigraphy
Heavy minerals
Palaeogeography
Palaeotectonics

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Zusammenfassung

Die kretazische Konvergenz im Grenzbereich zwischen dem südpenninischen Tethys-Ozean und dem apulisch/ostalpinen distalen Kontinentalrand ist durch Flyschsedimentation und Melangebildung gekennzeichnet. Die tertiäre kontinentale Kollision zwischen dem Nord- und Südrand der Tethys hat die kretazischen Verhältnisse jedoch stark verwischt. Entlang der heutigen Grenzzone werden die Zeugen der kretazischen Orogenese im wesentlichen in vier verschiedenen strukturellen Positionen angetroffen:

1) In der Arosa-Zone, einem aus kleinen Decken, Schuppen und Melanges komplex aufgebauten Gesteinskörper, der sich von Mittelbünden ins Rätikon erstreckt.
2) In einer Zone ähnlicher struktureller Lage, die sich von Liechtenstein ins südliche Allgäu fortsetzt und für die der Name Walsteral-Zone eingeführt wird.
3) In den Allgäuer und Lechtaler Alpen, wo Flysch- und Brekzienformationen in der ostalpinen Allgäu- und externen Lechtal-Decke und in der unterliegenden Schuppenzone (Kalkalpine Randzone) erhalten sind.
4) In der internen Lechtal-Decke, in der die hemipelagischen und turbiditischen Kreideschiefer das Hangende der ostalpinen Schichtserie bilden.

Die enge Vergesellschaftung der Flysche in der Arosa-Zone mit südpenninischen Elementen weist darauf hin, daß sie ursprünglich im ozeanischen Becken sedimentiert wurden. Für die Flysche in der Walsertal-Zone kann eine Ablagerung am distalen Kontinentalrand angenommen werden. Stratigraphisch reichen die Flyschsedimente in diesen beiden Zonen vom Albien bis ins Turonien. In der Allgäu- und Lechtaldecke (mit Ausnahme der internen Lechtaldecke) sind Flysch vom Aptien/Albien bis ins Santonien dokumentiert und leiten somit zur turbiditischen Gosau über.

Petrographische Analysen (Sandsteinkomponenten, Schwerminerale, Konglomeratgerölle) zeigen auf, daß die Flysche von verschiedenen aus ozeanischem und kontinentalem Grundgebirge bzw. deren Sedimentbedeckung zusammengesetzten Liefergebieten geschüttet wurden. Detritischer Glaukophan und Lawsonit in den Flyschsandsteinen des ostalpinen distalen Kontinentalrandes weist darauf hin, daß zusätzlich heute nicht mehr erhaltenen kretazischen hoch-P/niedrig-T metamorphe Terrains in den Liefergebieten anstanden. Grünschieferfazielle Chloritoide, Chinozoisite und Epidote zeigen die gleiche räumliche Verbreitung. Diesen Beobachtungen stehen interpretierte radiometrische Alter von konvergenzverknüpften metamorphen Serien in den Ost- und Westalpen gegenüber, die gleichaltrig oder jünger als die beobachteten Mineralumlagerungen sind. Dieser Widerspruch und die beginnende Umarbeitung von ozeanischem Material (Chromit) von der oberen Unterkreide an legen den Schluß nahe, daß die Konvergenz früher als allgemein angenommen eingesetzt hat.

Wir postulieren, daß die Konvergenz im Valanginien/Hauterivien mit südwärts gerichteter Obduktion von südpenninischer ozeanischer Kruste auf den distalen ostalpinen Kontinentalrand begonnen hat. Die Metamorphose könnte an oder nahe der Basis des ozeanischen Krustenkeils stattgefunden haben. Das erste Obduktionsereignis hat offensichtlich noch keine weitverbreitete terrigene Sedimentation bewirkt. Fortschreitende Einengung (und Subduktion) hat zur Ausbildung eines südvergenten heterogenen Überschiebungsgürtels geführt, der ab Aptien/Albien grobklastisches Material in ozeanische Becken im N und kontinentale Foreland-Becken im S lieferte. Im Coniacien wurden durch ein weiteres bedeutendes tektonisches Ereignis ozeanische und kontinentale Beckenteile eliminiert (u. a. Melangebildungen der Arosa-Zone und Walsertal-Zone) während in südlicheren Teilen des Ostalpins die Sedimentation fortdauerte.

Abstract

Cretaceous convergence along the Tethyan (South Penninic) ocean and the Apulian (Austroalpine) distal continental margin is documented by coeval flysch and melange formations, however, the present structural situation reflects the later Tertiary continental collision between the southern and the northern margin of the Tethys. Along the Penninic/Austroalpine boundary zone the signatures of the Cretaceous orogeny are preserved in essentially four different settings:

1) In the Arosa Zone, a complex body of small nappes, imbricates and melanges, situated in the Central Grisons and Rätikon area.
2) In a zone in equivalent structural position extending form Liechtenstein to the Southern Allgäu, for which the term Walsertal zone is introduced. It comprises mainly flysch and broken flysch formations and melanges and is imbricated with Austroalpine elements.
3) In the area of the Allgäu- and Lechtal Alps, flysch and breccia formations occur in the Allgäu and external Lechtal nappe, and in an imbricate zone below, the Kalkalpine Randzone.
4) In the internal Lechtal nappe, Early Cretaceous pelagic limestones of the continental margin are grading up into Mid-Cretaceous fine grained hemipelagic and turbiditic deposits.

The close association with oceanic sediments and basement suggests that most flysch sequences of the Arosa zone were deposited in the oceanic realm, whereas for the greater part of the flysches included in the Walsertal zone a continental margin origin is assumed. The flysch formations belonging to these two units cover the time interval from Albian to Turonian. The flysches and hemipelagites related to the Allgäu- and Lechtal nappe range, with some variations, from Aptian to Santonian.

Petrographic data (framework grain-, heavy mineral- and conglomerate component analysis) indicate that the flysch basins were supplied by variable source terrains composed of oceanic South Penninic and continental Austroalpine basement and sedimentary cover series. Moreover, detrital blue amphiboles and scarce lawsonite recognized in several flysch series indicate now vanished high-P/low-T metamorphic terrains, supposedly related to Cretaceous convergence, as additional sources of detritus. These minerals occur from at least the Early/Middle Albian till Coniacian. Radiometric ages of subduction related metamorphic rocks in the western and eastern Alps are generally coeval with or younger than the formations yielding the detrital high-P/low-T metamorphic minerals. The observed time interval, also characterized by the occurrence of reworked ophiolite derived chromite mineral grains points to a scenario of obduction/subduction and subsequent uplift already during the late Early Cretaceous.

We may assume that convergence started in Valanginian/Hauterivian times by southward directed obduction of a South Penninic oceanic slab onto the Austroalpine distal continental margin. High-P/low-T metamorphism could have taken place at or near the base of the overthrusted oceanic slab. The obduction event apparently is only locally recorded in the sediments in the adjacent basins. Continued compression and subduction resulted in the formation of a south verging oceanic/continental foldthrust belt supplying from the Aptian/Albian onwards coarse grained detritus to oceanic basins to the north and continental foreland basins to the south. A later major tectonic event during the Coniacian is considered to be responsible for imbrication and melange formation documented in the Arosa- and Walsteral zone. To the south, on some parts of the early Austroalpine nappe edifice sedimentation is continued.

1. Introduction

1.2. Regional Overview

In Switzerland, Liechtenstein, Austria and Germany evidence for the Cretaceous convergence at the South Penninic/Austroalpine continental margin is preserved along the western and northern border of the actual Austroalpine nappe edifice. Mid- to early Late Cretaceous flysch and melange formations formed during obduction and subduction of oceanic crust. They were strongly thinned and disrupted during later Tertiary continental collision and can be recognized in four different segments along the main Austroalpine thrust (Fig. 1):

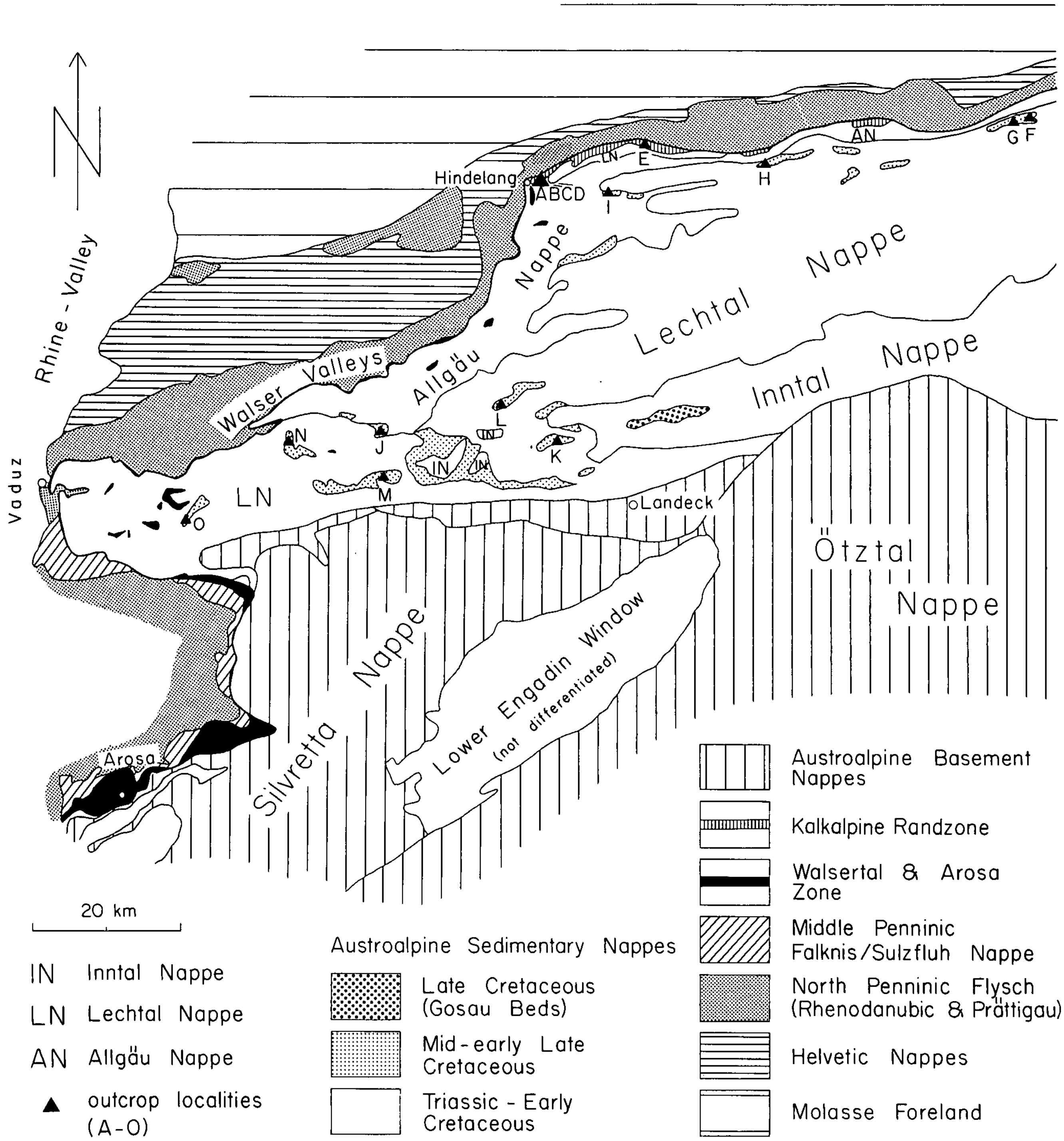


Fig. 1.
Tectonic sketch map of the western Eastern Alps with outcrop localities in the Austroalpine sediment nappes and Kalkalpine Randzone.

❶ The Arosa zone
is a highly tectonized ophiolite bearing unit, a few hundred to some thousand meters thick and sandwiched between Jurassic to Eocene formations of the Middle Penninic Falknis-Sulzfluh nappes respectively the North Penninic Prättigau Flysch nappe below and the Austroalpine crystalline basement (Silvretta) and sedimentary cover nappes above. Regionally, the Arosa zone extends from the central Grisons (Tiefenkastel) in the south to the Rätikon (Verspala, Tilisuna) in the north. In its southern continuation, the ophiolitic Platta nappe represents a relic of the South penninic oceanic domain (DIETRICH, 1970). The data on the flysch sediments and melanges of the Arosa zone included here are mostly based on P. LÜDIN's Ph.D. thesis worked out in the frame of the same project (LÜDIN, 1987).

❷ The Walsertal zone (new term)
extends from Liechtenstein through Vorarlberg (western Austria, Walser Valleys) to Hindelang in the Allgäu (southern Germany). It is a narrow flysch and melange zone, a some tens to few hundred meters thick, structurally intercalated between the Turonian-Maastrichtian supposedly North Penninic rhenodanubic Flysch nappe and the main Austroalpine

thrust of the Northern Calcalerous Alps (Allgäu and Lechtal nappes). These nappes belong to the Upper Austroalpine domain and are derived from an area adjacent to the Southern Alps (TOLLMANN, 1970). The badly defined southern transition to the Arosa zone is situated between southern Liechtenstein and the Rätikon area. Rocks derived from both units occur as thrust imbricates and in tectonic windows in the Lechtal nappe (e. g. ALLEMANN et al., 1957; BLASER, 1952; RICHTER, 1956; OTTE, 1972).

❸ The Allgäu and external Lechtal nappes bear variable turbidite and breccia formations. Highly tectonized flysch deposits of comparable composition occur in the small seam („Randcenoman", RICHTER et al., 1939) bordering the Austroalpine sedimentary nappes to the north (GAUPP, 1980, 1982). We shall refer to it as Kalkalpine Randzone (new term).

❹ The internal Lechtal nappe series (Triassic-Early Cretaceous)
comprises convergence related shaly series ("Kreide-Schiefer-Serie" after AMPFERER, 1913). They are generally in stratal continuity with the Early Cretaceous pelagic series and overthrusted by the structurally highest unit of the Austroalpine sediment nappes, the Inntal nappe. The sedimentary series of the Inntal nappe is unconformably overlain by the Late Cretaceous Gosau Beds.

1.2. Palaeotectonic Situation

Palaeotectonic models for the Alpine orogene suggest that the Austroalpine continental margin was situated on the northern margin of the African promontory (CHANNEL & HORWATH, 1976) respectively of an independent Apulian plate (BIJU-DUVAL et al., 1977). The movements of this promontory or independant plate were mainly controlled by the drift effected by the African plate during the Late Triassic to Cretaceous opening of the South Atlantic ocean (PITMAN & TALWANI, 1972). This concept basically goes back to ARGAND (1924).

During the Late Triassic and Jurassic, in the course of the sinistral movement of Africa with respect to Amerasia, rifting and formation of oceanic lithosphere in the South Penninic realm took place (TRÜMPY, 1975; LAUBSCHER & BERNOULLI, 1977; BERNOULLI, 1981). From different lines of evidence WEISSERT & BERNOULLI (1985) deduct that the South Penninic Central Tethys was a small transform-fault dominated ocean.

From Middle Cretaceous onwards compression prevailed along the Apulian/South Penninic continental margin due to the now N- and E-wards directed motion of the Apulian plate (e. g. DERCOURT et al., 1986). Important flysch deposits were formed during obduction/subduction processes along the continental margin (see for general models e. g. LAUBSCHER, 1970; DIETRICH, 1976; GEYSSANT, 1980). A generally south dipping subduction zone is suggested from palinspastic considerations and from the arrangement of the Cretaceous metamorphic belts (ERNST, 1971; TOLLMANN, 1980).

There is a general agreement of opinion about the initiation of subduction in Aptian/Albian or Cenomanian time (e. g. DIETRICH, 1976; OBERHAUSER, 1978), however, older clastic sequences, i. e. the Valanginian–Aptian Rossfeld-Schichten of the Lechtal nappe (FAUPL & TOLLMANN, 1979) and the present data are difficult to integrate into this picture, as they seem to document earlier tectonic movements involving also oceanic crust. The duration of subduction is disputed. A rather short subduction period till Cenomanian time is assumed by OBERHAUSER (1968) and FAUPL (1978), whereas TRÜMPY (1973, 1975), DIETRICH (1976) and OBERHAUSER (1978) propose a longer lasting subduction phase up to the Campanian or Maastrichtian.

From radiometric dating of supposedly subduction-related epi-and mesozonal metamorphism in the western part of the Eastern Alps it appears that the main early Alpine tectonic events could have taken place between 100 and 85 Ma (THÖNI, 1983). After numerical scales this timespan is covering the period Middle/Late Albian to the Coniacian/Santonian (HARLAND et al., 1982; ODIN et al., 1982).

Whether or not the South Penninic ocean was eliminated during Cretaceous subduction is a matter of debate. Arguments for the elimination, derived from the Tauern window appear to be partly based on weak biostratigraphic control as indicated by THIELE (1980). Biostratigraphic data from the Western Alps (LEMOINE et al., 1984) suggest that in this part of the Alps a remnant oceanic basin persisted through most of the Late Cretaceous. To the other hand the palaeogeographic configuration of the Western Alps probably cannot be projected in the Eastern Alps; as matter of fact continental collision may have started earlier to the east as a consequence of oblique convergence (e. g. GEYSSANT, 1980).

1.3. Stratigraphy

The palaeogeographic realms are generally defined by

1) their pre-Middle Cretaceous stratigraphy including basement
   and
2) their palinspastic position, derived from kinematic inversion.

In the context of plate tectonics, the South Penninic and Austroalpine formations are interpreted as oceanic and distal continental margin sequences respectively (LAUBSCHER, 1970; DIETRICH, 1976; TRÜMPY, 1975).

The South Penninic series (Fig. 2), now preserved in the Arosa zone (WEISSERT & BERNOULLI, 1985; LÜDIN, 1987) and the Platta nappe (DIETRICH, 1970) consists of Late Jurassic Radiolarite and Early Cretaceous Calpionella Limestone Formations overlying an Early to Middle Jurassic ophiolite sequence (peridotites, serpentinites, ophicalcites and pillow lavas). There is no clear evidence that basaltic eruptions continued till Middle Cretaceous as supposed e. g. by RICHTER (1963), DIETRICH (1969) or OBERHAUSER (1978). The late Early and Mid-Cretaceous is represented by siliceous limestone/shale and shale sequences which can be correlated with the time equivalent Palombini Shale and Lavagna Shale Formations in the Ligurian part of the Tethyan ocean in Italy (e. g. WEISSERT & BERNOULLI, 1985). The first occurrence of flysch deposits is of Aptian–Albian age as reported by DIETRICH (1970) from the Platta nappe.

The Austroalpine series (Fig. 2) contain Permian clastics and thick Triassic carbonate sequences of shallow marine and basinal environments overlying Palaeozoic

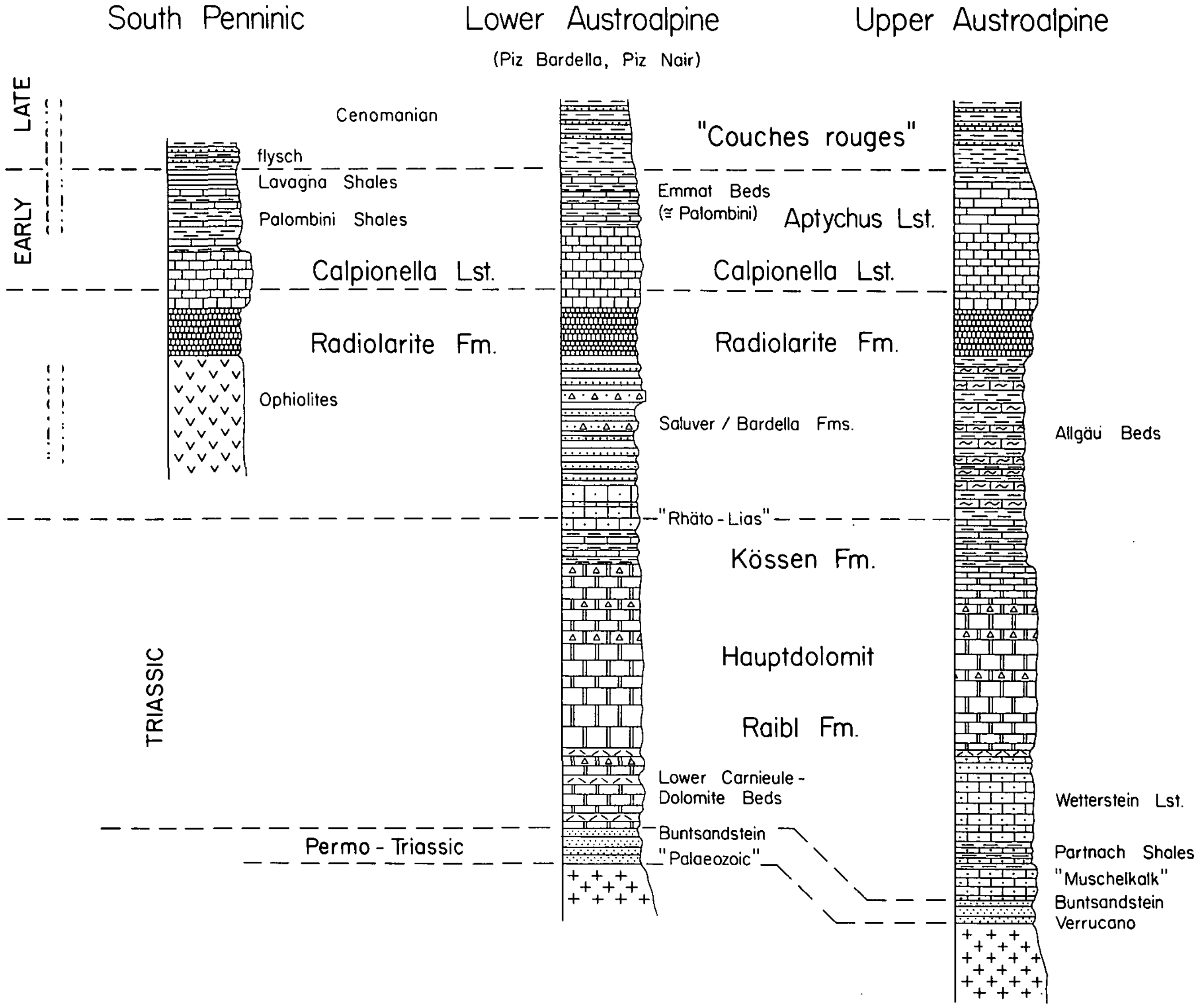


Fig. 2.
Comp site lithostratigraphic sections of the South Penninic and Austroalpine (Lower Austroalpine after FINGER, 1972).

sedi ients and continental basement. A pronounced pha: of rifting in the Austroalpine realm is doc nented by greatly varying formation thickness, syn: dimentary faulting and mass-flow deposits includ d in the Early to Middle Jurassic Allgäu beds of the Jpper Austroalpine realm (EBERLI, 1986). Coeval sedi ients in the Lower Austroalpine realm are compos d of various breccias and sandstones (Alv-, Pad lla-, Saluver- and Bardella Formations) deposited alon fault scarps and in small sized asymmetric basins FINGER, 1978). The further general sinking of the mar n is reflected by pelagic sediments of increasing wate depth in Late Jurassic and Early Cretaceous.

In he Lower Austroalpine realm quasioceanic condition: of carbonate-solution prevailed during the Early Cret ceous, as the Emmat Beds are comparable to the Sou Penninic Palombini Shales (FINGER, 1978). In the Upp r Austraolpine realm the sedimentation of pelagic lime: tones went up to Late Barremian or Early Aptian (RISC 1, 1971; CARON et al., 1982). These are greenish gray bioturbated marly limestones and marls to which we r fer as Aptychus Limestone Formation. All over the Austroalpine realm the Mid- and early Late Cretaceous is represented by partly "Couches rouges"-like marly limestones and/or marlstones and turbiditic deposits (RÖSLI, 1944; ZEIL, 1954; FINGER, 1978; RISCH, 1971; GAUPP, 1980; CARON et al., 1982).

The turn from a distensive to a compressive regime at the South Penninic/Austroalpine boundary is assumed to be documented by the onset of terrigenous sedimentation. Because of the general epi-metamorphic overprint in the Arosa zone biostratigraphic control is poor, but flysch sedimentation up to Turonian can be assumed (OBERHAUSER, 1983; LÜDIN, 1987). In the Allgäu- and external Lechtal nappe and Kalkalpine Randzone GAUPP (1980, 1982) described a hemipelagic-terrigenous sequence ranging from Aptian to Early Turonian, but correlations with flysch deposits comprised in the Walsertal zone appear to be incorrect. Farther to the east WEIDICH (1984b, b) recognized in the Lechtal nappe pelagic/hemipelagic and turbiditic series covering the time span from Coniacian to Santonian (Campanian?) forming the stratigraphic transition to Campanian–Maastrichtian turbiditic Gosau Beds.

1.4. Flysch, Broken Formations and Melanges

Immature terrigeneous detritus from basement and sedimentary cover rocks suggests strong orogenic uplift and erosion as a source of flysch sedimentation. This is the classical genetic connotation (TERCIER, 1947) of the originally descriptive term flysch introduced by STUDER (1827). Depending on the subsequent tectonic evolution of the sedimentary basins, the flysch sequences can be preserved in stratigraphic continuity with their basement or be shared off forming rootless tectonic units. Increasing deformation and dismembering of these rocks leads to the formation of broken flysch formations (HSÜ, 1968) and finally of tectonic melanges.

Melange formations are heterogeneous tectonic mixtures of block and/or lens-shaped components derived from different lithologies including continental/oceanic basement, flysch and other sediments comprised in a pervasively sheared matrix (GREENLY, 1919; HSÜ, 1974). Mixing of different lithologies can of course also occur by slumping and sliding in olisthostromes, but the latter features are not included by us in the term melange (HSÜ, 1974). In the case of tectonic overprinting the primary or penecontemporaneous sedimentary features may be obscured or completely wiped out and the distinction of a melange from pebbly mudstones e. g. may become impossible. If clear indications for a sedimentary origin as sedimentary contacts or soft sediment deformation are obliterated it is more to the point to use the term (tectonic) melange.

In melange units an original stratigraphic suite cannot be deduced from the observed superpositon of subunits and elements included (HSÜ, 1976). Dating of melanges is difficult or in cases even impossible, however, a lower age limit of a melange formation is given by the youngest components or the age of the matrix. For correlation between different melange units the only practicable approach is to establish an inventory of the elements and a characterization of the enclosing matrix.

1.5. Methods

For the description and correlation of the often dilaterated and regionally scattered flysch occurrences, three petrographical parameters beside field criteria were applied: heavy mineral content, sandstone framework grain and conglomerate component composition. For sandstone samples of variable grain size and preservation the heavy mineral analysis turned out to be the most reliable method. The combination of the three methods gives qualitative informations about the composition of the source terrains of the flysch formations. In several cases even some quanitative estimations can be deduced from it.

Heavy Minerals Analysis

Grain concentrates were produced by dissolving the carbonate fraction of crushed sandstone fragments (2–4 mm) in warm 10 % acetic solution (70°C) and by subsequent centrifuge aided gravity settling out of the sieve fraction 0.063–0.4 mm in bromoforme. The heavy mineral residue was mounted in piperine and quantitatively determined under the petrographic microscope by ribbon counting (150–250 grains). The dissolution of the carbonate, in particular dolomite cement is a long lasting procedure, because during reaction acetates are formed (personal communication R. STERN) which obviously prevent further reaction. This effect can be evaded by adding small quantities of H_2O_2 to the solution from time to time. The dissolution time can therewith be reduced a half.

The flysch sandstones contain variable amounts (up to 90 % of the heavy fraction) of diagenetic baryte (X-ray determination S. GRAESER). Since baryte and apatite in routine mineral mountings are hardly distingusihed, apatite is not included in the results. From repeated konoscopic measurements it appears that apatite, if present at all, is a minor constituent.

Sandstone Framework Grain Analysis

Where possible and if the mean grain size was not too small, the framework grain composition of the sandstones was quantified in feldspar- and carbonate stained thin sections of the samples used for heavy mineral analysis. With few exceptions the method proposed by DICKINSON (1970) was applied. In contrast to DICKINSON the contents in aphanitic lithic carbonate fragments are included in calculations (see e. g. Late Jurassic to Early Cretaceous Calpionella- and Aptychus Limestone, Triassic dolomites), because their extrabasinal derivation can be ascertained. In quantifying their occurrence in the sandstones more detailed information about the nature of the source terrains is obtained.

In addition midpoint-ribbon counting was used to avoid bias by grain size effects (VAN DER PLAS, 1962; WINKLER, 1984). The widely used point counting method is appropriate for volumetric modal estimates of rock constituents (CHAYES, 1956) whereas in source terrain evaluations the interest lays in the frequency of the different grain types identified in the sand fraction 0.063–2.00 mm. The most reliable method for number frequency estimates in thin sections is indeed the midpoint-ribbon counting. It takes into account all grains independant of their grain size passing with their gravity center inside of a given ribbon (larger than maximum grain size [VAN DER PLAS, 1962]) during the advancement of the thin section. It is evident that the apparent detrital grain composition of flysch sandstones is the product of progressive elimination of the less resistant components. The original sand derived from a particular source terrain is primarily determined by the climate prevailing in the source area and during transport. The detritus will again be modified to an extent depending on transport distance, relief and probable mixture with material derived from other sources. Finally the diagenetic processes will selectively eliminate low resistant components. For example the fact that plagioclase grains are generally smaller than monocrystalline quartz grains does not necessarily imply that plagioclase was less important in the source terrain, a conclusion that would result from point counting based data. The midpoint-ribbon counting will, therefore, give also proper emphasis to the less stable minerals and lithic grains.

Conglomerate Component Analysis

The components of conglomerates and breccias were determined and counted (fleet counting) in stained thin sections and a large grouping is applied to record many pebbles in a few groups. For sedimentary lithic clasts in particular a simple age related grouping was established. Carbonate cemented sandstone, arenaceous limestone and marly limestone clasts, frequently deformed by compaction were not included, because of their probable intrabasinal derivation.

2. Arosa Zone

2.1. Generalities

The Arosa zone represents a zone of small nappes, imbricates and melanges of oceanic (South Penninic) and distal continental lithologies (Lower austroalpine [e. g. WEISSERT, 1975]). Earlier workers (e. g. GRUNAU, 1947; RICHTER, 1957) interpreted the Arosa zone as a relic of a single palaeogeographic realm with continental basement and suggested that the ophiolites represent mafic rocks intruded into the Lower Austroalpine. In the wake of plate tectonics theory, the Alpine ophiolites were reinterpreted as derived from a Jurassic Atlantic type mid-ocean ridge system (LAUBSCHER, 1969; DIETRICH, 1976) and so therefore could not be derived from a realm with continental crust. Mesozoic kinematics of the European and Austroalpine margins and sedimentary evidences suggest that the South Penninic realm represents in our transsect an ancient oceanic transform fault system (WEISSERT & BERNOULLI, 1986; BERNOULLI & WEISSERT, 1985).

The South Penninic ophiolite series in the oceanic parts of the Arosa zone and its southern prolongation, the Plate nappe, are overlain by Late Jurassic-Middle Cretacous pelagic an hemipelagic deposits (see above) which are topped by various flysch sequences (WEISSERT & BERNOULLI, 1985; LÜDIN, 1987). Rare but significant biostratigraphic data from lithologically different flysch occurrences indicate that flysch sediments were deposited between the Albian and the Turonian (DIETRICH, 1970; OBERHAUSER, 1983; LÜDIN, 1987). Recently dated flysch occurrences (Schwerzi flysch and another minor, unnamed formation) provided foraminifera of Late Cenomanian–Turonian age (LÜDIN, 1987).

2.2. Compilation of Data and Interpretations

From P. LÜDIN's work (1987) it arises that in the Arosa zone three basic elements of variable scale can be distinguished:

1) Dekametric to kilometer thick imbricates of South Penninic and Lower Austroalpine lithologies, partly revealing internal stratigraphic continuity between the formations. The South Penninic Ophiolite-Radiolarite-Calpionella Limestone sequence is preserved in several places. It is in particular to note that it is frequently found in a tectonically overturned position (Totalalp imbricate near Davos, [BERNOULLI & WEISSERT, 1985]; Verborgne Wäng near Arosa, Crap Farras and Val Savriez in the Platta nappe [WEISSERT & BERNOULLI, 1985; LÜDIN, 1987]).
2) Imbricates of flysch and broken flysch formations. The flysch sandstones are characterized by variable clastic composition. They are derived from oceanic and continental basement and sedimentary cover rock sources. Broken flysch formations rarely are observed. This is probably the consequence of the high tectonic grade generally observed in the Arosa zone causing the inclusion of broken formations into tectonic melanges. Petrographical and lithologic comparision can help to distinguish betwen Jurassic spreading related Lower Austroalpine turbidite and breccia formations and convergence related South Penninic flysch sequences.
3) Tectonic melange formations which contain, in order of importance, South Penninic, Lower Austroalpine and rarely Middle Penninic decimetric to dekametric lenses and blocks imbedded in various matrix types. We can distinguish between "monogenic melanges" bearing different lithologies of one individual palaeogeographic realm and "polygenic melanges" representing mixtures of lithölgies derived from two or more palaeogeographic realms (see Table 1).

Table 1.
Tectonic melange types in the Arosa zone (after LÜDIN, 1987).

melange type	monogenic		polygenic		
elements derived from	South Penninic (SP)	Lower Austroalpine (LA)	SP + LA	SP + Middle Penninic (MP)	SP + LA + MP
lithologies comprised	oceanic basement, pelagic sediment. cover & flysches	distal cont. margin basement and sediment. cover (incl. Jurassic sandst. & breccias)	SP + LA	SP + MP rise basement and sediment. cover (incl.MP flysch), L. Cretaceous--Paleocene Couches rouges	SP + LA + MP
age of flysches	Albian--Turonian	Cenomanian (or younger)	Albian--Turonian	SP + Eocene	SP + LA + Eocene
occurrence	abundant	rare	very abundant	rare	rare
structural position	arbitrary	mainly top	arbitrary	base	base
inferred age of formation	early Late Cretaceous obduction/subduction			Tertiary cont.-cont. collision	

Polygenic South Penninic/Lower Austroalpine and monogenic South Penninic melanges are the most abundant in the Arosa zone. Monogenic Lower Austroalpine melanges are rarely observed and occur at the top of the Arosa zone, i. e. along the base of the overthrusted Austroalpine nappes. At the base of the Arosa zone near the contact to the Middle Penninic units a few tectonic melanges comprising also Falknis/Sulzfluh elements are found.

The observed tectonic style of the Arosa zone mainly mirrors the Tertiary thrusting of the Austroalpine nappes over the Middle Penninic and North Penninic units. The (re?)formation of tectonic melanges including Middle Penninic elements must be correlated with this event. Because of the upper Turonian time limit reflected by the youngest sediments, for the South Penninic–Lower Austroalpine melanges at last a Coniacian formation age can be envisaged. Between the early Late Cretaceous and the Late Eocene–Oligocene tectonic events there is a badly understood gap not documented by sediments.

3. Walsertal Zone

3.1. Generalities

The new term "Walsertal zone" is introduced for a highly complex assemblage of Mid-early Late Cretaceous flysch formations and melanges in Liechtenstein, Vorarlberg and southern Allgäu (see Figs. 1, 3).

The zone is only some tens to a few hundred meters thick and occupies a structural position resembling that of the Arosa zone. However, some important differences in lithologic content are noted.

Along its base the Walsertal zone is generally bounded by the Maastrichtian Rhenodanubic Fanola-, respectively the Zementmergel Formation (ALLEMANN et al., 1951; RICHTER, 1956). At the top it is overridden by the Austroalpine sediment nappes of the Northern Calcareous Alps. These are the Allgäu nappe to the east and the structurally higher Lechtal nappe to the west (Fig. 1,3).

The structural complexities and the uncertainties in palinspastic reconstructions are mirrored in the

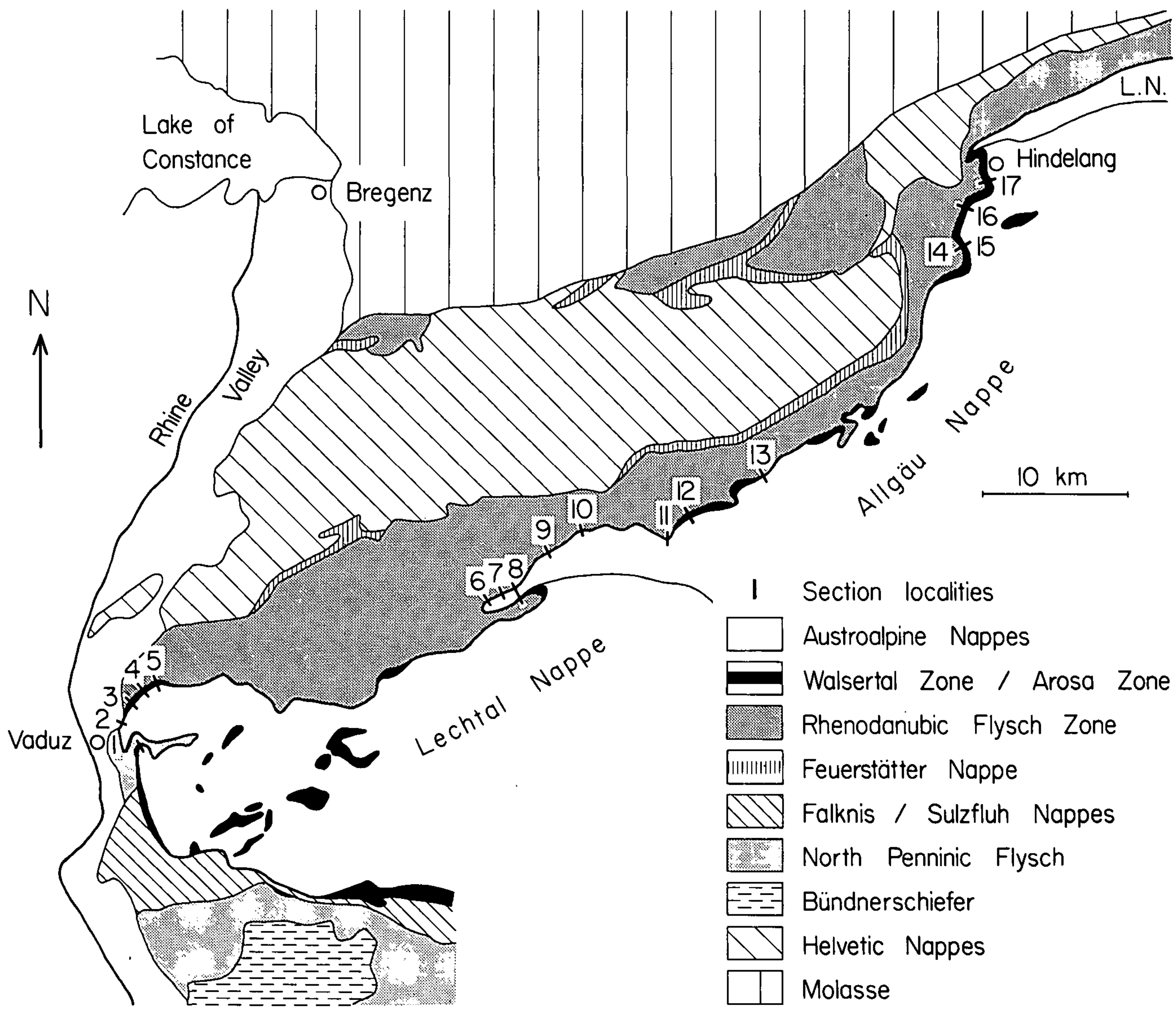


Fig. 3.
Location of sections in the Walsertal zone.

geologic nomenclature applied to the unit discussed here: "Quetschzone" (BLASER, 1952) and "Quetschzone (vorwiegend Aroser Schuppenzone)" by ALLEMANN (1957) in Liechtenstein, "Arosa-Zone" by RICHTER (1956, 1957), KALLIES (1961), GAUPP (1980) and "Randzone" by BLUMENTAL (1936) in Vorarlberg (Gross Walsertal), "Randcenoman" by MÜLLER (1973) in Vorarlberg and Allgäu, "Randzone" by D. RICHTER(1963) in the Allgäu Alps near Hindelang etc.

3.2. Section Localities

The sections studied are listed in Table 2 and their locations are indicated in Fig. 3. According to their tectonic position two groups are distinguished:

1) In sections 1–5 the sediments of the Walsertal zone occur below or are imbricated with the Lechtal nappe. Section 1 is situated along a major thrust in the Lechtal nappe. The Maastrichtian sandstones that belong to the Rhenodanubic Flysch and Middle Penninic formations (Maastrichtian pelagic limestones and Tertiary flysch of the Falknis nappe, see ALLEMANN, 1957) cropping out below the section are not attributed to the Walsertal zone.
2) In the other sections (6–17) the Walsertal zone is in contact with the Allgäu nappe. Sections 6 and 8 are situated in the boundary zone between Lechtal nappe and Allgäu nappe (Zitterklapfen Schuppe). Contrary to what is postulated by previous authors (e. g. OTTE, 1972) the flysch sediments of the Walsertal zone are always in tectonic contact with Early Cretaceous Austroalpine lithologies. Section 11 shows only an example of the complicated tectonic relationships in this locality. One of the surveyed sections (Köpfl) to the east of section 12 has not been illustrated because of the monotonous lithology, but has been drafted by BLUMENTHAL (1936, p. 468). The uppermost part of section 15 was interpreted after the map of RICHTER (1963).

A few samples come from sections not illustrated here: Sandstone no. WW 2079 was taken in the torrent

Table 2.
Outcrop localities in the Walsertal zone and references to them.

section number	name	locality (co-ordinates)	references
1	Bargella	along the south directed path contouring 1740 m (760 460/223 100)	ALLEMANN (1957, p. 216-217)
2	Beim Weiher	torrent E of the fishhatchery, 780-840 m (759 030/224 480)	
3	Efisaltobel	torrent E Schaan, 840-890 m (759 270/226 300)	BLASER (1952, p. 156)
4	Efiplanken-tobel	torrent ENE Schaan, 880-920 m (759 800/226 850)	BLASER (1952, p. 154)
5	Grossloch-bach	torrent ESE Planken, 1270-1350 m (761 100/227 640)	BLASER (1952, p. 152-153)
6	Weidenbach	torrent SE Garsella, 910-1030 m (~785 050/233 000)	BLUMENTHAL (1936, p. 462 ff.) RICHTER (1956, p. 362)
7	Steristobel	torrent E Garsella, 910-930 m (~785 360/233 460)	RICHTER (1956, p. 353) JACOBSHAGEN & OTTE (1968, p.102) OTTE (1972, p. 118)
8	Steintobel	torrent SE Sonntag, 850-1280 m	RICHTER (1956, p. 355) OTTE (1972, p. 119-120)
9	Blasenka	NW Blasenka peak, 1850-1940 m (~789 820/237 600)	BLUMENTHAL (1936, p. 453 ff.) MÜLLER (1973, p. 73)
10	Graue Furggel	gap between Zitterklapfen (S) and Grünes Gräserhorn (~791 480/238 560)	BLUMENTHAL (1936, p. 458) KALLIES (1961, p. 281)
11	Zellboden/ Läger Alpe	SE Bad Hopfreben, torrent NE point 1085 m, 1020-1100 m	KALLIES (1961, p. 279)
12	Üntschen-joch	Pass between Gross and Klein Walsertal, SE Schoppernau	BLUMENTHAL (1936, p. 466 ff.) KALLIES (1961, p. 278) MÜLLER (1973, p. 72)
13	Gemsteltal	S Bödmen (Kl. Walsertal), torrent S Hintere Gemsteltalalm, 1330-1380 m	MÜLLER (1973, p. 71)
14	W Rotspitz	Bsonderachtal S Hindelang, torrent SE Mitterhausalpe, 1190-1510 m	RICHTER (1963, p. 101)
15	NW Rotspitz	Bsonderachtal S Hindelang, torrent E Mitterhausalpe 1200-1520 m	RICHTER (1963, p. 101)
16	Seilers Gern	S Imberger Horn, ENE Strausberg-alpe, 1380-1480 m	MÜLLER (1973, p. 69)
17	Burgschrofen	Reichenbach N Imberger Horn, 1090-1190 m	RICHTER (1963, p. 99-100)

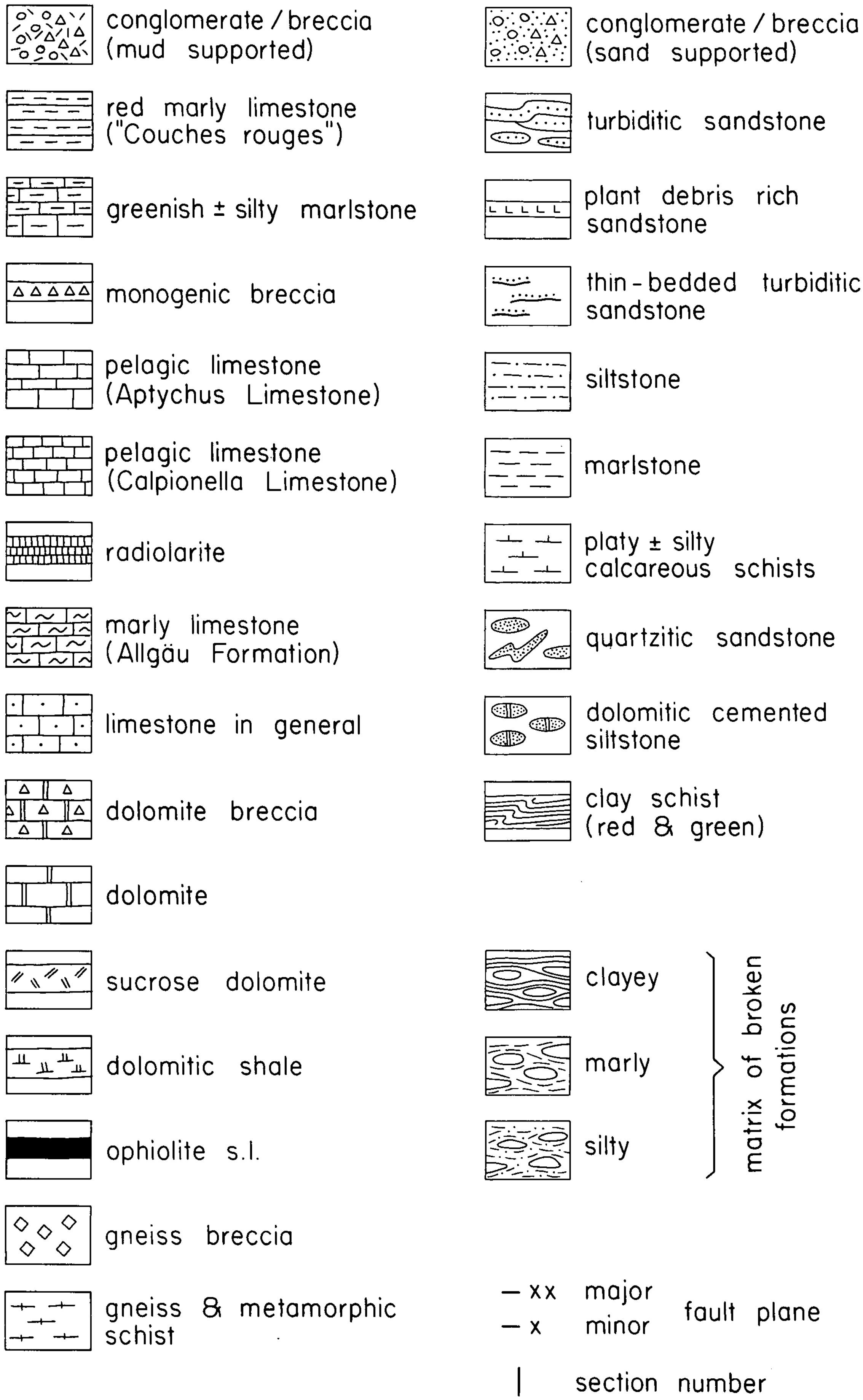


Fig. 4.
Legend for lithological sections.

between the localities of Kauf and Säss in Liechtenstein (coord. 761 120/222 610 [ALLEMANN, 1957]). The Verspala Flysch is represented by the samples PL 359 and PL 620 taken at the type locality (784 610/211 340). West of the Madrisa Horn at the Rätschenjoch, different flysch formations are included in the Arosa Zone. One example (no. WW 1778) is of interest for this study and is from coordinates 784 250/200 870 (see LÜDIN, 1987).

3.3. Grouping of Facies and Genetic Implications

In the Walstertal zone, a subdivision into four groups of tectonic-sedimentary associations can be made. As far as can be observed, these associations are always bounded by tectonic contacts. In the following we refer to Fig. 3 and Table 2 and Figs. 5 and 10 that illustrate the measured sections.

Flysch Formations

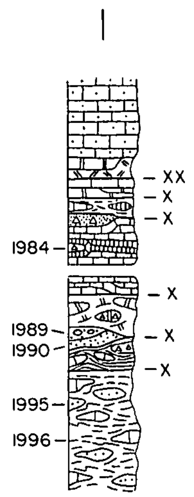
a) Flysch sequences are folded and faulted monogenic turbiditic deposits in which bedding of the sandstoenes and shales is preserved to a certain extent. These sequences can measure some tens to several hundreds of meters (sections 8, 9, 10, 12) or only a few meters (sections 6, 8, 15) in thickness. They can also be included as larger blocks in broken flysch formations (e. g. sections 4, 6)

b) Broken flysch sequences (cf. HSÜ, 1968) consist of lenticular, disrupted sandstone and turbiditic limestone beds embedded in an intensely shared matrix supposedly derived from originally interbedded turbiditic and hemipelagic marls and shales (e. g. sections 1, 4, 7, 14). In cases, however, lenses of extraformational origin are enclosed. For instance, along the base of the Walsertal zone flysch sequences are tectonically mixed with the underlying Rhenodanubic Flysch.

Melange of Type I

It consists of lenses and blocks, a few cm to serveral m across included in a sheared matrix of black, gray and greenish marls and shales (sections 3, 4, 7). The blocks are Triassic dolomites, limestones and quartzites, Jurassic marly limestones (Allgäu Beds), breccias, Radiolarites and Early Cretaceous Calpionella and Aptychus Limestones. The Triassic lithologies and the blocks from the Allgäu Formation must be derived from Austroalpine units, whereas for the Radiolarites and the Early Cretaceous pelagic limestones a South Pennine provenance is also possible. For one of this pelagic sequences a South Penninic provenance is proven by a block in which the oceanic stratigraphy of pillow lavas overlain by radiolarites and limestones is preserved (near section 7, see JACOBSHAGEN & OTTE, 1968).

The formation of this type of melange can be explained by shearing and tectonic mixing of Austroalpine and South Penninic elements with marls and shales older than or more or less coeval with the tectonic event. Tectonic overprint of older mass-flow deposits (pebbly mudstones, olisthostromes) is unlikely



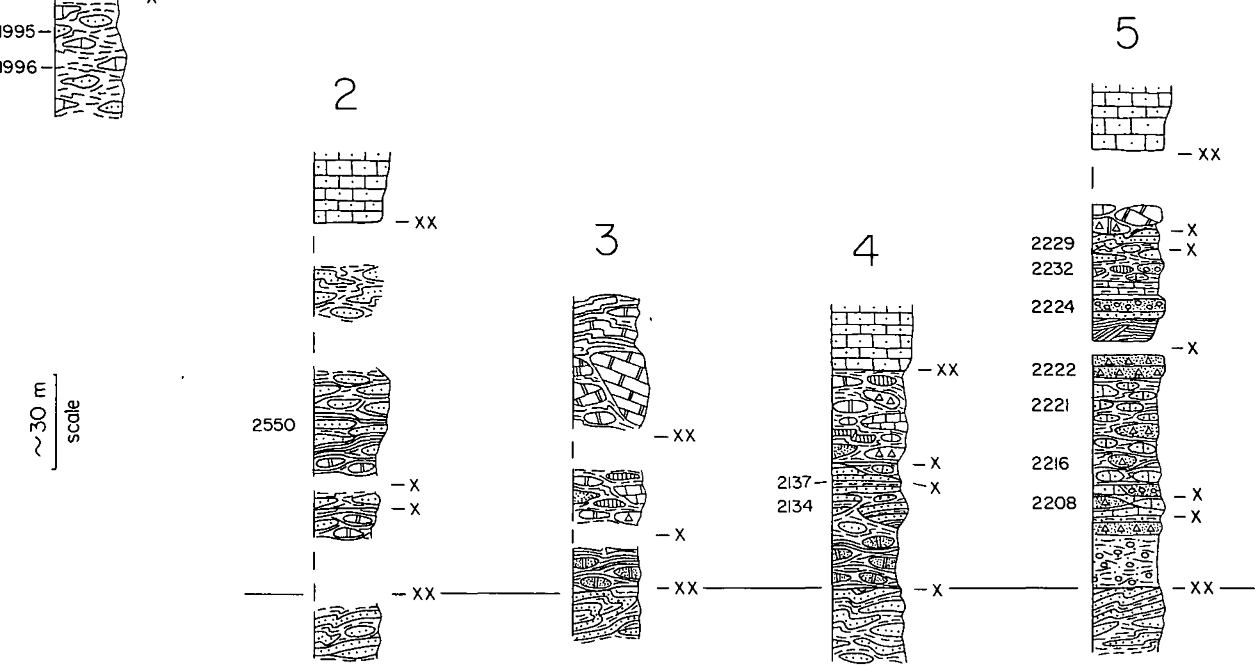


Fig. 5.
Lithologic sections in the Walsertal zone.
Reference line indicates tectonic contact between underlying Rhenodanubic Flysch and Walsertal zone above.

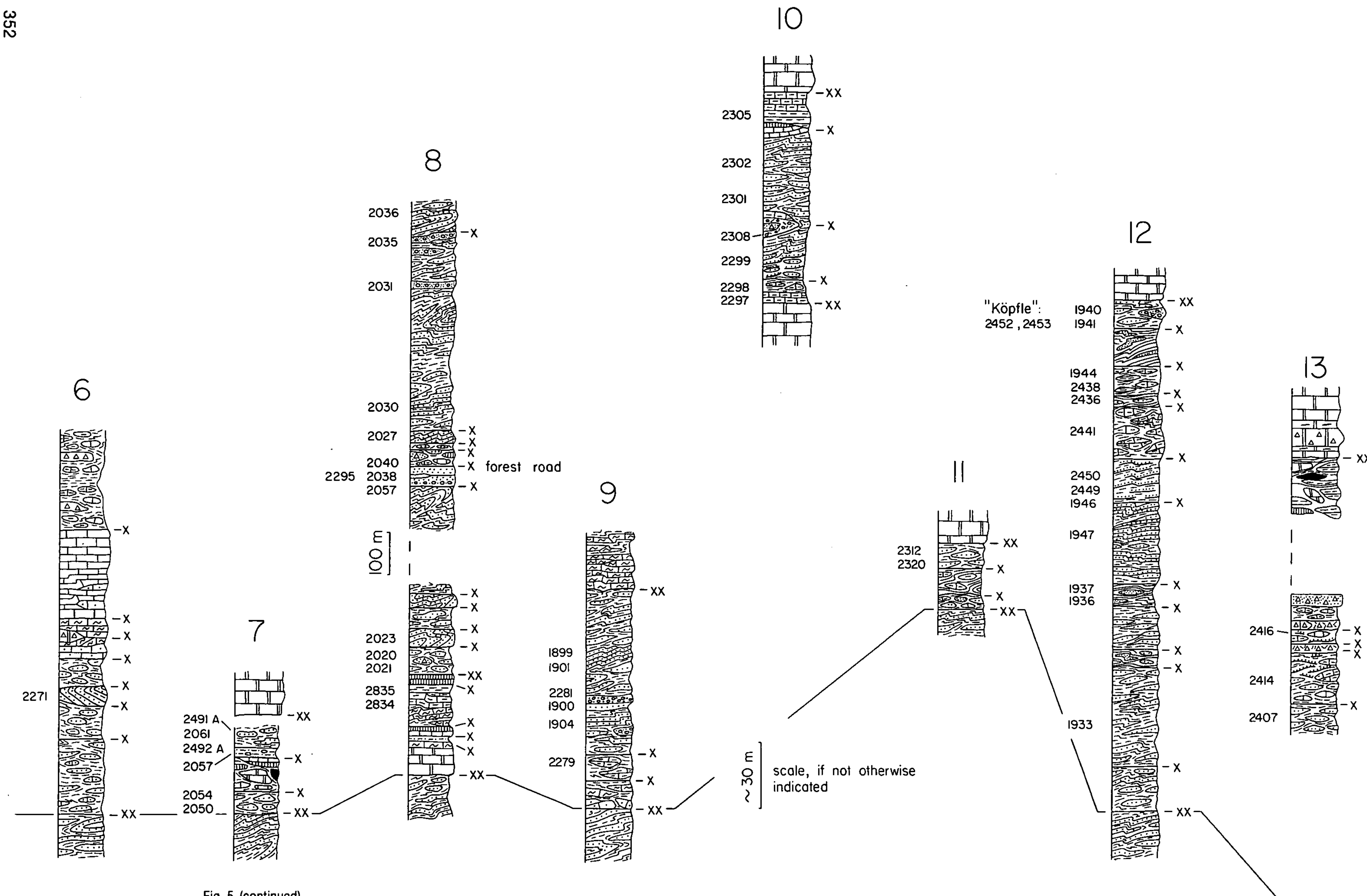


Fig. 5 (continued).

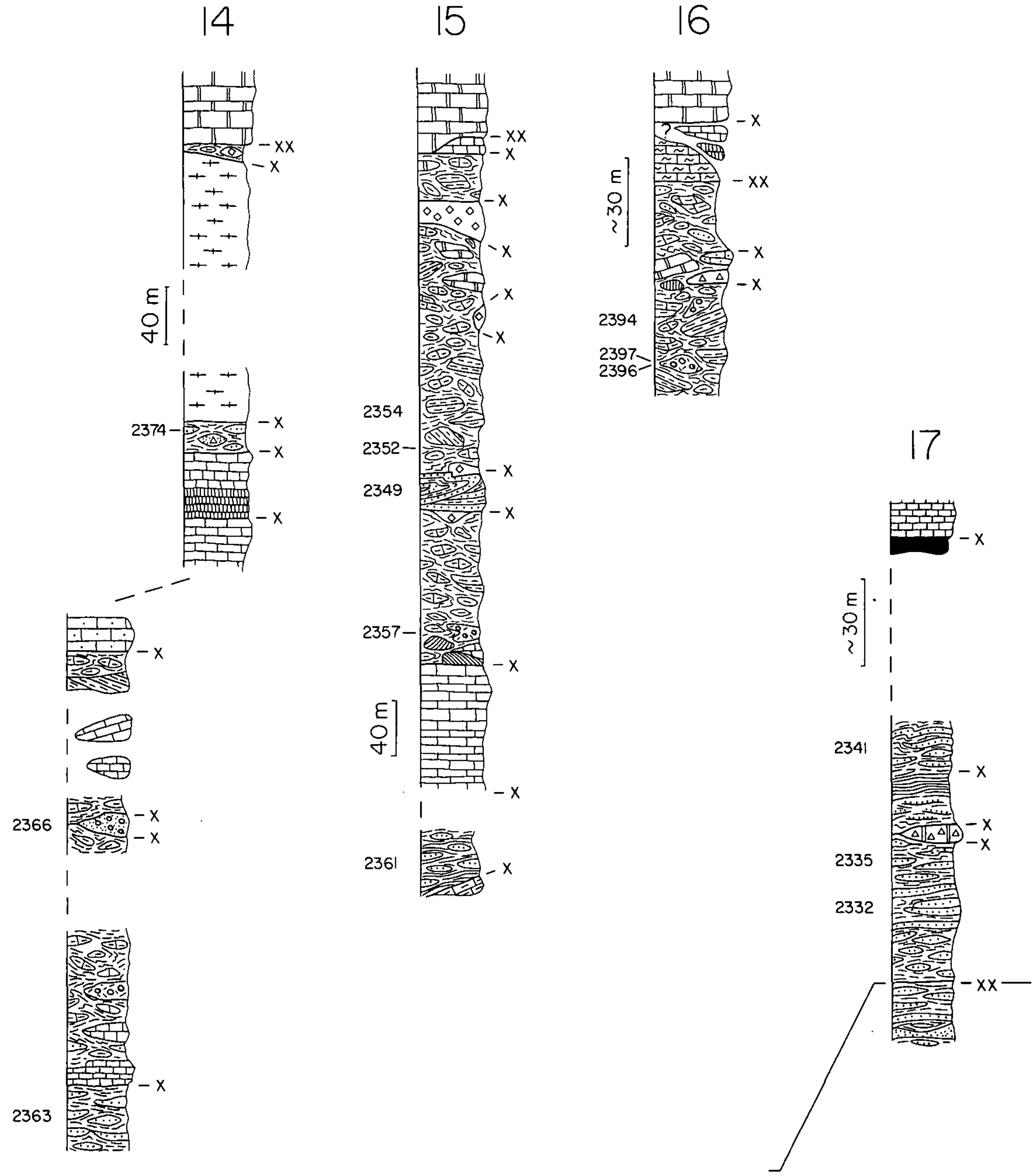


Fig. 5 (continued).

for this type of melange, because related ruditic deposits yielding the same elements and no sedimentary fabrics or sedimentary contacts between the different elements of this type of melange are recognized. This does not exclude that in this tpye of melange blocks of sedimentary breccias are tectonically included; in the case of the breccia encountered in section 4 the exclusively Triassic to middle Jurassic components suggest an age older than Cretaceous.

Melange of Type II

It contains mottled (bioturbated) greenish gray and red marly limestones and marlstones of "couches rouges"-type in different associations:

a) Sheared, elongated and folded lenses and blocks of marlstone (cm – several meters in size) are embedded in a gray and/or greenish gray marly sheared matrix (e. g. Sections 9, 12). The formation of this melange type is supposed to have occured by tectonic shearing of hemipelagic and pelagic sediments.

b) Lithologically more heterogeneous mixtures are composed of lenses and blocks (cm–dm) of greenish gray silty marlstones and marly limestones randomly distributed and oriented in a greenish/grayish laminated and deformed marly matrix. This matrix contains also larger blocks (up to several meters in size) of greenish gray and in particular of red marly limestones and blocks of mud-supported sedimentary breccias with intraformational clasts (see sections 15, 16, 10). From the random orientation of the more competent lenses, the more ductilly deformed sedimentary lamination and the presence of intraformational pebbly mudstones it can be concluded that sedimentary processes (submarine slumping, sliding of blocks, and debris flows) were active before melange formation, but tectonic overprint is obvious. Extraformational inclusions of gneiss, breccias, dolomites, and packages of flysch sandstones are considered to thave been entirely imbricated by tectonic processes.

c) In a third variety the presence of Calpionella and Aptychus Limestones and related breccias as blocks and lenses is characteristic. These are included in the common sheared greenish mottled marly limestones and marls (sections 6, 13, 14). In the breccias, the Early Cretaceous limestones can represent the only constituent (sections 6, 13) or can be associated with radiolarian chert fragments (section 13). Red marly limestones were not found with this melange type. The blocks of monogenic breccias point to early Cretaceous submarine? erosion and redeposition of pelagic formations, however, they were tectonically included into the younger hemipelagic marls and marlstones.

Individual Blocks and Slices
of meter to some 100 m size are bounded by tectonic contacts. These comprise a variety of lithologies including: gneiss and gneiss breccias of Austroalpine origin in sections 14, 15, Austroalpine Triassic dolomites and limestones and Lower to Middle Jurassic Allgäu Beds, Lower Austroalpine Saluver-like conglomerates, sandstones and associated limestones and marls (section 5), Calpionella/Aptychus Limestones and Radiolarite in various sections. Ophiolites generally are rare (sections 13, 17) and South Penninic Palombini and Lavagna Shales, which represent very important constituents in the Arosa zone, seem to lack in the Walsertal zone. It can be noted that Austroalpine elements are predominating over South Penninic ones. The time of inclusion into the Walstertal Zone cannot be determined directly but could have happened during different phases of thrusting in the Late Cretaceous and in the Tertiary.

3.4. Petrography of Flysch Sandstones

Heavy Minerals

The sandstones sampled in flysch and broken flysch sequences can, according to framework grain analysis and biostratigraphic data be grouped as follows (see Fig. 6):

○ Flysch 1
This group is composed of different turbidite sequences in which the heavy mineral spectrum is dominated by chromite s. l. After MÜLLER (1973) it is of picotite composition. Flysch 1a represents an important turbidite series and flysches 1b–e are individual flysches of local and smaller occurrence.

○ Flysch 2
contains two heavy mineral populations: Flysch 2a is also characterized by high chromite contents, but is well distinct by the presence of chloritoid, blue amphibole and lawsonite. Flysch 2b shows a spectrum dominated by tourmaline and about equal proportions in zircon and chromite. Some rare glaucophane grains are present (see also WINKLER & BERNOULLI, 1986).

○ Flysch 3
represents a group of sandstones containing higher proportions of tourmaline and zircon but low proportions of chromite. Subgroups 3a and 3b are distinguished by considerable contents of chloritoid in the latter one. However for some individual fine grained samples the attribution is less certain. This is mainly due to the mica-like hydrodynamic behaviour of chloritoid which is more abundant in fine grained parallel or ripple laminated sandstones.

○ Flysch 4
is a heterogeneous group of flysches containing few or no chromite, but variable amounts of the other heavy minerals.

○ Saluver-like sandstones
In contrast to most flysch sandstones the heavy mineral content of these sandstones lacks chromite and is strongly restricted to the most stable ones tourmaline, zircon and very subordinate amounts of rutile, brookite or anatase.

3.5. Framework Grain Analysis

The advanced diagenetic overprint of the sandstones is obvious. The general Fe-calcite cemented sandstones show growth of dolomite, quartz and baryte (very abundant in the heavy mineral separates) within the cement. Quartz grains are marginally replaced by dolomite. Palgioclase and aphanitic volcanic/hypabyssal rock fragments are also internally replaced by calcite/dolomite and sometimes only relic structures are observed. Carbonate clasts, especially dolomites are better preserved. K-feldspar was not detected except in one conglomerate sample from Flysch 3a near Üntschenjoch (locality Köpfl). There the K-feldspar is present in a micro-granitic clast and several individual relic grains mainly replaced by dolomite. This indicates that at least Flysch 3a must have contained originally an unknown amount of K-feldspar.

From these observations it arises that in the sandstones the original grain spectrum is not fully preserved. But we assume that all flysches underwent more or less the same diagenetic alterations and that sandstone petrography can be used for correlation of the regionally scattered flysch occurrences.

The basic Q-F-L triangle (Fig. 7) shows that the flysch sandstones can be classified as lithic arenites with about 30–60 % quartzeous grains. Flysch 4a and 4c have very high quartz contents. The Saluver-like sandstones plot also near the Q-pole, but contain different lithic clast types. Compared to the Q-F-L diagram, in the Qm-F-Lt triangle a slight shift towards the Lt-pole is observed in all samples. A considerable shift is exercised by the glaucophane-bearing flysch (2a) because of the especially high content of radiolarian chert fragments which here are included in the Lt-pole.

Diagrams calculated from lithic fragment types are significant for correlation purposes. From the Lvh-Ls-Lm ternary diagram (Fig. 7) it arises that the flysches of group 1 and Flysch 2a which are rich in chromite contain high proportions of sedimentary lithic clasts (Fig. 8). In Flysches 1a, 1b, 1c and 2a these are mostly micritic limestones of the Calpionella and Aptychus Limestone Formations (in coarse fragments calpionellids and radiolarians are observed) and less Triassic dolomite and sparitic limestones of Liassic affinity. In Flysches 1e, 2b and 4b dolomitic clasts are very frequent. This holds also for one sample (WW 2036) which is attributed to flysch 1a in the outcrop. Low chromite-bearing flysches (3a, 3b, 1d) contain less sedimentary lithic clasts (Fig. 8) but more vol-

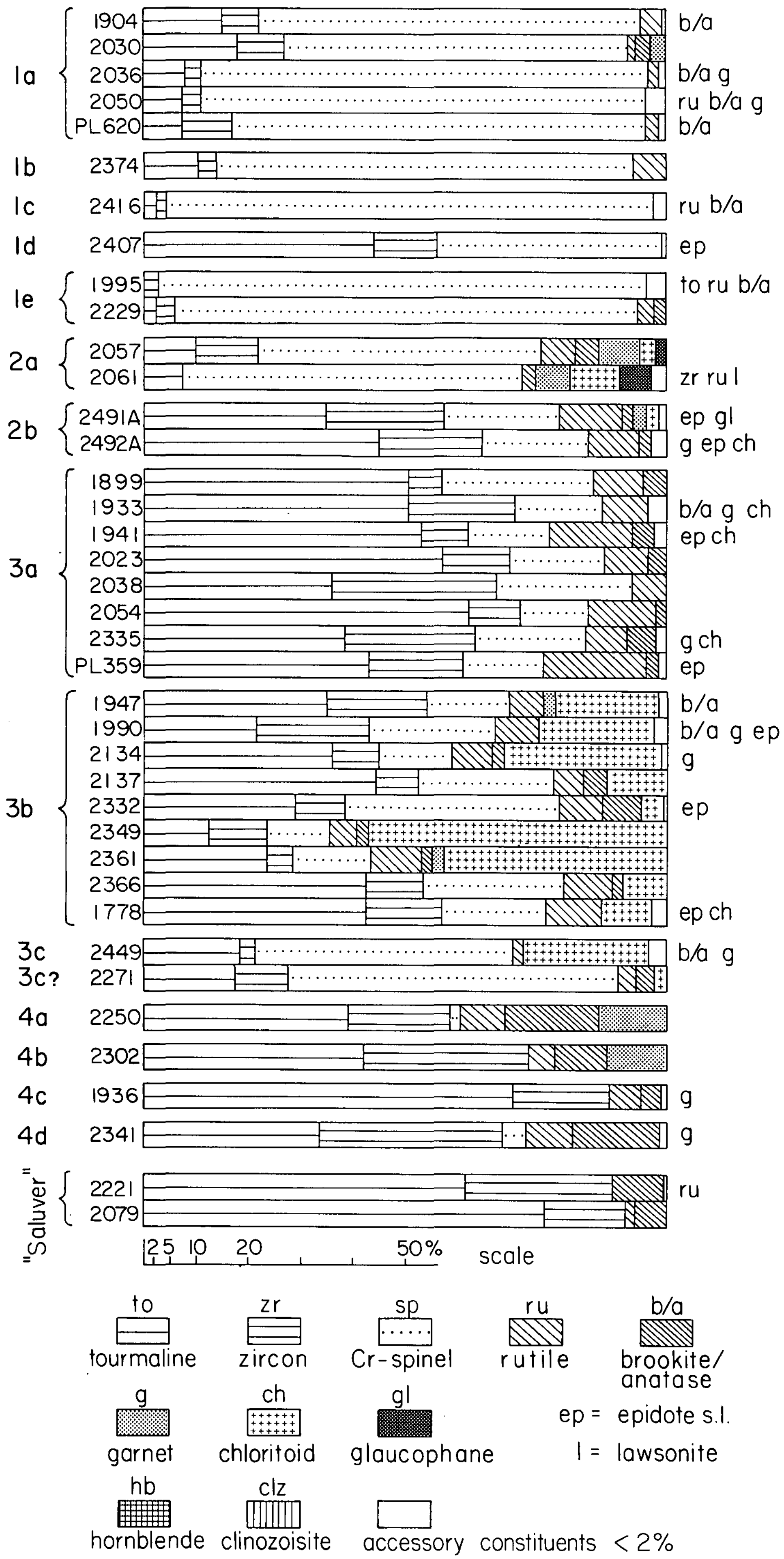


Fig. 6.
Heavy mineral assemblages in the Walsertal zone.
Numbers 1a–4d indicate flysch sandstone formations (see Figs. 7, 8, 9, 10).

Table 3.
Mean terrigeneous framework grain proportions in flysch formations of the Walsertal zone (standard deviations between brackets).

formation	1a	Verspala	1b	1c	1d	1e	2a	2b
samples	1904,2020 2030,2036	PL 620	2374	2414 2416	2407	1995	2061	2491 A 2492 A
1. Q_m	24.9 (10.9)	36.6	3.3	39.3	51.6	26.3	29.3	33.3
2. Q_p	0.8 (0.8)	1.3	0.3	1.6	1.0	0.6	2.6	0.8
3. Q_T	2.6 (0.7)	1.6	0.0	3.8	1.0	4.0	1.3	0.6
4. C	2.2 (0.8)	1.3	1.3	1.3	0.0	0.0	7.0	3.3
5. P	11.2 (4.7)	9.6	2.3	9.7	13.3	21.0	6.3	17.8
7. L_{vh}	13.7 (2.7)	12.3	5.6	21.0	15.6	19.0	15.3	18.4
8. L_s	40.2 (18.3)	25.6	87.0	17.0	9.6	23.3	31.0	19.3
9. T_{QM}	2.2 (0.6)	5.3	0.0	2.3	3.0	1.0	2.0	3.1
10. M_p	1.0 (1.3)	1.0	0.0	0.5	1.0	1.0	2.3	1.2
M	1.1 (0.4)	5.0	0.0	2.8	3.6	3.6	2.6	1.8

	3a	Verspala	3b	Rätschen-joch	3c
	1899,1933,1941,2027, 2038,2040,2312,2320, 2335,2453	PL 359	1990,2134,2137, 2349,2361,2363	1778	2449
Q_m	37.9 (8.1)	39.3	45.9 (6.9)	49.3	37.9
Q_p	1.1 (0.7)	1.3	1.8 (1.1)	2.0	1.6
Q_T	1.8 (1.0)	2.3	2.2 (1.3)	3.3	4.0
C	1.1 (0.8)	0.6	1.1 (0.7)	0.3	1.8
P	*16.8 (5.0)	20.3	13.0 (3.0)	10.3	13.3
L_{vh}	26.5 (5.2)	22.3	19.8 (4.4)	16.3	15.9
L_s	8.9 (5.8)	8.0	4.1 (3.7)	0.3	15.4
T_{QM}	2.8 (1.3)	3.6	6.1 (3.5)	9.3	5.6
M_p	0.7 (0.7)	0.3	0.6 (0.6)	2.0	0.5
M	2.3 (2.1)	1.6	5.2 (2.4)	6.3	3.5

	4a	4b	4c	"Saluver"		radiolarite breccia
	2250	2299,2301	1937	2079	2221	1984
Q_m	70.0	53.7	93.7	72.6	78.0	12.3
Q_p	0.3	0.0	0.7	0.6	0.6	0.0
Q_T	2.6	1.0	2.4	3.6	6.6	2.0
C	1.3	1.5	0.7	2.0	0.0	10.3
P	14.3	10.2	1.0	**6.3	3.6	5.3
L_{vh}	6.6	5.0	1.3	14.6	4.0	3.0
L_s	3.3	27.2	0.0	0.0	5.0	64.3
T_{QM}	0.0	0.3	0.0	0.0	1.0	2.3
M_p	0.3	0.5	0.0	0.0	1.0	0.0
M	1.0	0.6	0.3	0.0	0.0	0.3

Triangles in Fig. 5:

$Q - F - L$: (1+2+3+4) – (5) – (7+8+9+10)
$Q_m - F - L_t$: (1) – (5) – (2+3+4+7+8+9+10)
$L_q - L_{vh} - L_{sm}$: (2+3+4) – (7) – (8+9+10)
$L_{vh} - L_s - L_m$: (7) – (4+8) – (2+3+9+10)

* small amounts of K-feldspar
** plagioclase and K-feldspar

canic/hypabyssal and metamorphic lithic rock fragments. The distinction of Flysch 3b and 3a is based on different chloritoid contents and can be correlated with the slightly higher amounts of metamorphic lithic grains in the chloritoid-bearing Flysch 3b (see triangle Lvh-Ls-Lm in Fig. 7).

Two samples from the Verspala Flysch (PL 620, PL 359) and one sample from the Rätschenjoch (WW 1778) can be correlated with the flysch populations 1a, 3a and 3b respectively. The Turonian age of the Verspala Flysch (OBERHAUSER, 1983) is in line with our dating in Flysches 1a and 3a.

A fine breccia, interbedded with Radiolarites (section 1, Bargella, sample WW 1984) contains in decreasing order dolomitic, radiolarian chert and continental basement rock fragments. The high abundance of radiolarians in the matrix points to a Jurassic age of the breccia.

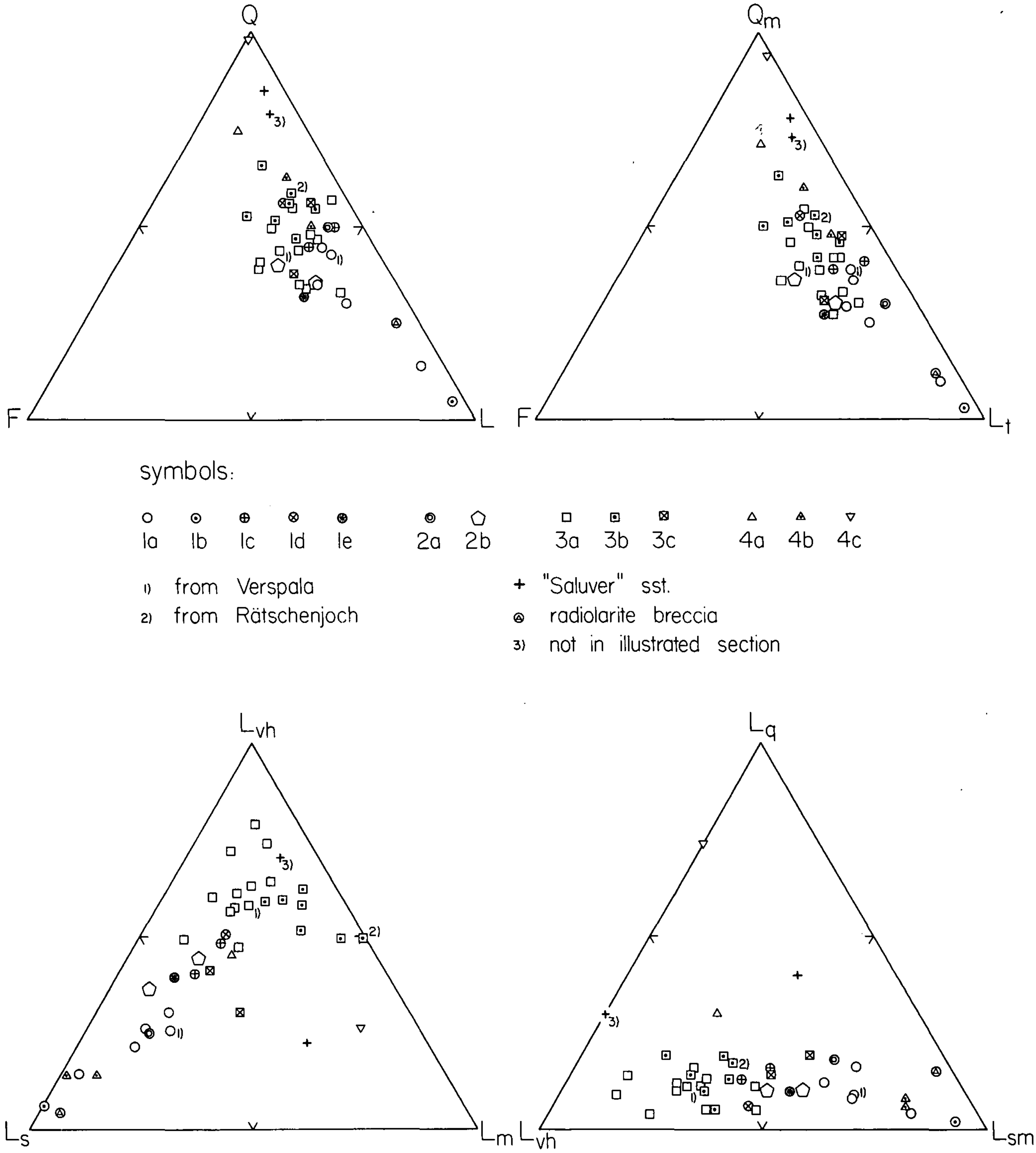


Fig. 7.
Triangular plots comparing detrital modes for flysch formations in the Walsertal zone (for calculation see Table 3).

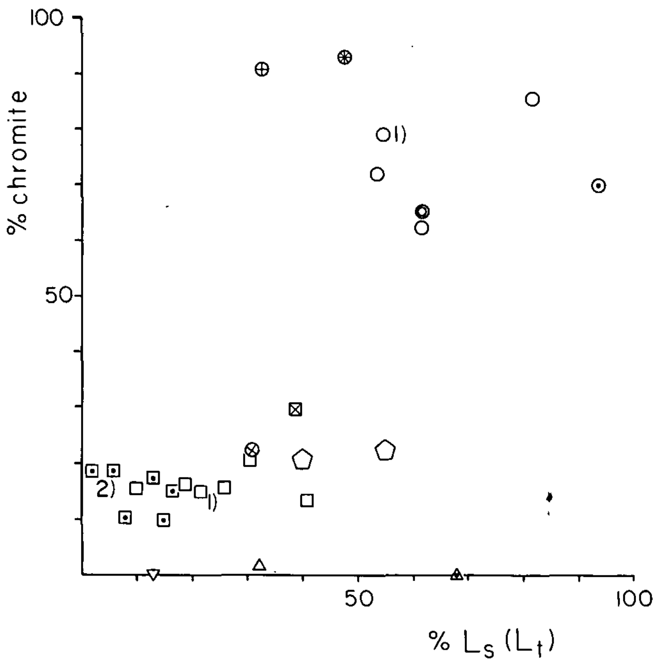


Fig. 8.
Correlation diagram between proportions of chromite and sedimentary lithic clasts (from total lithic clasts) in flysch sandstones of the Walsertal zone (symbols see Fig. 7).

3.6. Conglomerate components

In conglomerates and breccias the following groups of rock fragments are distinguished (Tab. 4):

Sedimentary rock fragments

- Quartzous sandstones, slightly metamorphic, consisting of quartz, some feldspar and lithic fragments in a mica-bearing matrix and partly cemented by silica (Permo-Triassic)
- Dolomites, mainly with a micritic and sparitic texture, minor dolomitic limestones, dolomitic oolithes and bio-pel-sparites (Triassic)
- Sparitic, spongiolithic, siliceous and marly limestones mostly of Liassic affinity
- Radiolarian chert of Middle-Late Jurassic
- Limestones with calpionellids, radiolarians and sometimes Saccocoma, respectively very fine grained fossil free micritic limestones of similar texture (Late Jurassic – Early Cretaceous)

Basement rock fragments

- Tectonic quartzites of variable granulometry
- Gneiss and metamorphic schists consisting of quartz, feldspar and different micas (muscowite, chlorite, biotite) in variable proportions, and phyllites
- Porpyhries and volcanic fragments with a fine grained matrix with phenocrysts of quartz, feldspar, mica etc. and some ignimbrite grains.
- Microcrystalline magmatic rocks with fine grained quartz, feldspar (mostly plagioclas) and mica aggregates
- Spilite consisting of plagioclase laths in a chlorite matrix with opaque inclusions.

The results of the conglomerate component analysis are listed as mean values in Table 4. From Flysch 3b only one conglomerate sample was available, but the composition grossly seems to be similar to that of Flysch 3a. The very different heavy mineral composition of the most abundant Flysches 3a and 1a is reflected by the conglomerate composition: Flysch 1a contains mainly sedimentary, in particular Late Jurassic – Early Cretaceous limestone pebbles whereas in Flysch 3a Triassic dolomite and continental basement rock fragments prevail.

In the flysch conglomerates no serpentinite fragments were recognized, even if their presence in the source area is suggested by the occurrence of chromite mineral grains in the heavy mineral fraction. Serpentinites seem to be of too low resistance to be preserved as big clasts. In sandstones few grains were observed and grouped with the volcanic hypabyssal rock fragments.

The Saluver-like series, particularly those of section 5 contain mostly Triassic dolomite and Permo-Triassic quartzous sandstone fragments.

Table 4.
Components of conglomerates (in percent) in flysch sequences of the Walsertal zone.

pebble types	Flysch 3a	Flysch 3b	Flysch 1a	"Saluver"
sample number	1900,1940,2037, 2224,2232,2281, 2295, 2452	1989	2030,2031,2035	2208,2216,2222
Calpionella & Aptychus Lst.	3.5	2.0	73.0	0.0
radiolarite	5.5	1.0	0.5	0.0
sparitic & spongolithic siliceous limestone	2.0	0.0	7.0	0.0
dolomite (micrite & sparite)	45.5	25.0	15.0	64.0
metamorphic sandstone	3.0	5.5	0.0	23.5
"spilite"	2.0	0.0	0.0	0.0
tectonic quartzite	11.0	13.0	0.5	9.5
gneiss & phyllite	6.5	21.5	3.5	1.5
porphyry & volcanic	18.5	25.0	0.5	1.5
microcrystalline magmatic rock	2.5	7.0	0.0	0.0

3.7. Age control

Earlier biostratigraphic data from the Walsertal zone generally indicated Aptian/Albian to Cenomanian ages for the terrigeneous sequences (OTTE, 1972; MÜLLER, 1973). We can present new biostratigraphic data based on planktonic foraminifera (det. M. CARON) recognized in carbonate stained thin sections. Because of the generally high diagenetic overprint, calcareous nannoplankton and foraminifera are only poorly preserved in marls and shales.

The biostratigraphic results are listed in Table 5. The calibration of planktonic foraminifera follows ROBASZYNSKI & CARON (1979) and that of the calcareous nannoplankton PERCH-NIELSEN (1978). It should be noted that the ages of the turbiditic flysch sequences are de-

Table 5.
Biostratigraphic data from the Walsertal zone.

formation	section: sample no.	foraminifera	nannoplankton	age
Flysch 1a	8 Steintobel 2020,2021,2031, 2030,2036	Hedbergella spp., Ticinella spp., Whiteinella sp., Rotalipora spp., Globotruncana pseudolineiana ? Marginotruncana spp. (rich assoc.)		Late Turonian - - Coniacian
Flysch 1b	14 W Rotspitz 2374	assoc. of Rotalipora spp., Praeglobotruncana gibba		Cenomanian (- E. Turonian)
Flysch 1c	13 Gemsteltal 2416	Ticinella spp., Rotalipora spp., Planomalina praebuxtorfi, Planomalina buxtorfi		L. Albian - Early Cenomanian (Vraconian)
Flysch 1e	1 Bargella 1996	rich assoc. of Rotalipora spp. (turbiditic sorting?)		Middle? Cenomanian
Flysch 3a	8 Steintobel 2023,2027	Rotalipora spp. with R. cf. cushmani, R. cushmani, Praeglobotruncana gibba, Whiteinella sp.		(L. Cenomanian) - - E. Turonian
	9 Blasenka 1901		Eprolithus spp., E. floralis Quadrum gartneri	
Flysch 2a	7 Steristobel 2061	Rotalipora spp. with R. appenninica, R. reicheli, Marginotruncana spp. with M. sigali, M. schneegansi		L. Turonian - - E. Coniacian
Flysch 3c	12 Üntschenjoch 2449	rich assoc. of Ticinella spp. and Hedbergella spp. with T. roberti and T. distalis		Late Albian
	1946		Vekshinella matalosa, Eiffellithus sp., E. floralis, Glaucolithus sp.	
Mélange II				
greenish-gray silty marlstones	12 Üntschenjoch 2441 15 NW Rotspitz 2352	Hedbergella spp., Ticinella spp., Rotalipora spp.		Aptian - Albian (Cenomanian)
greenish-gray marly limestones	10 Graue Furggel 2297,2298 9 Blasenka 2279 12 Üntschenjoch 1944	Rotalipora spp. with R. appenninica, R. brotzeni, R. montsalvensis, R. cushmani, R. greenhornensis, R. deckei-reicheli		Cenomanian
	8 Steintobel 2834,2835	Hedbergella spp., Rotalipora spp. with R. appenninica, R. cf. brotzeni, R. montsalvensis, R. cf. reicheli, Praeglobotruncana stephani, P. gibba		Early Cenomanian
red marly limestones	12 Üntschenjoch 2436,2438 10 Graue Furggel 2305 16 Seilers Gern 2394 15 NW Rotspitz 2354	Hedbergella spp., Rotalipora spp., R. ticinensis, R. appenninica, R. reicheli, R. greenhornensis, Praeglobotruncana spp., P. gibba		(L. Albian) - Cenomanian p.p. Vraconian
pebbly mudstones	15 NW Rotspitz 2357	Rotalipora spp. with R. appenninica, R. gandolfi, R. brotzeni		? Early Cenomanian
	10 Graue Furggel 2308 16 Seilers Gern 2396, 2397		Eprolithus spp., E. floralis, E. apertior?, Braarhudasphaera regularis, Radiolithus planus, Eiffellithus sp., Prediscosphaera sp.	(Albian) - Cenomanian

rived from reworked faunas and we therefore are dealing with maximum ages.

The youngest faunas were recognized in Flysches 1a and 2a with the genus *Marginotruncana* ssp. As no younger forms are comprised in these flysches they can be classed into the Late Turonian – Early Coniacian interval. The presence of *M. sigali* and *M. schneegansi* in Flysch 2a can be correlated with the *Marginotruncana schneegansi*-zone covering the Late Turonian to earliest Coniacian (ROBASZYNSKI & CARON, 1979). In the thin-bedded facies of Flysch 3a in the Steintobel and Blasenka sections (resembling the "Bändermergel" of GAUPP, 1980) an association pointing to a Late Cenomanian – Early Turonian age was found.

This is not in agreement with GAUPP (1980) who correlates the Middle Albian – Early Cenomanian Losensteiner-Schichten included into the Kalkalpine Randzone with sandstones in these outcrops. From Flysch 3b no fauna was available.

Some flysches of local occurrence could be dated as listed in Table 5. They reveal generally Late Albian to Cenomanian ages. Flysch 1c can be classed in the so-called "Vraconian" (Latest Albian).

In the melanges of type II the oldest terms recognized are Aptian–Albian greenish gray silty marlstones. The greenish and red marly limestones of Couches rouges affinity revealed Cenomanian ages. The likewise Cenomanian faunas comprised in the matrix of the Couches rouges-bearing pebbly mudstones indicate a more or less contemporaneous reworking of marlstones by gravity flows.

From melange of type I no direct biostratigraphic data are available. However, the youngest lithologies comprised in it are Late Jurassic – Early Cretaceous Calpionella and Aptychus limestones and a Cretaceous age of formation can be assumed.

3.8. Summary of the Lithological and Petrographical Characteristics of the Flysch Formations

Based on the data and correlations presented earlier, the flysches recognized in the Walsertal zone can be defined according to lithology and petrographic composition. Turbidite facies is described in terms of MUTTI & RICCI LUCCHI's (1975) classification. Two groups of flysch occurrences are distinguished (see Figs. 5, 6, 7):

3.8.1. Flysch Sequences of Regional Occurrence

These occur generally as relatively little tectonized turbiditic sequences of considerable thickness and more rarely as broken formations.

Flysch 1a shows a variety of gray carbonate rich turbidite facies: medium bedded turbidites of facies C2 and D1–D2, but also pelitic turbidites (facies D3) up to several m thick, floored by a very thin sandy base. The latter beds are in the same sequence with coarse tail graded sandstones (B, C1), conglomerates and clast supported breccias (A). Best outcrops are met in section 8, upper part.

The heavy mineral content is largely dominated by chromite (60–80 %), lithic carbonate fragments (mostly Calpionella and Aptychus Limestone) are very abundant, baryte occurs in moderate proportions, some chessboards twinned plagioclase grains. Late Turonian – Early Coniacian.

Flysches 3a and 3b are grouped together because their lithologies are very similar. However, on fresh broken surfaces, the sandstones of Flysch 3b have more greenish aspect. Three facies can be distinguished:

1) Very thin-bedded (in the range of some cm) fine grained turbidites of facies D2–D3 occurring in bundles of several to some tens of meter thickness (3a: sections 8, 9; 3b: 3, 12). These particular sediments resemble closely the "Bändermergel", described by GAUPP (1980) from the Losensteiner Schichten.
2) Medium bedded and grained turbiditic sandstones in alternation with gray turbiditic and green hemipelagic pelites (Facies C2, D1–D2, respectively G). Sediments of this type occur in Flysch 3a of section 12, lower part. In Flysch 3b also thick carbonate free green and red shales and some red marly shales are associated with them (sections 3, 15, 17). In sections 3 and 4 several meters thick intervals of greenish, reddish and gray silty shales with lenses of dolomite cemented very fine grained sandstones occur. This facies probably represents the basal member of Flysch 3b.
3) Conglomerates, pebbly sandstones (A1) and very coarse grained, coarse tail graded and amalgamated sandstones (B1, C1). From Flysch 3b only few occurrences are known (sections 1, 14). In Flysch 3a these lithologies are present in sections 8, 12 and at the locality "Köpfl" near 12.

   In Flysch 3a tourmaline is the predominate heavy mineral (45–70 %), while chromite decreases to 15–30 %. Continental basement and dolomitic rock fragments are abundant, baryte occurs in variable proportions. In the thin-bedded facies 1 an Early Turonian age is indicated.

   In Flysch 3b the mineral content is qualitatively similar to Flysch 3a, but in addition abundant chloritoid (up to 60 %) and a higher abundance of metamorphic rock fragments is noted, baryte occurs also in variable proportions.

3.8.2. Flysches of Local Occurrence

Flysch 1b occurs in a broken formation (section 14) and consists of carbonate rich marls with light gray sandstone lenses (several cm to some tens of cm in size). Pebbly mudstones with intrabasinal marl- and sandstone clasts are associated. Another conglomerate type also present in the same outcorp differs in its composition from the sandstones yielding mainly dolomitic pebbles. The heavy mineral fraction consists of 80 % chromite. Sedimentary lithic fragments (Calpionella and Aptychus Limestone) are very frequent, serpentinite grains are present. A Cenomanian age can be indicated.

Flysch 1c occurring in section 13 has a twofold appearance: bundles of thin-bedded (some cm) graded, soft sandstones to siltstones (facies D2, D3) are associated with lenses of hard, medium grained turbiditic sandstones. Both lithologies are intensely sheared with marly shales known from melange of type IIc.

The sandstones are very rich in chromite, rich in sedimentary lithic clasts, and show a notable presence of serpentinite grains and chessboard twinned plagioclases. A Late Albian – Early Cenomanian age is indicated.

Flysch 1d occurs in section 13 below Flysch 1c and associated rocks. It consists of lenticular, fine to coarse grained carbonate rich turbiditic sandstones embedded in presumably turbiditic, gray dark weathering, sheared marly shales. Flysch 1d has a relatively montonous heavy mineral content of equal proportions of tourmaline and chromite with minor zircon.

Flysch 1e is present in the lowermost part of section 1 as sheared, dark, calcareous marls and thin layers of graded sandstones to siltstones. These sediments include lenses of turbiditic sandstones and micritic limestones. The latter are light to medium gray and show a particular orange weathering. This flysch is rich in chromite and in lithic fragments of micritic limestone and dolomite in equal proportions. It is probably of Middle Cenomanian age.

Flysch 2 (see WINKLER & BERNOULLI, 1986) is preserved in section 7 as a broken formation. The lower three meters of it consist of dark greenish gray, silty and marly shales with small lenses (some cm) of green, glauconitic quartzites and very fine grained sandstones. The upper part consists of strongly sheared, greenish-brown, marly shales with lenticular, disrupted fine to medium grained turbiditic sandstones. In this part two petrographically different sandstone types (2a and 2b) are present, but they are macroscopically very similar. The silty shales present in the lower part, from heavy mineral evidences (sample WW 2075) can be correlated with the sandstones of type 2a. Flysch 2a yields glaucophane and lawsonite, but chromite predominates the heavy mineral fraction, sedimentary lithic clasts (micritic limestones) and radiolarian chert fragments are very abundant, some serpentinite grains are present. A Late Turonian – Earliest Coniacian age can be indicated. In Flysch 2b tourmaline dominates the heavy mineral spectrum, only few grains of glaucophane are present. Volcanic/hypabyssal and sedimentary lithic fragments (mostly dolomitic) occur in approximately equal amounts. Baryte is very abundant.

Flysch 3c is a slightly folded and faulted flysch in section 12. It shows fine grained small-scaled rippled sandstones, siltstones and marls (facies D2, D3) representing deposits of diluted turbidity currents. This flysch is rich in chromite (50–60 %) and yields minor amounts of tourmaline and chloritoid. Sedimentary lithic fragments are slightly predominant. Some serpentinite grains are present. The age is Late Albian.

Flysch 4a is the prevailing formation in section 2 and consists of fine grained turbiditic sandstones (10–30 cm, facies D1–D3), partly with calcareous tops, and gray turbididitc marly shales in alternation with green and gray carbonate free hemipelagic pelites (G). From the generally normal polarity of the turbiditic beds, it is supposed that the thick, green and red pelites in the lower portion of the outcrop are the basal member of the flysch. These shales contain also small lenses of slightly dolomitic terrigeneous limestones. The quartzous sandstones are slightly chromite bearing. Glauconite and baryte are abundant.

Flysch 4b occurs in section 10. It shows a thickening upward sequence grading up from highly bioturbated siliceous hemipelagic shales with very thin silty layers (facies G) into thin to medium grained and bedded turbiditic sandstones and shales (facies D, rarely C2).

The lower siliceous shales show brown to black weathering. It consists of strongly silicified chromite free sandstones but is rich in tourmaline and zircon. The main detrital constituents are micritic dolomite clasts. Uncertain attribution!

Flysch 4c is mainly observed in section 12 and consists of brown and black weathering turbiditic, highly quartzous sandstones (D1) embedded in red and green clays (facies G). The clays make up the larger part of this flysch. The quartzeous layers resemble the "Ölquarzit" known from younger South Penninic Flysches (e. g. WINKLER, 1983; WINKLER et al., 1985, Schlieren-Flysch, Wägital-Flysch). Although this flysch is in close contact with Flysch 3a, the genetic relations are not sure.

The quartzitic sandstones do not yield chromite. The heavy mineral fraction is strongly dominated by tourmaline. Glauconite is abundant. Uncertain attribution.

Flysch 4d is recognized in section 17 as medium bedded (20–30 cm) but very fine grained and calcareous turbiditic sandstones and gray marls (D1, D2), topped by green carbonate free shales (G). Below this, a calcareous and silty turbidite sequence (facies D3) grading upward into red carbonate free shales is exposed. This facies is tentatively correlated with Flysch 4d.

The heavy mineral fraction contains equal proportions of zircon and tourmaline, few chromite (5 %) and considerable amounts of apatite. Glauconite is rare. Because of fine grain size no framework analysis is available.

3.9. The Nature of the Inferred Source Terrains

As the sedimentary clasts contained in the flysch sequences can be correlated with South Penninic and Austroalpine sediments it seems likely that the various basement rock fragments are derived from the Jurassic South Penninic oceanic basement and from the Palaeozoic basement of the Austroalpine distal continental margin. We have no clear evidence for the erosion of a synorogenic volcanic arc associated with the active continental margin during the Cretaceous. From our petrographic data it results that the source terrains of the flysches were of variable composition.

1) Flysch sandstones with high amounts of chromite in the heavy mineral fraction (1a, b, e, 2a) were supplied from source terrains where oceanic basement rocks were largely dominating. This interpretation is supported by the low amounts of continental basement derived clasts. To the other hand they contain high proportions of Late Jurassic – Early Cretaceous limestone clasts (see Fig. 8). The detrital grain assemblage therefore suggests source terrains which were mainly composed of South Penninic ophiolitic basement and its sedimentary cover. Detrital glaucophane and lawsonite mineral grains recognized in Flysch 2a (WINKLER & BERNOULLI, 1986) indicate that also high-p/low-T metamorphic rocks were exposed in one source terrain.

2) A much greater proportion of Austroalpine continental basement rocks in the source areas is suggested from Flysches 3a and 3b. The continental basement, in contrast to the Mesozoic carbonate sequences, supplied diagnostic heavy minerals (tourmaline, zircon) to the flysches and chromite contents were highly diluted (see Fig. 8). Furthermore, we observe higher amounts of Triassic dolomite clasts in the sandstones and conglomerates.
The Austroalpine continental basement is represented by felsic and intermediate magmatic respectively metamorphic rock fragments. The abundance of chloritoid in Flysch 3b and 3c points to the exposure of low-grade metamorphic phyllitic rocks. They could be derived from Palaeozoic formations, but because of the presence of high-p/low-T minerals an Early Alpine age of the chloritoid cannot be excluded (see later discussion).
3) Beside these two well distinct classes, a group with mixed detritus is distinguished. Its sandstone composition points to more or less equal amounts of oceanic and continental rocks in the source area (Flysches 1c, 2b, 4d).
4) Because of the uncharacteristic petrographic composition of Flysches 4a, 4b, 4c their relation to the proposed configuration of the Mid-early Late Cretaceous source terrains must be doubted (see later discussions).
5) The Saluver-like sandstones and breccias are characterized by a monotonous and ultrastable heavy mineral assemblage of continental and recycled origin. We associate the Saluver-like sandstones and breccias with Jurassic extensional tectonics and fault scarps. This is supported by the exclusive presence of Palaeozoic and Triassic clasts. For this reason, probably the chromite-free and exclusively dolomite clast-bearing Flysch 4b should be included here.

3.10. Sandstone Composition and Plate Tectonic Environment

An ultimate goal of DICKINSON's (1970) modal analysis of sandstones is the recognition of the plate tectonic setting in which the sandstones were deposited (DICKINSON & SUZCEK, 1979; DICKINSON, 1985). It can be argued that this model is strongly generalizing, nevertheless an attempt is made to compare it with our framework grain data. In Fig. 9 we have recalculated and plotted our data in the ternary diagramm of DICKINSON (1985) leaving out the lithic carbonate clasts. It should be noted, however, that in midpoint ribbon-counting the quartz contents are slightly lower (1–6 % from own comparisons) compared to pointcounting and plagioclase contents slightly higher (4–9 %). Taking also into account these differences, our flysch data points fall into the upper part of the "recycled orogen" field (Fig. 9). DICKINSON (1985) considers different compressional settings providing this kind of sands. Of these the "suture belts" where structurally juxtaposed sequences of oceanic and continental origin are exposed to erosion match well with our interpretation of the flysch source terrains.

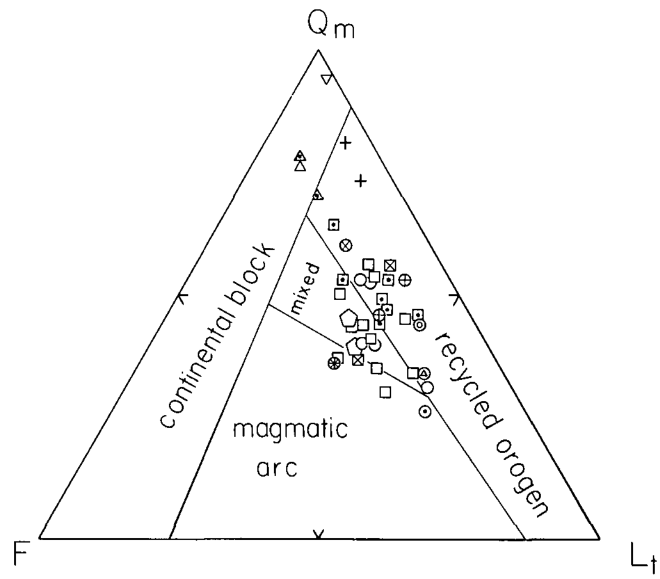


Fig. 9.
Framework grain data of the sandstones in the Walsertal zone compared with interpretated plate tectonic settings (after DICKINSON, 1985).
Symbols as in Fig. 7.

3.11. Compilation of Data and Interpretations

The Walsertal zone comprises flysch and broken flysch formations of a large variety in turbiditic facies and mineralogical composition (see Fig. 10). These sediments are imbricated with melange formations and individual slices of pre-Late Cretaceous Austroalpine and lesser South Penninic lithologies.

All Flysches, except Flysch 4b and 4c are chromite-bearing. The palaeogeographic position of these two formations is not clear, if the presence of chromite is considered as the main characteristic of turbidite deposits related to the South Penninic Austroalpine convergence zone. Flysch 4c resembles to some extent the argillaceous/quartzitic interval known from the Maastrichtian Fanola Series in the area (KALLIES, 1961). Flysch 4a contains some (second cycle?) chromite, but its relation to the Cretaceous tectonic event is not certain. Some poorly preserved foraminifera would point to a Tertiary age (personal communication M. CARON).

Melange I is considered to represent a purely tectonic assemblage of Austroalpine and South Penninic elments and reflects probably an early to mid-Cretaceous tectonic event of accretion or ramping at the convergent margin.

Melange II contains red and green marly limestones of Cenomanian age which can be compared with the coeval Lower Austroalpine Couches rouges deposits. They were tectonically mixed with Austroalpine elements in early Late Cretaceous. However, intraformational debris flows and slumps in melange type IIb are original sedimentary phenomenons from which a tectonically active substratum can be inferred already for Mid-Cretaceous times.

It should be noted that the occurrence of Melange I is linked to the Lechtal Nappe, that of Melange II to the Allgäu Nappe.

From the age relations of the sequences it can be assumed that during the Albian and the Cenomanian locally restricted flysch sequences were deposited

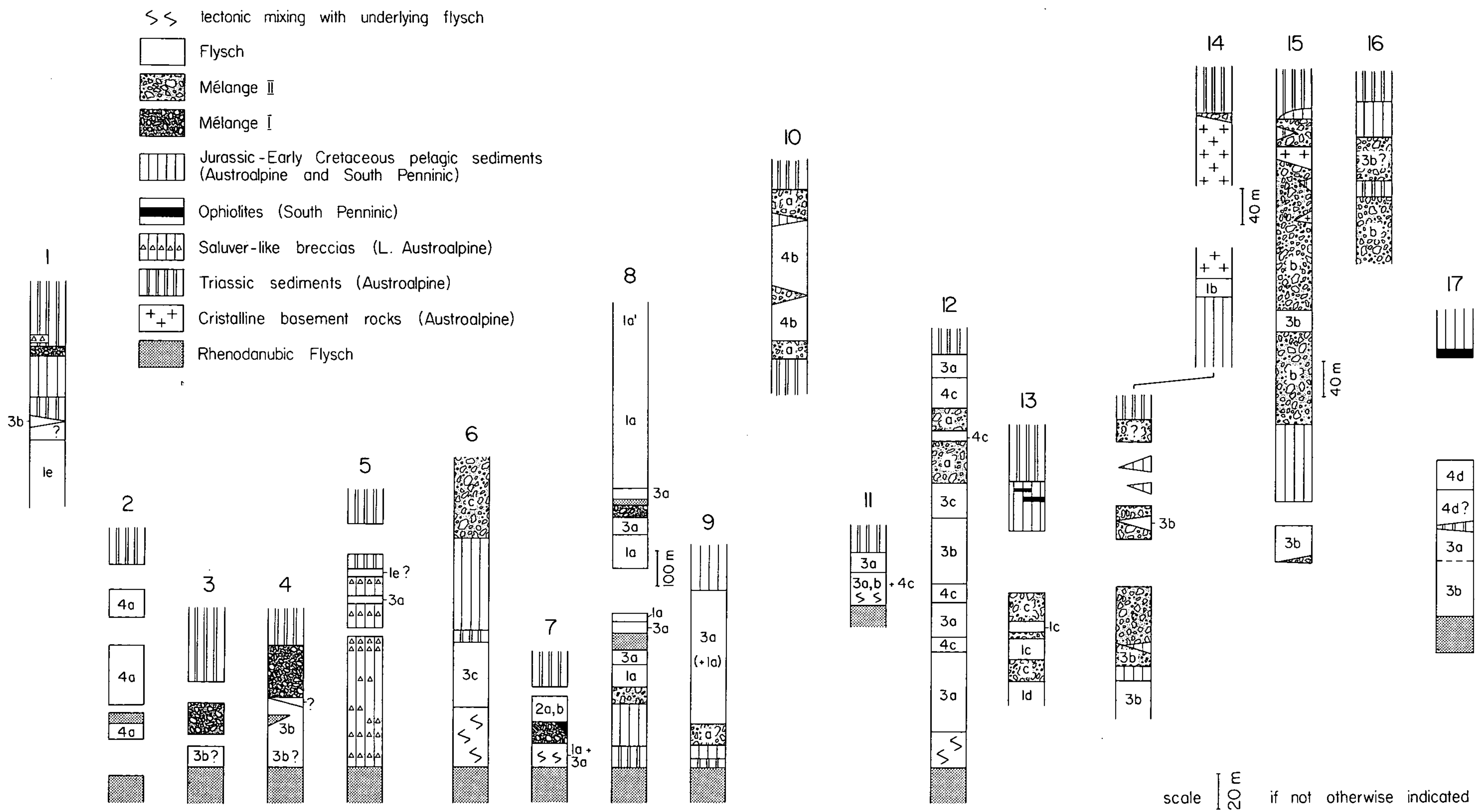


Fig. 10.
Composite sections in the Walsertal zone (for section location see Fig. 3 and Table 2).

±coeval with the Couches rouges-like sediments. The major flysch sequences, however, were deposited later, during the Turonian and ?Early Coniacian. This trend can be correlated with a progressive tectonic evolution, uplift of source terrains and development of sedimentary basis at the convergent margin. As no sediments younger than Late Turonian – Earliest Coniacian appear to be present in the Walsertal zone, a Coniacian tectonic event, eliminating sites of sedimentation must be assumed.

The tectonic imbrication observed in the Walsertal zone has obliterated the stratal continuity and original substratum of the flysch deposits cannot be directly deduced. A comparison with the Arosa zone does help to solve the problem. P. LÜDIN's work (1987) reveals that the general lithological associations in both units are significantly different. Whereas in the Arosa zone the Palombini Shales and ophiolites represent major constituents (WEISSERT & BERNOULLI, 1985; P. LÜDIN, 1987), these elements are scarce in the Walsertal zone. Likewise, sediments of the Couches rouges type, which are widespread in the Walsertal zone (especially where it is linked to the Allgäu Nappe), cannot be related to the South Penninic sediment series. Mid-early Late Cretaceous Couches rouges sediments are in particular characteristic of the Lower Austroalpine units (RÖSLI, 1944; FINGER, 1972). In the Walsertal zone the imbrication of the flysch deposits with mainly distal continental margin elements therefore suggests that they formerly were deposited on continental basement. But vice-versa, for the Arosa zone the inclusion of the flysch sediments in South Penninic melanges points to their original oceanic derivation.

4. Allgäu Nappe and External Lechtal Nappe

4.1. Generalities

The Mid- to early Late Cretaceous terrigeneous deposits of the Allgäu- and external Lechtal nappes are generally thought to have been deposited during contemporaneous tectonic activity in the Austroalpine realm (ZEIL, 1956; GAUPP, 1980). The turbiditic and hemipelagic sediments are found in places in normal stratigraphic contact with pre-Mid-Cretaceous formations; in other places they are imbricated with the older Austroalpine formations. This is particularly the case in the marginal imbricates formerly called "Cenoman-Randschuppe" (see Fig. 1). Because of its misleading age relation we shall refer to it as Kalkalpine Randzone.

In earlier interpretations the Mid to early Late Cretaceous sediments were considered to represent shallow water deposits ("transgressive Oberkreide") onlapping onto structurally deformed Austroalpine pelagic carbonate sequences (ZEIL, 1956; MUELLER, 1973). The obvious deep water turbiditic origin of most of these sediments was recognized recently by LÖCSEI (1974), FAUPL (1978) and GAUPP (1980).

A lithostratigraphic subdivision was provided by GAUPP (1980) who distinguished three formations: the Late Aptian- Early Albian Tannheimer Schichten (after ZACHER, 1966), the Late Albian–Early Cenomanian Losensteiner Schichten (after LÖCSEY, 1974) and the Late Cenomanian–Turonian Branderfleck Schichten (GAUPP, 1980). WEIDICH (1984a) indicated for the type locality of the Branderfleck Schichten a Coniacian age. The Branderfleck Schichten occur in the external Lechtal nappe (including the Falkensteinzug) and the Tannheimer- and Losensteiner Schichten are restricted to the Allgäu nappe. All three formations, however, are described from the Kalkalpine Randzone (GAUPP, 1980).

Older interpretations related the clastic deposits to a "Vindelizisches Urgebirge" (GÜMBEL, 1894), to a "Rumunian" (KOCKEL, 1923; FAUPL, 1978) or an "Ultrapienidic ridge" (TRAUTH, 1934; TOLLMANN, 1963) as a source terrain. Obviously these different names reflect different palinspastic concepts. The newer of these interpretations, relate this orogenic ridge to the elimination of the Penninic ocean. If this was the case in the transsect of the Eastern Alps, we would expect a Cretaceous collision of a mid-Penninic continental rise (Ultrapienninic ridge) with the Austroalpine margin (TOLLMANN, 1963; OBERHAUSER, 1968). However, terrigeneous detritus of the flysch deposits suggests only South Penninic and Austroalpine source areas and a possible elimination of the South Penninic ocean by Late Cretaceous times is still a matter of debate.

4.2. Outcrop Localities

The Mid-early Late Cretaceous sediments were studied in the Kalkalpine Randzone east of Hindelang (sections A to D in Fig. 1, Table 6), in the Falkensteinzug (a digitation of the Lechtal nappe, locality E), along the northern margin of the Lechtal nappe (sections F–H), in the Allgäu nappe (section I) and in an isolated occurrence of unknown origin imbricated between the Allgäu and the Lechtal nappe (locality J).

4.3. Outcrop Description and Data

Krähenwand

(Section A, Figs. 1,11)

The outcrop shows, in tectonically overturned position, the transition from Aptychus Limestone to green and red bioturbated marly limestones, which in turn grade into greenish gray marls alternating with dark silty marls and into a prograding turbidite sequence of reddish weathering gray sandstones. The stratigraphically lower part with marls and silty marls is referred to the Tannheimer-Schichten, the silty to sandy series to the Losensteiner-Schichten (GAUPP, 1980). Some of the sandstones are amalgamated and slumped.

In sample WW 2865 *Hedbergella* ssp, *Globigerinelloides* aff. *algeriana* and questionable first *Ticinella* ssp., in sample WW 2867 *Hedbergella* ssp. and *Ticinella* ssp. were determined confirming the Late Aptian age reported by RISCH (1971). The prograding series of the Losensteiner Schichten was dated by RISCH (1971) as Early-Middle Albian. This is in particular supported by the presence of the ammonite brood *Leymeriella tardefurcata* in early terms of the prograding series, indicative for the Early Albian (e. g. ROBASZYNSKI & CARON, 1979).

The sandstone samples in the Losensteiner-Schichten (WW 2874/12) contains high amounts of metamorphic lithic grains (Fig. 16, Table 7) and

Table 6.
Outcrop localities in the Allgäu and Lechtal nappes and in the Kalkalpine Randzone.

section	name	locality	references
A	N Krähenwand	NNE of Hindelang Hirschbach, 1340 m	RISCH (1971, p. 30 ff.) GAUPP (1980, p. 182 ff.)
B	SE Steinköpfl	SE Steinköpfl and NE of Hindelang, edge of the forest at 930 m	GAUPP (1980, p. 182 ff.)
C	Weissenbach	right hand unnamed torrent entering the Weissenbach at 1100 m, SE Unterjoch	GAUPP (1980, p. 188 ff.)
D	Kleebach	tributary to the Weissenbach NE Hindelang, 1140-1300 m	GAUPP (1980, p. 188 ff.)
E	Stoffelmühle	road and torrent outcrops E of Stoffelmühle near Pfronten/ Steinach	GAUPP (1980, p. 192 ff.) WEIDICH (1984, p. 31 ff.)
F	Wetzstein-Laine	Wetzstein-Laine ESE of Ohlstadt, 1130-1240 m	ZEIL (1954, p. 17 ff.) WEIDICH (1984, p. 51 ff.)
G	Kaltwasser-Laine	Kaltwasser-Laine SE of Ohl-stadt, 830-880 m in left hand tributary	ZEIL (1954, p. 17 ff.) WEIDICH (1984, p. 50 ff.)
H	Branderfleck	NW of the Ahornspitz near Schwangau/Füssen, E slope of Branderfleck-Sattel, 1580-1620 m	GAUPP (1980, p. 192 ff., 1982) WEIDICH (1984, p. 37 ff.)
I	Tannheim	NE Tannheim/Innergschwend and SE Einstein peak, several torrents between 1270 and 1360 m	ZACHER (1966, p. 218) GAUPP (1980, p. 182 ff.)
J	Mohnenfluh	NW of Lech, slopes E of Mohnenfluh and Kitzbach	AMPFERER (1932, p. 31 ff.) RICHTER (1969, p. 126)
K	Appenzell	Madautal, northern tributary to the Wasserfalltal NE Saxer Spitze, 1920-2120 m	AMPFERER (1932, p. 28 ff.)
L	Holzgau	valley N of Holzgau/Lechtal	HANIEL (1929, p. 23) AMPFERER (1932, p. 27) HUCKRIEDE (1958, p. 82 ff.)
M	Spullersee	E of the Spullersee, near the walk leading to the Gehrengrat, 1970-2030 m	HELMCKE & PFLAUMANN (1971) HELMCKE (1974)
N	Hutlaalpe	NE of Unterhutlaalpe S Buchboden (Gross Walsertal)	OTTE (1972, p. 83 ff.)
O	Sarotlatal	left hand tributary to Sarotlabach NE Wasenspitz/ Brand, Montafon, 1370-1400 m	LEUTENEGGER (1928, p. 58 ff.)

glaucophane, lawsonite and chloritoid in the heavy mineral fraction (Fig. 15). This is also the earliest occurrence of detrital high-P/low-T minerals reported from Alpine flysch in the area.

SE Steinköpfl

(Section B, Figs. 1, 11)

This short profile was correlated by GAUPP (1980) with the Losensteiner-Schichten in the previous section. It also contains a prograding sequence of gray, deeply weathered sandstones and gray marls. At the top, the thick sandstones are partly amalgamated. In the middle part some thick marlstone beds of blueish and ocre weathering appear. No age diagnostic fossils were found.

The quartz-rich sandstones (WW 2631/1, 2634/2) show more or less equal amounts of volcanic/ hypabyssal, sedimentary and metamorphic lithic framework grains (Fig. 16, Table 7). The heavy mineral spectrum is dominated by chloritoid (Fig. 15). Petrographically, these sandstones are different from those of Krähenwand section, but can be compared with those in the Tannheim outcrops (see below).

Weissenbach

(Section C, Figs. 1,11)

In the area of the Weissenbach GAUPP (1980) has found important outcrops of the Losensteiner-Schichten. The present section was measured in a small tributary of the river. It shows a tectonic assemblage of at least two turbidite series different in facies, petrography and preservation:

1) Massive, up to meter thick, partly amalgamated and coarse grained sandstones occurring over the whole section. Coarse pebbly sandstones with well rounded clasts probably belong to these turbidite sandstones.
2) A broken flysch formation consisting of fine to coarse grained sandstones embedded in sheared, light gray marls and silty marls, only found in the middle and lower half of the outcrop.

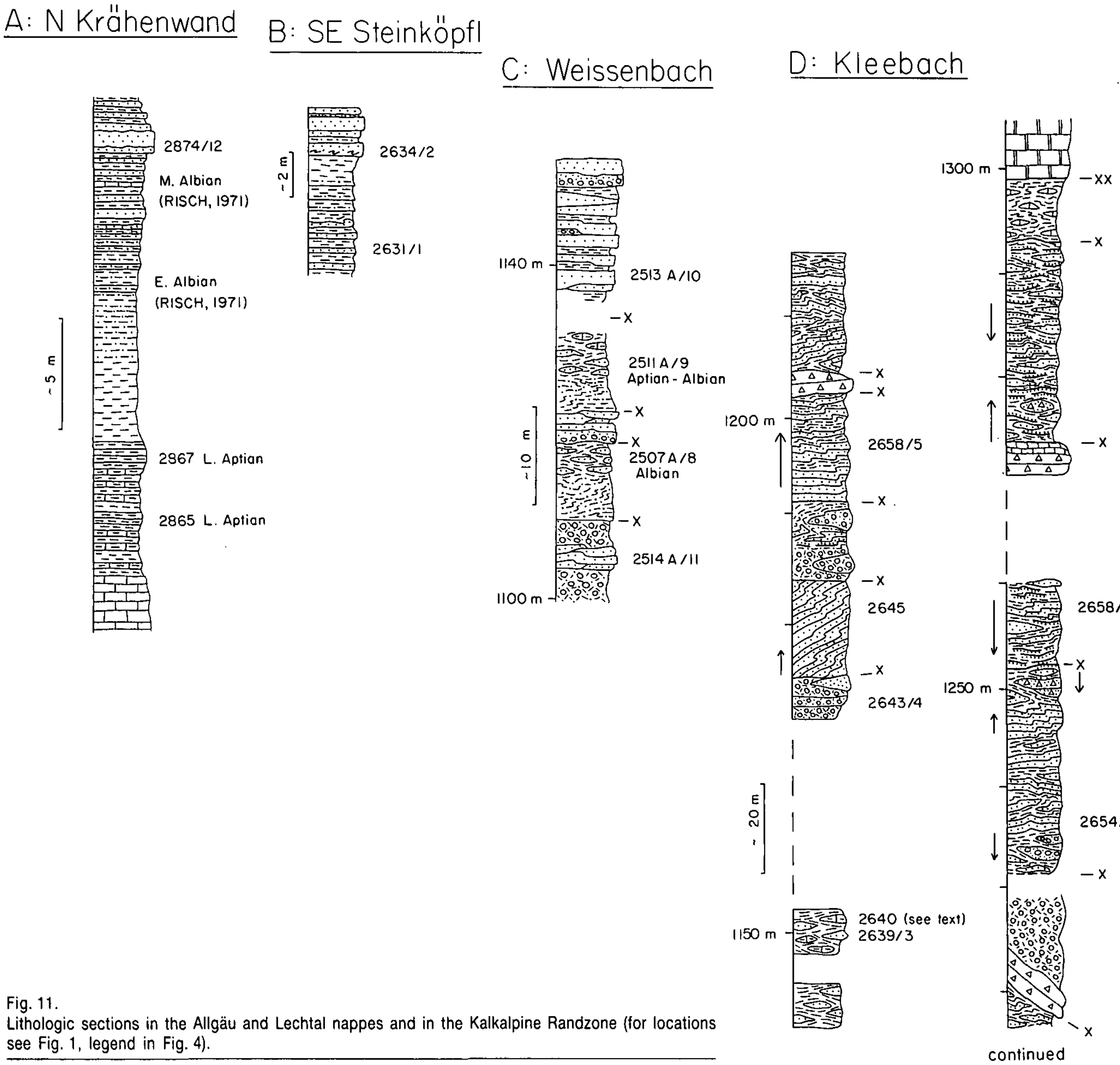


Fig. 11.
Lithologic sections in the Allgäu and Lechtal nappes and in the Kalkalpine Randzone (for locations see Fig. 1, legend in Fig. 4).

The presence of *Hedbergella* ssp. (generall small, rarely thick walled and one with a big last chamber) and rare *Ticinella* ssp. indicate an Aptian–Albian age for the broken flysch formation.

Two samples from the massive sandstone facies (WW 2513A/10), WW 2514A/11) show medium quartz contents and high contents in volcanic/hypabyssal lithic fragments (Fig. 16, Table 7). Equal amounts of chromite, tourmaline and zircone in the heavy mineral fraction suggest a correlation with two sandstones in the Kleebach section (WW 2643/4, WW 2645). According to the lithic clast contents in the broken flysch formation two different sandstones populations can be distinguished, but the samples are of variable grain size. The coarse sandstone (WW 2507A/8) is very rich in dolomite clasts (about 80 % of Ls), the fine grained sandstone (WW 2511A/9) contains less and nearly exclusively micritic limestone fragments.

Kleebach

(Section D, Figs. 1,11)

This section is an example for the variety of flysch sandstones in the Kalkalpine Randzone. The sandstones are imbricated with monogenic carbonate breccias and occur in normal and overturned position. GAUPP (1980) attributed them to the Losensteiner- and Branderfleck-Schichten. The monogenic breccias should be characteristic for the Brandfleck-Schichten.

The breccia cropping out at about 1200 m altitude (Fig. 11) contains clasts of skeletal, crinoidal, oolithic/onkolithic and pelagic limestones and a few dolomite clasts. The matrix is crinoid bearing micrite. The breccia at 1220 m is composed of a variety of carbonate clast comprised in a crinoid bearing micrite matrix (clast types are: crinoidal limestones with dolomite clasts; oolithic limestones; dolomites; bivalve- and foraminifera-bearing limestones; micritic limestones with *Globocheta* sp., pelagic bivalves and radiolarians; chromite- and glauconite-bearing clastic terrigeneous limestones with *Orbitolina* sp.). It is overlain by a heterogenous carbonate debris flow with rounded sparry and micritic dolomite and limestone fragments. An other bed of monogenic breccia crops out at about 1270 m and is composed of strongly silicified limestones with pelagic bivalves and aptychi. It is topogra-

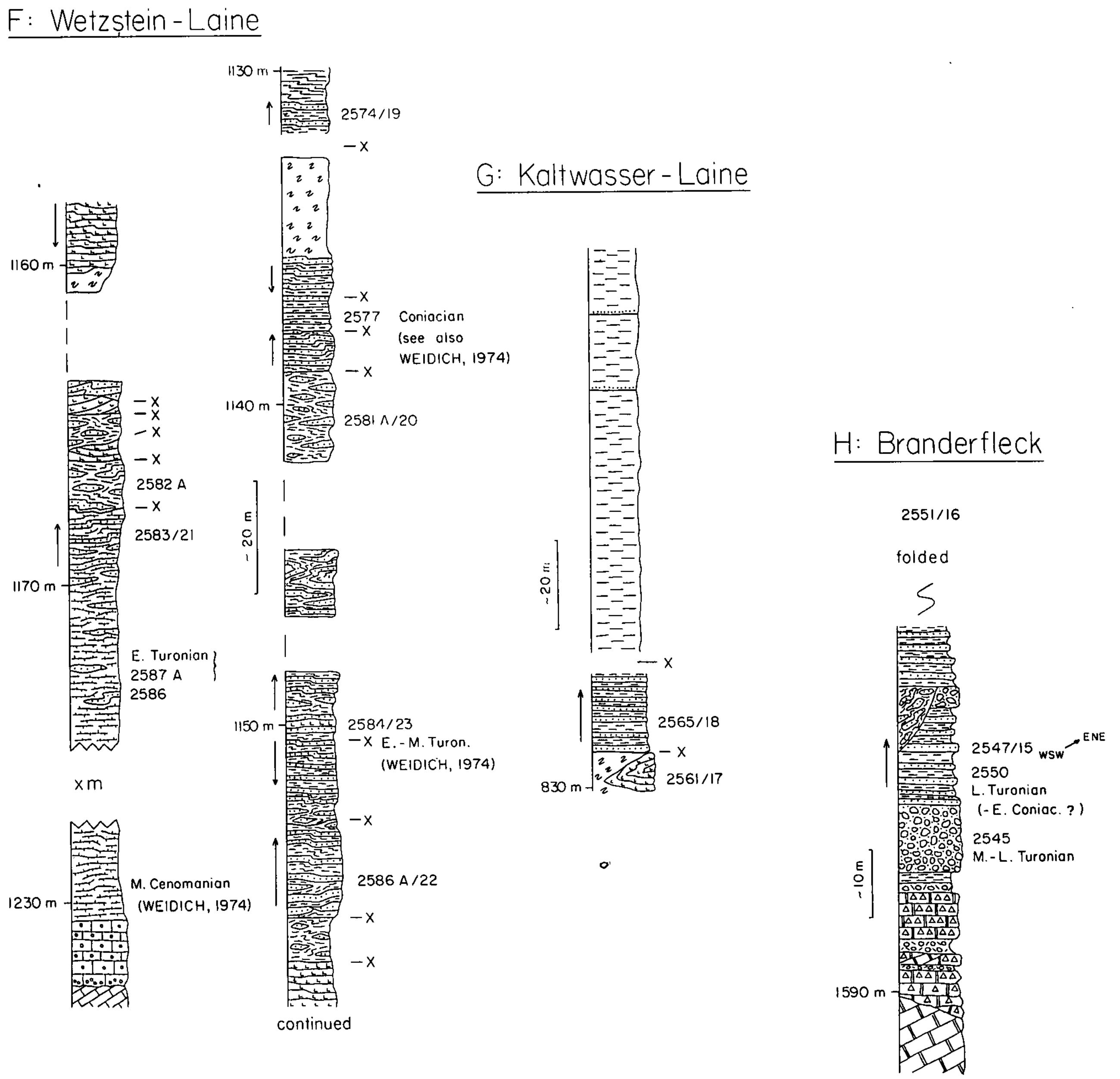


Fig. 11 (continued).

phically overlain by a limestone block (?) of the same lithology.

In the lowest part of the section (1150 m) fine grained sandstone lenses are included in grayish green and reddish marls and marlstones with *Ticinella* ssp. and few badly preserved keeled planktonic foraminifera (*Rotalipora* sp.?). This sets a Late Aptian–Early Albian maximum or probable Cenomanian age.

The mineralogical composition of the sandstones is very variable and only two closely spaced samples (WW 2643/4 and WW 2645), one (WW 2645) from very thin bedded "Bändermergel" (GAUPP, 1980), can be correlated. Sandstones of the same composition were also found in the Weissenbach section (see above and Figs. 15, 16).

Sandstones WW 2654/6 and WW 2658/7 both contain glaucophane in the heavy mineral fraction but otherweise their mineralogical content qualitatively and quantitatively is very different (see Figs. 15, 16).

Stoffelmühle
(Locality E, Figs. 1,12)

The profile is situated in a syncline of the Falkensteinzug (WEIDICH, 1984a, b). It is characterized by monogenic dolomite breccias, thin bedded turbidites interbedded with thick gray marlstones (well visible along the road) and red and green marly limestones and marls with sporadic up to 10 cm thick turbiditic beds rich in marly intraclasts. These sandstones crop out in the torrent E of Stoffelmühle.

WEIDICH (1984a) documented Cenomanian to Campanian ages in the scattered outcrops. His Cenomanian and Turonian ages for the monogenic breccias are in our opinion questionable, because the contacts of the undated breccias with dated marlstones are tectonic. In addition we think that the occurrence of Campanian marls is not sufficiently documented in this locality.

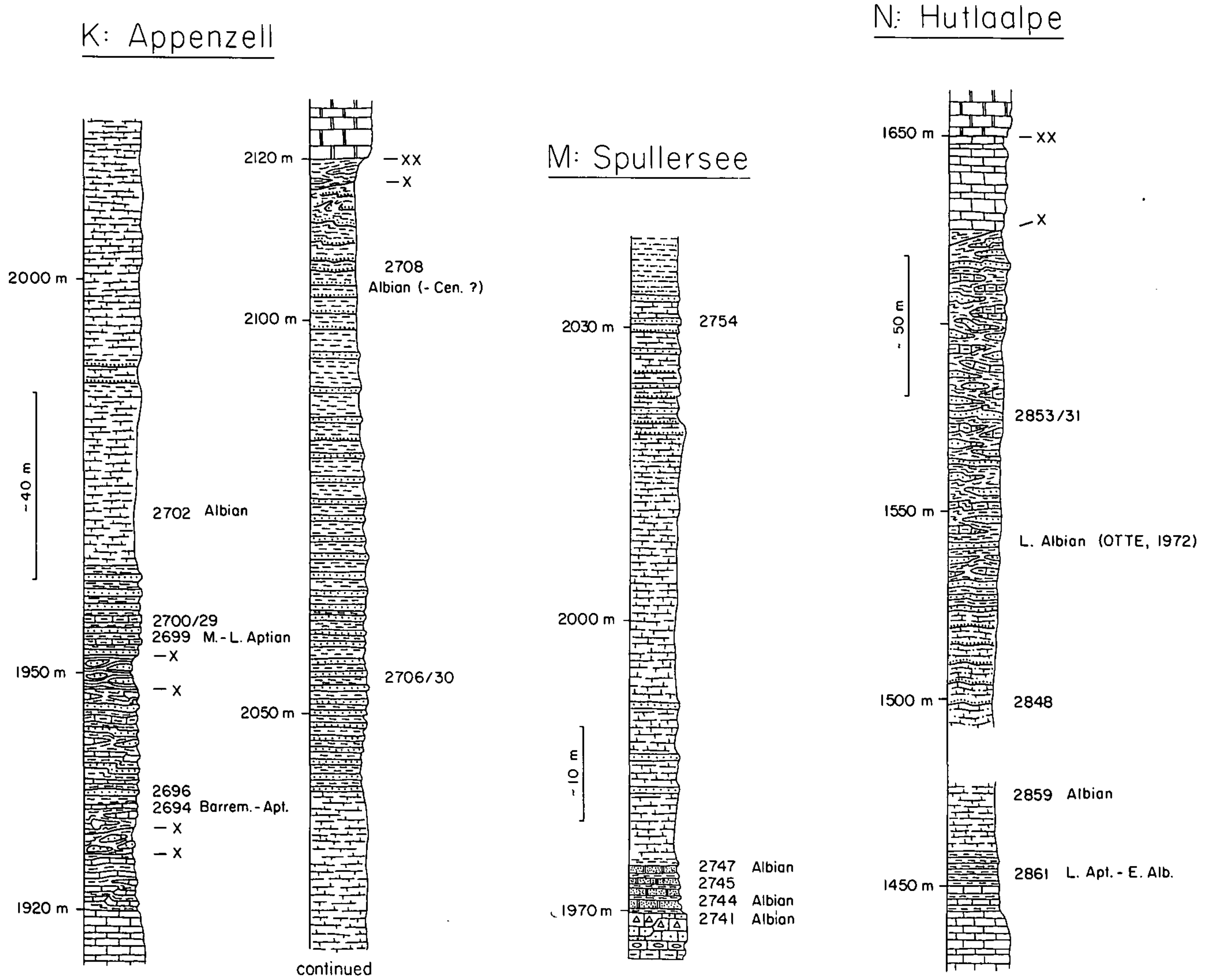


Fig. 11 (continued).

Two sandstones from this locality (WW 2682/14, WW 2556/13) show detrital glaucophane in the heavy mineral fraction, but otherweise they are different in composition (Figs. 12, 15, 16). The glaucophane-poor sandstone WW 2556/13 and the marlstone WW 2559 yielded *Dicarinella* cf. *primitiva, Marginotruncana pseudolinneiana, M.* aff. *sinuosa* and *M.* aff. *coronata*, an association of Late Turonian–Coniacian age. From the gray marls (2681) associated with the glaucophane-rich sandstone (WW 2682/14) specimens of *Rotalipora brotzeni, R. reicheli, R. cushmani, R. thomei, Praeglobotruncana stephani* and *P. gibba* were isolated. This association is correlated with the end of the *R. reicheli* and the beginning of the *R. cushmani* zone covering approximately the Middle Cenomanian. These datings are in accordance with WEIDICH (1984a).

Wetzstein-Laine

(Locality F, Figs. 1,11)

This section shows a tectonically overturned and dismembered, nevertheless continuous Cenomanian to Turonian limestone, marl and sandstone sequence (see WEIDICH, 1984a, b). In the small creek Wetzstein-Laine, descending from about 1230 to 1130 m altitude the following sediments can be observed (from older to younger):

1) Cenomanian (WEIDICH, 1984a) biosparitic *Orbitolina*-bearing limestones.
2) A series of gray marls grading up into bluish weathering marly shales with thin intercalations of graded sandstone beds (e. g. WW 2586, WW 2583/21). This succession resembles the facies observed in the road outcrop at Stoffelmühle. From about 1165 m downwards the situation is tectonically complicated. However, the petrographically identical sandstone type (sample WW 2586A/22) appears again between 1160 and 1150 m altitude, the sandstones are medium bedded turbidites alternating with thick bedded marls.
3) Soft, thin to medium bedded, grayish green turbiditic sandstones with abundant plant material. This facies occurs in variable positions (Fig. 11) and was dated at 1150 m as Middle Turonian by WEIDICH (1984a). The same sandstones were reworked in slumps and intraformational debris flows which crop out above 1160 m and between 1130 to 1140 m altitude (see also Kaltwasser-Laine).
4) Generally thin bedded turbiditic sand- and marlstones, partly disrupted and tectonically mixed (e. g. samples WW 2582A, WW 2581A/20, WW 2574/19). This facies also occurs in the Kaltwasser-Laine section.

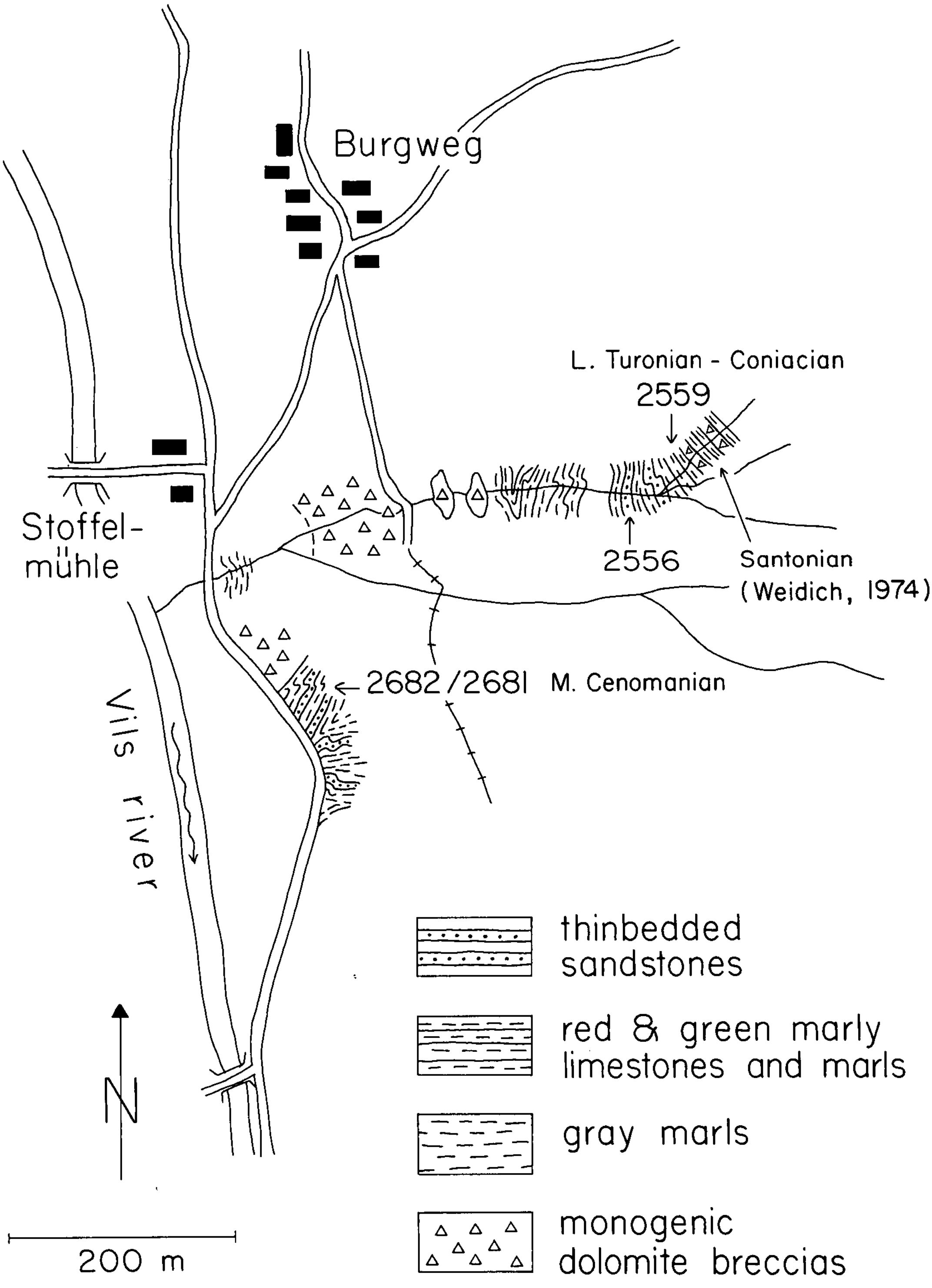


Fig. 12.
Outcrop sketch near Stoffelmühle (after WEIDICH, 1984a).

5) Below 1140 m there is a short sequence of brownish red and gray marlstones dated by WEIDICH (1984a) as Coniacian.

Our biostratigraphic data can be summarized as follows: isolated specimens of *Praeglobotruncana stephani, Whiteinella paracubia, W. archaeocretacea, Dicarinella* cf. *algeriana* and small *Marginotruncana* sp. in sample WW 2587A date the first sandstones in the prograding sequence as Archaeocretacea Zone of earliest Turonian age. Thin sections of the red marly limestone 2577 yield *Marginotruncana pseudolinneiana, M. sigali, M. schneegansi* and *M. fornicata* confirming the Coniacian age given by WEIDICH (1984a).

In the heavy mineral fraction of the Cenomanian–Turonian prograding series (WW 2586, 2583/21, 2586A/22) glaucophane and scarce lawsonite occur. In samples WW 2583/21 and WW 2586A/22 considerable amounts of clinozoisite are also found. By framework grain analysis these sandstones are grouped by relatively high contents in sedimentary lithic clasts (Fig. 16). The plant debris-bearing sandstones (WW 2584/23) and the thin-bedded sandstones (2574/19, 2581A/20, 2583A) are generally rich in chromite and can be correlated by this and framework grain analysis with samples from the Kaltwasser-Laine section (WW 2561/17, WW 2565/18). In contrast to WEIDICH's (1984) opinion the present Cenomanian to

Coniacian section contains lithologically and petrographically clearly distinct turbiditic deposits.

Kaltwasser-Laine
(Locality G, Fig. 11)

The upper, fine grained and mostly hemipelagic part of the section corresponds to the profiles B and A of WEIDICH (1984a, b) in the left hand tributary. It contains poorly outcropping and tectonized marlstones and marls of Late Turonian–Coniacian age. The lower part is situated in the main valley and shows at the base of the outcrop a folded block of dark graded sandstones and marls included in an intraformational debris flow comparable to those described from the Wetzstein-Laine. The sandstone (WW 2561/17) is similar in composition to the plant debris-bearing one in the former section but contains also small amounts of hornblende (Fig. 15). Microprobe analysis (det. J. ALBRECHT) show them to be of magnesio-hornblende and ferro-tschermakite composition. The thin bedded turbidite series (represented by sample WW 2565/18) overlying this debris flow is comparable to that outcropping in the Wetzstein-Laine (WW 2574/19, WW 2581 A/20).

Branderfleck
(Locality H, Figs. 1,11)

On the eastern slope of the Branderfleck-Sattel a section in the Lower and Upper Branderfleck-Schichten is exposed (GAUPP, 1980, 1982; WEIDICH, 1984a, b). The Lower Branderfleck-Schichten unconformably overlie Triassic Hauptdolomite. They consist of monogenic carbonate breccias with mainly dolomite and to a smaller and variable extent Permian and Triassic limestone, sandstone and quartzite clasts. Pebbly mudstones with green, red, yellow and brown matrix are intercalated. The matrix contains calcareous nannofossils.

This series is toped by thick, clast supported carbonate breccias of biosparitic *Orbitolina* limestones and thin bedded, more terrigenous turbiditic sandstones and marls all attributed to the Upper Branderfleck-Schichten. The chaotic complexe cutting down in the series (Fig. 11) is an intraformational slump/debris flow, but not an olisthostrome (GAUPP, 1980; WEIDICH, 1984), as it contains only beds and components characteristic for the Upper Branderfleck-Schichten in this place.

In the Upper Branderfleck-Schichten, our biostratigraphic data confirm the Turonian age proposed by GAUPP (1980). The matrix of the lower clast supported debris flow (WW 2545) contains *Marginotruncana pseudolinneiana, M. renzi, M. sigali, M. schneegansi, M. coronata* and *M. marginata* in thin section, but no Coniacian forms; it is thus of Middle to Late Turonian age. In the turbidite series sample WW 2550 contains *Hedbergella simplex, Dicarinella canaliculata, Marginotruncana pseudolinneiana, M. coronata* and *M. sinuosa* which can be correlated with the *M. sigali* Zone covering the Late Turonian and ?earliest Coniacian. Because also in other nearby localities investigated by WEIDICH (1984a) the Coniacian marker foraminifera *Dicarinella primitiva* and especially *D. concavata* are poorly documented in the Upper Branderfleck-Schichten, we doubt that the formation reaches up to the Coniacian as supposed by WEIDICH (1984a).

Two turbidite sandstone samples (WW 2547/15, WW 2551/16) are petrographically very similar (Fig. 15, 16). The heavy mineral fraction is dominated by chromite, but small amounts of the other usually common minerals including glaucophane s. l. occur. The framework grain analysis of the lithic sandstones show about equal amounts of volcanic/hypabyssal and sedimentary, but little metamorphic lithic clasts.

Tannheim
(Locality I, Fig. 1)

The type locality of the Tannheimer-Schichten was described by ZACHER (1966) and GAUPP (1980). The formation is discontinuously outcropping in several small torrents near Innergschwend NE of Tannheim and S of the Einstein peak. For a detailed description we refer to ZACHER (1966) and GAUPP (1980).

The Tannheimer-Schichten consist of marly to silty variegated shales grading up from the Barremian/Aptian Aptychus Limestone of the Allgäu nappe. They are topped by the Losensteiner-Schichten of probably Cenomanian age (GAUPP, 1980). The sequence is overthrusted by the Lechtal nappe.

Two samples (Figs. 15, 16), a fine grained sandstone (WW 2677) from the Tannheimer-Schichten outcropping in the easternmost creek at 1330 m and a coarse grained sandstone from the Losensteiner-Schichten (WW 2679/24) show similar heavy mineral spectra. The presence of small *Hedbergella* ssp. places sample WW 2677 in the Albian what is in accordance with ZACHER (1966).

The heavy mineral and framework grain contents (Figs. 15, 16) allow to correlate these samples best with those from the SE Steinköpfl section (WW 2631/1, WW 2634/2) but differ from other occurrences of Losensteiner-Schichten in the Weissenbach, Krähenwand and Kleebach sections.

Mohnenfluh
(Locality J, Figs. 1,13)

In the area east of the Mohnenfluh (near the village Lech) between the underlying Allgäu nappe and the overthrusted Lechtal nappe there occur tectonically imbricated terrigeneous, hemipelagic and pelagic series (AMPFERER, 1932; RICHTER, 1969). These Mid- and early Late Cretaceous deposits could originally have been linked to the Allgäu- and external Lechtal nappe. We shall describe the outcrops in three parts (Fig. 13).

1) In the Kitzbach, to the west of point 1848 at 1790–1780 m in altitude we find a tectonized series of greenish gray bioturbated limestones and marls of Aptychus Limestone affinity. They are passing downsection into reddish brown weathering limy marls with tectonically inserted dark gray shales and fine grained sandstones. The limestones (WW 2802) reveal a rich *Ticinella* ssp. fauna indicating an Albian age.
   In the sharp bend of the Kitzbach and downriver to 1740 m strongly tectonized terrigeneous turbidite series, marly shales and blocks of pelagic limestones occur. The upper, sandstone rich part is dominated by thick bedded coarse tail graded massive sandstones (sample WW 2811/16) associated with pebbly siltstones and finer grained turbiditic beds (WW 2816/27). The petrographical data (Figs. 15, 165) show that they are similar in composition. These variably grained sandstones contain only small amounts of chromite but high proportions in tourmaline and zircon. They are therefore significantly different from the thin bedded ones occurring downriver near the small bridge (see samples

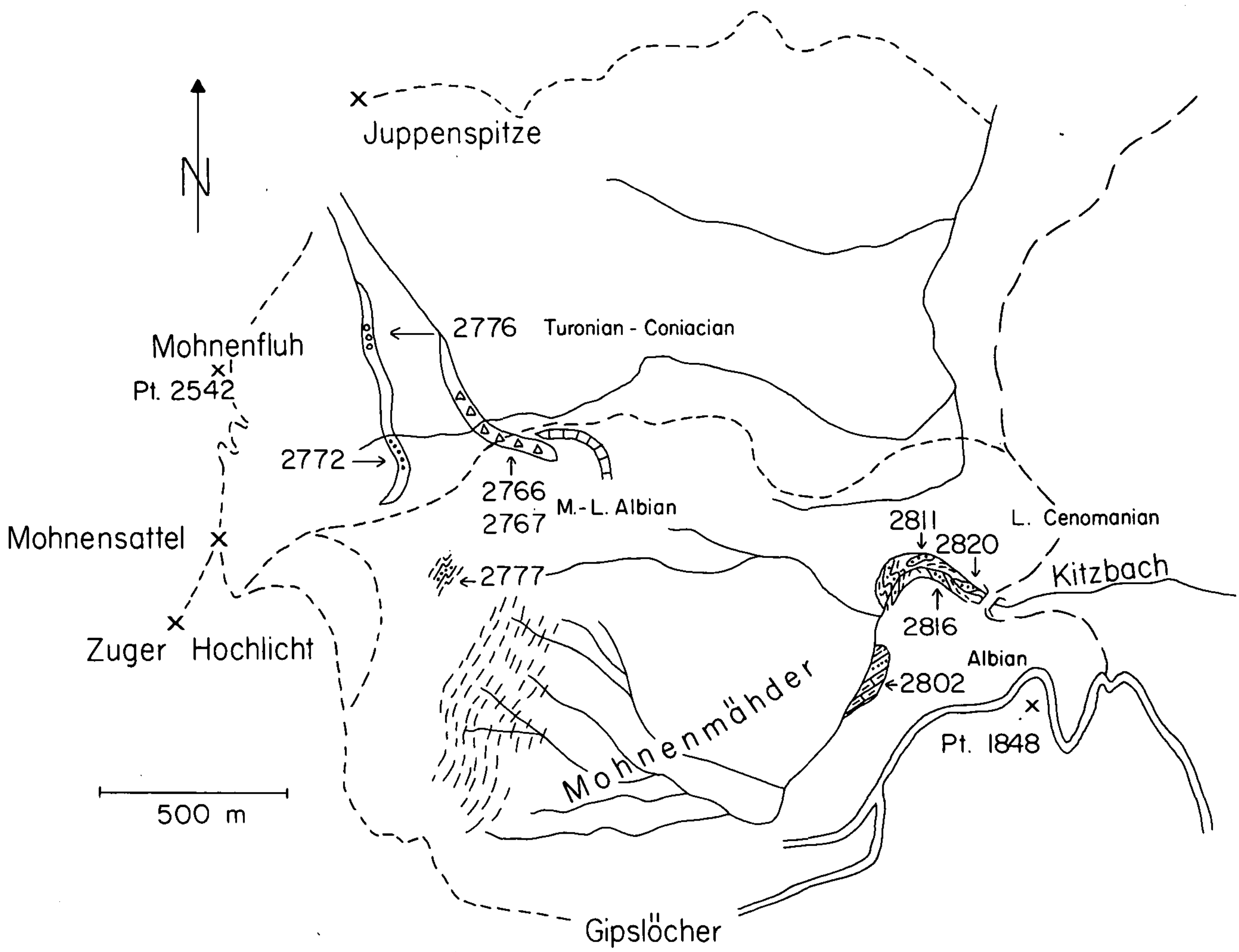


Fig. 13.
Outcrop sketch in the Mohnenfluh area (for legend see Fig. 4).

WW 2820/28 in Figs. 15, 16) which show high contents in chromite and sedimentary lithic clasts. The same sample WW 2820 in thin section reveals *Ticinella* ssp., *Orbitolina* sp., *Rotalipora* ssp. with *R. brotzeni, R. montsalvensis* and probable *Praeglobotruncana gibba*. This association points to an about Middle Cenomanian age.

2) In the branched source area of the Kitzbach (see Fig. 13, Mohnenmähder) thick series of gray to black marls and silty shales crop out. Other isolated occurrences of black shales and dark brownish weathering quartzeous turbidite sandstones (see location of sample WW 2777) are probably related with the shale series. The quartzeous sandstone (not represented in figures) yields 85 % of chromite, 6 % of tourmaline and 8 % of zircon in the heavy mineral fraction and is lithologically different from any other sandstones in the area.

3) Along the eastern slope of the Mohnenfluh, generally covered by debris and vegetation, two bands of clastic sediments appear (Fig. 13). The lower one, crossed by the trail leading to the Mohnen-Sattel consists of a carbonate breccia about 30 m thick and fining upward, overlain by some sandstones. The contact with the underlying Aptychus Limestone, Radiolarite and Allgäu Formation is not exposed, but could well be stratigraphic. The clast supported breccia (WW 2766) contains mainly Calpionella- and Aptychus Limestone fragments whereas dolomite, radiolarite, biosparite, oolithic and siliceous limestone clasts are subordinate. The sandstones (WW 2767/25 in Figs. 15, 16) bear high amounts of sedimentary lithic clasts, but are also exceptionally rich in plagioclase grains. In the breccia limestone clasts of Aptian–Early Albian age can be identified. The sandstones contain pre-Cenomanian *Hedbergella*- and *Ticinella* faunas. A Middle to Late Albian age can therefore tentatively be inferred.
The upper outcrop (Fig. 13) is more complex. It contains tectonically imbricated turbiditic sandstones (WW 2772), pebbly mudstones, clast supported conglomerates (WW 2776), marly shales, blocks of limestones, dolomites, radiolarites, radiolaritic shales and red nodular limestones. Because of the very high content of chromite in the heavy mineral fraction of sample WW 2772 (Fig. 15), this sandstone cannot be correlated with those associated with the breccias below. The conglomerates (e. g. WW 2776) yield Calpionella and Aptychus Limestone, dolomite, red and green Radiolarite and siliceous limestone pebbles in about equal proportions. In the matrix *Rotalipora* ssp. with *R. appenninica* and a few double keeled globotruncanids of Turonian–Conianican affinity were observed.

4.4. Compilation and Interpretations

Along the northern margin of the Austroalpine nappes the Mid- to early Late Cretaceous sediment series are represented by a variety of clastic and hemipelagic deposits. For most of them a deep water hemipelagic and mass flow origin is undisputed. In some outcrops the sequences discussed overlie the Early Cretaceous Aptychus Limestone without apparent stratigraphic gap (see sections N Krähenwand, Tannheim and ?Mohnenfluh, in other outcrops there is an angular unconformity at their base (Branderfleck, Wetzstein-Laine). Evidently, these series can be traced down to continental crust and were deposited on the continental part of the convergent margin (ZEIL, 1956; ZACHER, 1966; GAUPP, 1980, 1982; WEIDICH, 1984a, b). We do not consider the Kalkalpine Randschuppe as an individual palaeogeographic realm, but as a tectonic unit containing imbricated Mid- to Late Cretaceous sequences derived from the Allgäu- and the external Lechtal nappe.

Combined, the sediments of the different tectonic units cover the entire Aptian–Santonian interval (e. g. GAUPP, 1980; WEIDICH, 1984a, b). We think that the local occurrence of Campanian strata (Stoffelmühle, WEIDICH, 1984a, b) is not well documented.

The biostratigraphic calibration of the Losensteiner-Schichten and the Lower Branderfleck-Schichten is still unsufficient and the great variety of facies occurring in these formations hampers simple lithologic and petrographic correlations. Concerning the age of the dolomite breccia formations some sparse biostratigraphic data are available indicating Cenomanian–Turonian ages (Branderschrofen, Stoffelmühle [WEIDICH, 1984a]). However, for the limestone breccia occurring in the Mohnenfluh area we can infer a Middle–Late Albian age. This points to a longer time interval of carbonate breccia formation.

In the Allgäu nappe the locally preserved transition from the Early Cretaceous Aptychus Limestone to marly and silty (Couches rouges-like) and turbiditic deposits documents the progressive terrigeneous influence on the distal continental margin series. The general pattern suggests a rather quiet tectonic evolution in the realm from where the Allgäu nappe is derived.

In contrast, in the external Lechtal nappe, the sedimentary record points to pronounced tectonic activity preceding and during clastic sedimentation. This is documented by carbonate breccias and shallow water Orbitolina limestones (GAUPP, 1980, 1982; WEIDICH, 1984a,b) overlying unconformably pre-orogenic Austroalpine Mesozoic sediments. The clastic content indicates that continental basement in early stages was not exposed to erosion. The time of local tectonic uplift, emersion, erosion and breccia formation covers about the interval from the Aptian to the Turonian. The more extensive turbiditic and hemipelagic sequences were deposited from Cenomanian till Santonian.

The clastic composition of the different turbidite series is generally comparable to that described earlier from the Walsertal zone (see Figs. 6, 7, 15, 16). Therefore similar source terrains composed of South Penninic oceanic and Austroalpine continental basement and their overlying sediments are evident. However, in the Allgäu and external Lechtal nappes we observe a pronounced occurrence of glaucophane (2–25 % of the heavy mineral fraction), garnet and lawsonite. The presence of Late Jurassic and Early Cretaceous shallow water limestone clasts in conglomerates of the Losensteiner Schichten (GAUPP, 1983) does not necessarily indicate continental collision with a hypothetical Middle or South Penninic ridge comparable with the "Ultrapienidischer Rücken" e. g. TOLLMANN (1965) and OBERHAUSER (1968). Reworked shallow-water material containing e. g. dasyclad algae including *Clypeina jurassica* are described by SCHÜTZ (1979) from carbonate breccias in the Aptychus Limestone Formation in the nearby Lechtal nappe to the east (Thiersee- and Karwendel-Mulde). The derivation of the clasts from eroded equivalent Austroalpine series is therefore plausible and has no far going consequences for the general tectonic interpretation.

5. Internal Lechtal Nappe

5.1. Generalities

In the western part of the internal Lechtal nappe (Lechtal Alps) the Lower Cretaceous limestones are generally overlain by fine grained hemipelagic and terrigeneous sediments ("Kreideschiefer" [AMPFERER, 1913]). Locally Orbitolina- bearing breccias and conglomerates associated with coarse sandstones are preserved (HUCKRIEDE, 1958). The contact with the underlying Aptychus Limestone is gradational (e. g. HUCKRIEDE, 1958; HELMCKE, 1968; HELMCKE & PFLAUMANN, 1971; OTTE, 1972). In earlier literature these terrigeneous sediments were interpreted as post-tectonic and "transgressing" onto previously deformed Austroalpine sediments (AMPFERER, 1913; AMPFERER & ASCHER, 1925; RICHTER, 1969). The total stratigraphic range of the Kreideschiefer is not yet well established, but an Aptian to at least Early Cenomanian age seems well documented (e. g. HUCKRIEDE, 1958; HELMCKE & PFLAUMANN, 1971). In the Rätikon area OBERHAUSER (1963) proposes also Cenomanian and Early Turonian ages.

To the east, in the Lechtal nappe of the Bavarian apart of the Northern Calcareous Alps and in the lower Inn Valley regionally scattered outcrops may be combined to a stratigraphically complete sequence ranging from the Cenomanian to the Santonian (HERM et al., 1979; WEIDICH, 1984a, b).

5.2. Outcrop Localities

Our own reconnaissance work is restricted to the western part of the internal Lechtal nappe (Fig. 1 and Table 6). Because of the generally fine grained nature of the sandstones, only in a few cases framework grain analysis can be provided.

5.3. Outcrop Description and Data

Appenzell

(Section K, Figs. 1,11)

In the northern tributary to the Wasserfalltal NE of the Saxer Spitze a continuous section crops out. At the base (1920 m Altitude) the thin bedded Aptychus Limestone shows a gradual increase in interlayered dark gray marly shales. In thin section the limestone sample (WW 2694) reveals very small *Hedbergella* ssp., some of them with conically shaped chambers indicative for the Aptian stage. Higher up, thin bedded, graded, calcareous sandstones (e. g. WW 2696) are intercalated. This terrigeneous trend increases up-section: between 1950 and 1965 m up to 20 cm thick sandstone beds (e. g. WW 2700) occur which are topped by thick turbiditic silts and marls. Here, the turbidites alternate with light gray, mottled pelagic limestones and marls. The limestone sample WW 2699 contains very small *Hedbergella* ssp. and a broken *Schakoina* aff. *cabri*. A Middle to Late Aptian age can therefore be assumed. Up to this point the series is somewhat faulted.

From 1965 m to about 2040 m altitude the section is dominated by silty, mottled, greenish gray, platy limestone (e. g. WW 2702) and marly schists. This limestone sample reveals a very rich association of *Hedbergella* ssp. and *Ticinella* ssp. indicating a general Albian age. Up-section the marlstones become more abundant, marking also the transition to an upper composite turbiditic cycle. The latter consists of generally thin bedded sandstones and shales (sandstone beds of 10–20 cm) showing first a slightly prograding and then at the top, a marked fining-upward trend to silty turbidites (e. g. WW 2708). The uppermost part of the section is strongly disturbed by the overthrust of the Hauptdolomite of the Saxer Spitze massif. The silty turbidites contain *Hedbergella* ssp. and *Tichinella* spp. of the Albian; the Cenomanian seems not to be present in this section.

It appears that the two turbiditic cycles can be distinguished also petrographically (Figs. 15, 16). All sandstones investigated are very rich in chromite, but the lower cycle yields also small amounts of garnet (WW 2696, 2700/29). Different source areas are also suggested by sedimentary lithic clasts and organic fragments. In comparison with 2700/29, the sandstone 2706/30 derived from the upper composite turbidite cycle is very rich in reworked Lower Cretaceous pelagic limestone clasts, echinoid, algal and bryozoan fragments as well as some *Orbitolina* ssp.

The Appenzell section therefore documents an older, minor pelagic turbiditic cycle of Aptian age developing from Lower Cretaceous pelagic limestones. This cycle is overlain by a thick series of Albian hemipelagic marlstones that grades into a thick, fining upward upper turbiditic cycle, still of Albian age.

Holzgau

(Locality L, Figs. 1,14)

In the Höhenbach valley north of the Holzgau village, the northern limb of the Holzgau syncline is exposed (HANIEL, 1929; AMPFERER, 1932). The studied area (Fig. 14) shows Lower Cretaceous Aptychus limestones and parts of the Kreideschiefer, filling the core of the syncline. Earlier authors (HANIEL, 1929; AMPFERER, 1932) considered these to be of Late Cretaceous age, but HUCKRIEDE (1958) suggested an Albian age.

The Aptychus Limestone crops out north of the upper bridge. It consists of thin bedded, light gray and mottled limestones. Dark weathering, calcareous turbiditic sandstones and shales (10–20 cm in thickness) are intercalated. The calcareous sandstones contain high amounts of chromite (about 65 %) and minor proportions of tourmaline, zircon and minerals of the TiO_2-group (sample WW 2712 in Fig. 15).

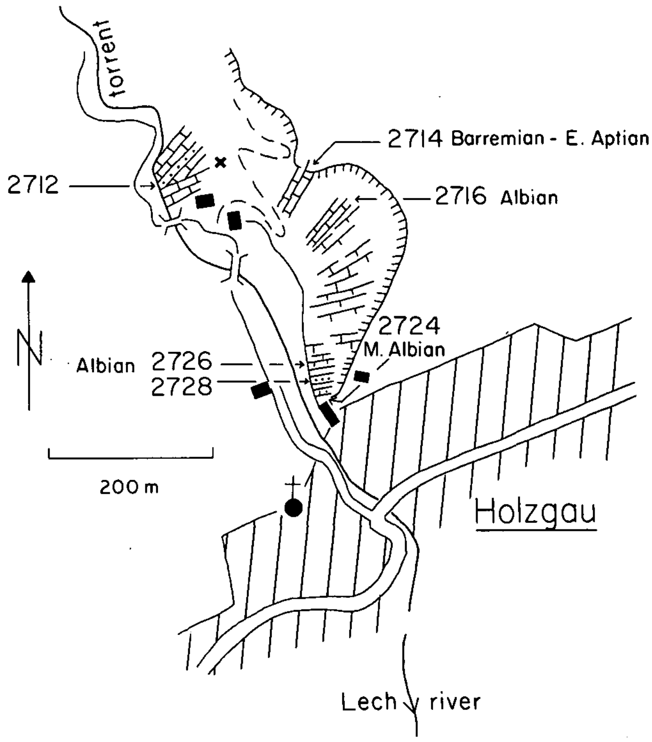


Fig. 14.
Outcrop sketch near Holzgau (for legend see Fig. 4).

In the wooded slopes E of the torrent the series can be traced up-section. Although the section is not complete and some tectonic complications could occur between the outcrops, the mottled greenish gray limestones and marls in the locality of sample WW 2714 can be considered as the stratigraphic continuation of the Aptychus limestone. The sample shows a rich association of *Hedbergella* spp. indicating a Barremian to Early Aptian age. Up-section the slope is mostly occupied by mottled, greenish gray, platy silty limestone and marl schists resembling the Albian schists in the Appenzell section. *Ticinella* spp. in sample WW 2716 suggests a likewise Albian age.

Finally, in the last outcrops near the village, a sequence of mottled greenish gray limestones and marls interrupted by a few meters of fine-grained turbiditic sandstones and shales is exposed. Limestone WW 2726 contains *Hedbergella* spp. and *Ticinella* spp. indicating Albian age. A similar limestone, sample WW 2724, contains in addition *Biticinella breggiensis*, indicative for the Middle Albian. The sandstone WW 2728 yields some chromite and relatively much chloritoid.

Spullersee

(Section M, Figs. 1,11)

The section (for location see Table 6) starts in a small torrent dividing up-hill. Below 1970 m altitude, the sediments underlying the Kreideschiefer are exposed. They are represented by a very reduced pelagic series (8–10 m) covering probably the Late Jurassic to Mid-Cretaceous time interval. The outcrop is situated in a part of the Lechtal nappe (Zürs ridge) with Late Jurassic to Early Cretaceous condensed sedimentation related to submarine erosion and omission (e. g. HELMCKE & PFLAUMANN, 1971). The base of the condensed series consists of Jurassic red marly limestones and nodular limestones. The limestones are overlain by irregularly bedded bioclastic arenites and

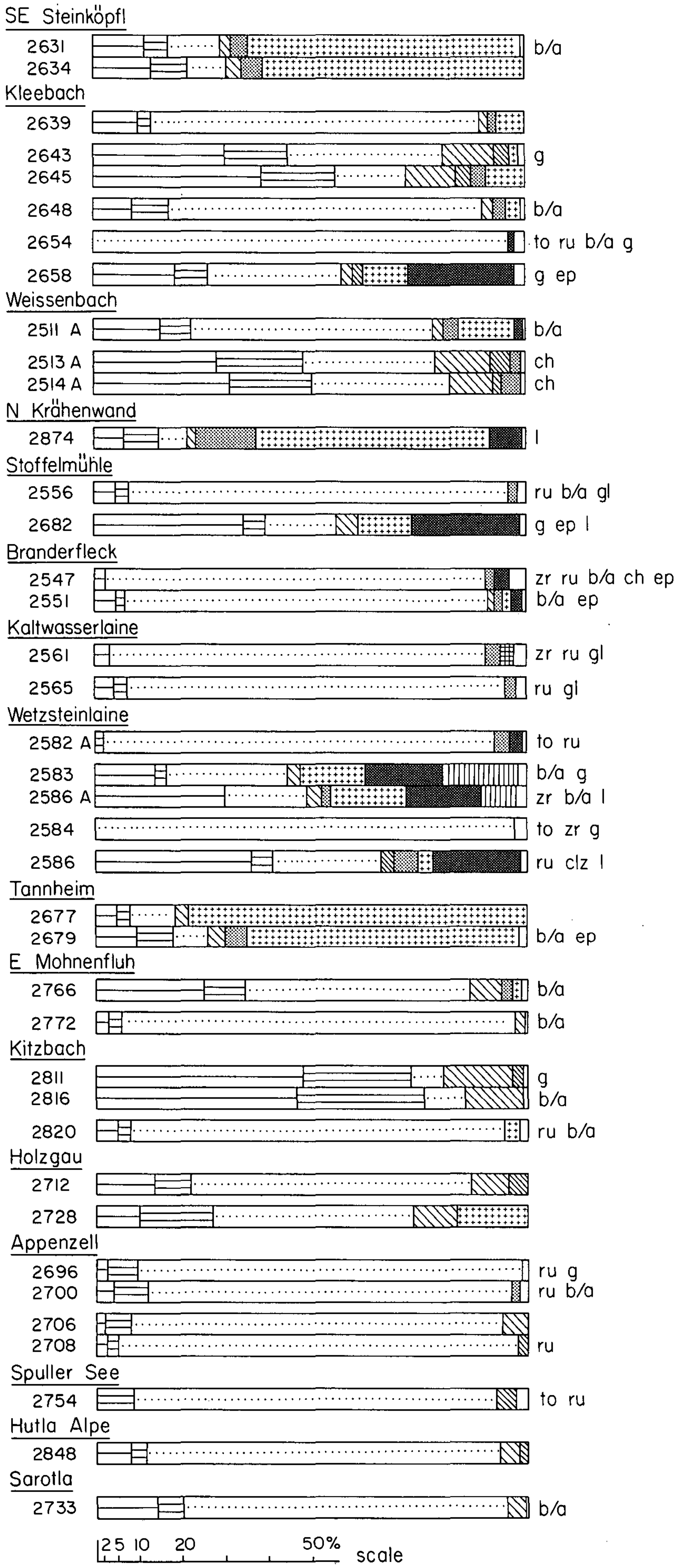


Fig. 15.
Heavy mineral assemblages in the Allgäu and Lechtal nappes and in the Kalkalpine Randzone (for legend see Fig. 6).

breccias with omission surfaces. The transition zone to the Kreideschiefer shows irregularly bedded, repeated graded, fine carbonate breccias overlain by a 2 cm thick radiolarite bed (sample WW 2741). The fine breccias contain fragments of micritic Calpionella and Radiolarian bearing, limestones, coarse bioclastic limestones, siliceous limestones and sparry respectively micritic dolomites. The sand matrix comprises echinoid debris and abundant *Ticinella* ssp. indicating an Albian age. The overlaying radiolarite bed therefore represents the "Younger Radiolarite Beds" (TRAUTH, 1948) for which we can indicate also an Albian age.

The contact between the condensed series below and the Kreideschiefer is tectonically slightly overprinted (Fig. 11). The Kreideschiefer start with thin bedded, fine-grained turbiditic calcarenites and shales showing a thinning/fining upward trend. The arenites yield reworked planktonic foraminifera and radiolarians. The radiolarian shells are generally dissolved, and the molds calcite-filled, the foraminifera are silicified and the matrix is dolomitized. *Hedbergella* spp. and *Ticinella* spp. in sample WW 2744 and *Ticinella* spp. in sample WW 2747 suggest an Albian age for the only several meters thick sequence, too.

Up-section, the sequence is overlain by more and less silty, gray, platy limestone and marl schists with scarce intercalations of graded sand beds. This facies strongly resembles the hemipelagic Albian strata rec-

Table 7.
Terrigeneous framework grain proportions in flysch sequences of the Allgäu and Lechtal nappes and Kalkalpine Randzone. For calculations see Table 3; numbers behind the diagonal strokes refer to numbers in Fig. 16.

	2631/1	2634/2	2639/3	2643/4	2648/5	2654/6	2658/7	2507A/8	2511A/9	2513A/10	2514A/11	2874/12
1. Q_m	49.0	51.3	3.6	43.0	46.3	35.6	0.0	18.3	32.6	40.0	46.6	38.6
2. Q_p	0.6	1.0	0.0	2.0	1.0	2.0	0.0	1.0	1.3	1.0	2.0	2.0
3. Q_T	1.6	2.3	0.3	1.3	2.6	2.3	0.0	2.0	1.6	3.6	3.3	3.6
4. C	1.3	0.3	5.6	0.6	2.0	4.6	36.0	0.6	3.0	0.3	1.0	0.3
5. P	13.0	8.6	3.6	12.3	9.0	11.6	0.0	2.3	2.6	10.3	7.6	5.6
6. K	0.0	0.0	0.0	0.3	0.6	0.6	0.0	0.3	1.6	0.6	0.6	2.6
7. L_{vh}	13.6	13.6	4.6	23.0	16.3	26.6	0.6	7.3	25.0	29.3	23.6	13.6
8. L_s	6.6	4.6	82.0	8.0	17.0	9.3	63.3	66.6	29.3	6.0	9.6	7.3
9. T_{QM}	3.3	6.0	0.0	4.6	3.0	1.6	0.0	1.0	1.6	3.3	1.3	10.6
10. M_p	0.3	0.3	0.0	0.6	0.6	1.0	0.0	0.0	0.0	1.0	1.0	2.0
M	10.0	11.6	0.0	4.0	1.3	4.3	0.0	0.3	1.0	4.3	3.0	13.3

	2556/13	2682/14	2547/15	2551/16	2561/17	2565/18	2574/19	2581A/20	2583/21	2586A/22	2584/23	2679/24
Q_m	15.6	47.6	19.0	29.3	18.3	34.3	37.6	43.3	47.6	30.0	3.0	51.0
Q_p	1.0	0.3	1.3	0.6	1.3	1.3	0.3	0.3	0.6	2.3	0.0	1.6
Q_T	1.6	1.0	1.3	2.0	1.0	1.0	1.0	1.3	0.6	0.3	0.0	3.0
C	2.6	3.6	4.0	7.0	0.3	1.0	2.6	2.0	1.6	1.3	0.0	0.0
P	2.3	7.6	3.3	4.6	3.6	7.6	3.0	8.6	9.0	13.3	0.6	10.6
K	10.6	6.3	3.0	6.6	4.3	7.0	7.0	6.3	1.6	7.3	0.3	1.0
L_{vh}	19.3	18.6	39.6	34.0	50.6	36.3	33.0	23.0	14.0	23.3	76.6	9.3
L_s	45.3	10.3	23.0	12.3	11.0	6.6	10.6	14.0	20.3	17.6	12.6	4.0
T_{QM}	0.3	1.6	1.0	1.0	1.6	0.3	1.3	0.3	1.6	2.6	1.3	4.6
M_p	0.0	0.6	3.0	0.3	2.3	0.6	0.6	0.0	0.3	0.3	2.6	0.6
M	1.0	2.0	1.3	2.0	5.3	3.6	2.6	0.6	2.3	1.3	2.6	14.0

	2767/25	2811/26	2816/27	2820/28	2700/29	2706/30	2853/31
Q_m	49.0	32.3	35.0	41.0	36.0	37.5	38.0
Q_p	0.0	0.0	0.6	1.6	2.3	1.5	2.3
Q_T	0.0	0.6	0.6	5.0	7.6	1.0	3.3
C	0.0	1.0	0.6	1.0	0.6	2.5	2.6
P	26.0	18.6	17.6	11.6	10.6	3.0	8.6
K	0.0	0.0	0.0	0.0	0.0	0.0	0.0
L_{vh}	7.0	28.3	26.3	5.0	28.3	1.5	20.6
L_s	14.0	14.6	13.6	31.3	7.3	57.0	11.0
T_{QM}	0.0	2.0	2.6	2.6	2.6	1.0	8.3
M_p	0.0	0.3	0.6	0.0	2.0	0.0	0.0
M	4.0	2.0	2.0	0.6	2.3	0.0	5.0

ognized in the Appenzell and Holzgau sections described above. Still higher up, this series reflects increasing terrigeneous influx, documented also by some thicker turbiditic beds observed at the place where the track to the Gehrengrat crosses the section (2030 m altitude, sample WW 2754). Upward to Point 2818 situated E of the Planitzerjoch Spitze, isolated outcrops display increasingly marlier lithologies of the Kreideschiefer series.

Hutlaalpe

(Locality N, Fig. 1,11)

In the gully cut into the slopes NE of the Unterhutlaalpe Middle Cretaceous hemipelagic and terrigeneous sequences are well exposed. They gradually develop from Lower Cretaceous Aptychus Limestone and belong like these to the Wandfluh-Schuppe below. Towards the top they are progressively deformed and finally overthrusted by a thrust sheet of Aptychus Limestone and by the dolomites of the Staffelfelder-Braunarlspitz-Schuppe (OTTE, 1972).

The massive Aptychus Limestone at the base up-section first becomes interbedded with dark marly shales. This sequence is overlain by red, greenish gray and gray bioturbated marly limestones of Couches rouges type. A red marly limestone (WW 2861) yields *Hedbergella* ssp. and *Ticinella* spp. in thin-section indicating a Late Aptian to Early Albian age. These mainly pelagic series are followed by hemipelagic, increasingly terrigeneous deposits. The lower hemipelagic part consists of gray, more ore less silty, platy marly limestone and marl schists comparable to earlier described lithologies in the Appenzell, Spullersee and Holzgau sections. Also in this section *Hedbergella* spp. and *Ticinella* spp. suggest an Albian age (sample WW 2859). Up-section, the hemipelagic lithologies are progressively replaced by fine to medium grained turbidite sands and shales. In the uppermost, tectonically deformed part of the sequence, discontinuously silty, bioturbated marlstone beds also occur. They probably represent the hemipelagic deposits originally interlayered with the turbidites.

Petrographically, the turbidite series are represented by the samples WW 2848 and 2853/31 (see Figs. 15, 16). The sandstones appear to be very rich in chromite (WW 2848) as it is commonly observed in the Kreide-

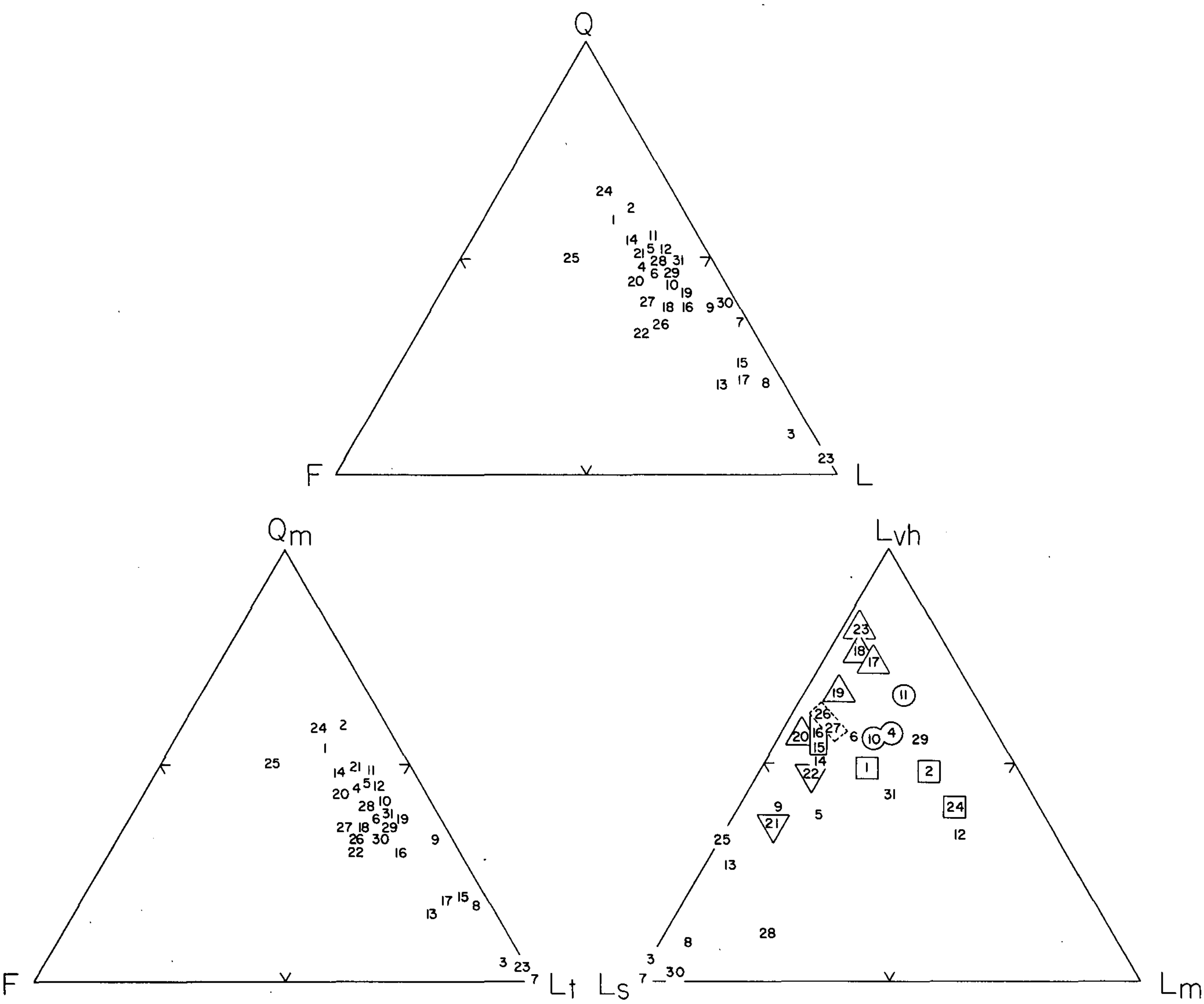


Fig. 16.
Triangular plots comparing detrital modes of flysch sequences in the Allgäu and Lechtal nappes and Kalkalpine Randzone.
The numbers refer to those indicated behind the diagonal stroke given with the sample numbers in the text, the lithologic sections and Table 7; the symbols indicate correlable samples.

schiefer series. The sandstone framework grain analysis (WW 2853/31) shows about equal amounts of sedimentary, volcanic/hypabyssal and metamorphic lithic clasts. In the lower part of the section we can confirm the age data of OTTE (1972). In the upper turbiditic series no new data are available, but we think that a Late Albian age suggested by OTTE (1972) is plausible.

Sarotlatal
(Locality O, Fig. 1)

Only as few provisional data can be presented from this locality. It is situated in a syncline of the Zimba-Schesaplana-Schuppe (KOBEL, 1969) belonging to the western Lechtal nappe. The syncline extends south of the Lenzikopf, the Wasenspitz and the Valbonakopf towards the Ill Valley near Bludenz and Bürs. In its core it contains the so-called Kreideschiefer, the age of which is poorly established here.

In the left hand tributary to the Sarotlabach (see Table 6), dismembered, variable lithologies can be observed:

1) Slices (several meters thick) of dark gray marly limestones with thin, cm-sized, partly graded laminae of silt. This lithology is comparable with the Kreideschiefer present in the Lorüns quarry (BERTLE et al., 1979). There, the marl limestones rest conformably, but with a considerable sedimentary hiatus on a condensed Jurassic pelagic limestone sequence and a Late Cenomanian to Early Turonian age is indicated by OBERHAUSER (1963).
2) Incompetent, soft marl shales and
3) Thin bedded, very fine grained turbiditic sandstones and shales, interbedded with brownish gray (hemipelagic) marls. The sandstones (sample WW 2733, Fig. 15) appeared to be very rich in chromite.

For lithologic and petrographic reasons the turbiditic layers may be correlated with other turbidites described from the Kreideschiefer in the previous sections. However, the dark, laminated marly limestones present in the Lorüns quarry and in the Sarotla Valley represent an unusual lithology.

5.4. Compilation and Interpretations

The Kreideschiefer series of the internal Lechtal nappe are gradually developing from Lower Cretaceous pelagic limestones (Appenzell-, Holzgau- and Hutlaalpe sections) or rest conformably on a condensed Jurassic to Middle cretaceous pelagic sequence series (Spullersee section, Lorüns quarry). The former, basinal situation seems to be more common whereas the second case occurs in relation with local submarine swells (HELMCKE & PFLAUMANN, 1971). The pre-existing ridges seem to be inherited from an earlier, Jurassic differentiation during tensional tectonics and to be buried during Middle Cretaceous subsidence by the basinal Kreideschiefer.

In the Hutlaalpe section in relatively external position Couches rouges-like hemipelagic sediments occur which are also widespread in the Allgäu nappe and in the Walsertal zone. In the Appenzell and Holzgau sections early chromite-bearing calcareous turbidites are intercalated with Barremian/Aptian Aptychus Limestone. The Spullersee section displays a Late Jurassic to Mid-Cretaceous condensed series firstly overlain by Albian carbonate turbidites without terrigeneous detritus. But the most extensive lithologies present in the Kreideschiefer series are Albian platy limestones and marl-schists recognized in the sections Appenzell, Holzgau, Spullersee and Hutlaalpe. These hemipelagic sediments are partly grading up-section into turbidites of likewise Albian age (Appenzell, Holzgau, Hutlaalpe). Reworked Orbitolina and other shallow water carbonate fragments are common.

The dominance of chromite in the heavy mineral fraction shows, that oceanic crust in lithosphere represented an important part of the source areas. The always subordinate occurrence of tourmaline, zircon and minerals of the TiO_2-group suggests that continental basement or terrigeneous Austroalpine Permo-Triassic and Middle Jurassic sequences were of minor importance.

The typical Kreideschiefer series in the Lechtal Alps covers the entire Aptian–Albian, probably also the Early Cenomanian time interval (see HUCKRIEDE, 1958; HELMCKE & PFLAUMANN, 1971; OTTE, 1972). Other occurrences of so-called "Kreideschiefer" of Cenomanian–Turonian age and related to the Allgäu nappe in the Walser valleys (SCHIDLOWSKI, 1962; OTTE, 1972; RICHTER, 1956; JACOBSHAGBEN & OTTE, 1968) because of their tectonic position and different lithologies are individual facies not comparable with typical Kreideschiefer.

In the type area of the Lechtal Kreideschiefer (AMPFERER, 1913) the lack of sediments younger than Early Cenomanian points to an important Cenomanian tectonic event eliminating this site of sedimentation. This is suggested by different authors (e. g. ZEIL, 1956; TOLLMANN, 1966).

The position of the terrigeneous source areas with respect to the Kreideschiefer basins is still speculative. It could be argued that the material was derived from earlier accreted oceanic and continental terrains present in the Dinarid segment of the Apulian promontory, as it is also discussed for the Late Valanginian–Early Aptian Rossfeld-Schichten far to the east (FAUPL & TOLLMANN, 1979). However, for the moment the model proposed by GAUPP (1980, 1982) seems also plausible. It suggests that the internal Lechtal nappe was partly separated from the source terrains in the north by the tectonically active external Lechtal nappe ("Pfronten ridge", respectively front of the Lechtal nappe, GAUPP, 1980, 1982) forming a barrier for coarse grained turbidites.

6. Summary and Discussion

In the four compartments described the actual situation observed today is strongly determined by the Late Eocene–Oligocene overthrusting of the Austroalpine continental margin on Middle Penninic and North Penninic units belonging to the European continental margin. The reconstruction of the Cretaceous situation and convergent evolution is therefore difficult. This holds especially for the problem of melange formation where we do the simple assumption that melanges containing exclusively South Penninic and Austroalpine elements not younger than early Late Cretaceous were formed during the Cretaceous convergence. However, the

Table 8.
Compilation of data and interpretation.

	Arosa zone	Walsertal zone	Allgäu-and external Lechtal nappe Kalkalpine Randzone	internal Lechtal nappe
stratal continuity	very rarely preserved		rarely preserved	preserved
tectonic grade	melanges & broken flysch fms.		broken flysch fms.	absent
ophiolitic elements	abundant	very rare	absent	absent
flysch lithology	very coarse to fine arenites			fine arenites
heavy minerals: in add. to tourmaline, zircon and TiO_2-group	chromite	chromite, chloritoid (glaucophane, garnet)	chromite, chloritoid glaucophane, garnet	chromite
age of flysches & hemipelagites	poor control Albian-Turonian	Albian- -Turonian/E.Coniacian	Aptian-Santonian	Aptian-Albian (E.Cenomanian)
metamorphic overprint	prehnite/pumpellyite to greenschist(south)	high diagenetic grade		
inferred source terrains	South Penninic oceanic and Austroalpine continental basement & sedimentary cover series in foldthrust belt			
site of flysch & melange formation	oceanic slope and trench basins	foldthrust foreland basins		
important features	abundant ophiolitic elements (generally in reversed position), first occurrence of reworked chromite in late Early Cret.	distal continental margin elements largely predominate	first occurrence of high-P/low-T minerals in E.-M. Albian	first occurrence of chromite in Barremian/Aptian

compartments evidently contain flysch formations which were deposited during the Cretaceous convergence and are defined by their actual tectonic positions, their lithologic content and stratigraphic range (see Table 8).

The Arosa zone and Walsertal zone suffered strongest tectonic overprint and the stratal continuity is very rarely preserved. They essentially consist of South Penninic and Austroalpine slices, melanges, broken flysch and flysch formations. In the Walsertal zone the Austroalpine distal continental margin elements largely predominate. To the contrary, in the Arosa zone the South Penninic ophiolitic and sedimentary cover elements are very abundant. There, in some places, the succession pillow basalts – Radiolarite – Calpionella Limestone, mostly in a tectonically overturned position, can be observed (WEISSERT & BERNOULLI, 1985; LÜDIN, 1987). Both units occupy a comparable tectonic position below the Austroalpine nappe edifice. However, from the stratigraphic range of the overthrusted units (Falknis/Sulzfluh nappes, Prättigau- and Rhenodanubic Flysch) it is evident that the structural alignment, the Walsertal zone in front below the Austroalpine sediment nappes and the Arosa zone in the rear mainly below Austroalpine basement nappes was established by the Tertiary continental collision. Therefore, it cannot be ruled out a-priori that these units during Cretaceous and Early Tertiary remained in more ore less vertical superposition and that the main deformation and melange formation took place during the Tertiary overthrusting.

The Kalkalpine Randzone occupies a similar structural position as the Walsertal zone, but is distinct from it by the less pronounced tectonic overprint and the lack of ophiolitic blocks and melange formations. Flysch and breccia formations related to the Allgäu- and Lechtal nappe are frequently observed in stratigraphic continuity with Early Cretaceous Austroalpine series and are only moderately deformed.

Because of the general metamorphic overprint in the Arosa zone the biostratigraphic control is poor, but from the data Albian to Turonian ages for the different flysches comprised can be reasonably assumed (LÜDIN, 1987). This is also the time range of the flysches and hemipelagic series found in the Walsertal zone. In the Allgäu- and external Lechtal nappe the hemipelagic and terrigeneous series cover the Aptian to Santonian interval (GAUPP, 1980, 1982; WEIDICH, 1984a, b). The Coniacian-Santonian lithologies represent deep-water equivalents of the shallow-water Gosau Beds situated in the more internal parts of the Lechtal- and Inntal nappe (WEIDICH, 1984b). The Coniacian–Santonian lithologies represent deep-water equivalents of the shallow-water Gosau Beds situated in the more internal parts of the Lechtal- and Inntal nappe (WEIDICH, 1984b). The internal Lechtal nappe of the Lechtal Alps received fine-grained hemipelagic and turbiditic elements only from the Aptian to the Albian or possibly the Early Cenomanian. These age relations must be respected in paleotectonic reconstructions.

Tectonic events occurring in one place do not exclude continued sedimentation in other places (e. g. TOLLMANN, 1966; WEIDICH, 1984b). Our biostratigraphic data for the Walsertal- and Arosa zone indicate Turonian to Early Coniacian ages for the younger sediments. If the geological record is complete this site of flysch and melange formation should have been eliminated at the Turonian/Coniacian boundary or in the Coniacian. For the Kalkalpine Randzone GAUPP (1980, 1982) suggests an Early Turonian age for the youngest sediments and therefore a similar timing as for the Arosa zone can be assumed. GAUPP also suggests that the thrusting of the Lechtal nappe onto the Allgäu nappe occurred in the latest Albian. However, this seems not to be the case everywhere because a conglomerate (Mohnenfluh), stacked between these two nappes, after our biostratigraphic data is of Turonian–Coniacian age. In the internal Lechtal nappe (at least in the Lechtal Alps) the tectonic emplacement of the Inntal nappe in Cenomanian seems well documented, but in other places sedimentation continued.

The petrographic data from the flysch formations indicate that the terrigeneous material was supplied by source terrains variably composed of pre-convergence South Penninic and Austroalpine lithologies. The South Penninic basement is documented as source by chromite and to a smaller extent by serpentinite clasts in the non-metamorphic flysches of the Walsertal zone, Allgäu- and external Lechtal nappe. The siliciclastic material is derived from the Austroalpine continental basement. The reworked sedimentary lithic clasts can be correlated with lithologies present in both palaeogeographic realms. This is in accordance with previous authors (MÜLLER, 1973; DIETRICH, 1976; FAUPL, 1978; GAUPP, 1980, 1982; WEIDICH, 1984b). But from our heavy mineral data some trends in their distribution can be observed. Chloritoid is an important constituent in the Walsertal zone and Allgäu- respectively external Lechtal nappe. Glaucophane and sparse lawsonite are frequently found in flysches of the Allgäu- and external Lechtal nappe and in one section in the Walsertal zone (WINKLER & BERNOULLI, 1986). In the internal Lechtal nappe the terrigeneous deposits generally show a homogeneous heavy mineral composition dominated by chromite.

Concerning the position of the sedimentary basins it is obvious that the hemipelagic and turbiditic series present in the Allgäu- and Lechtal nappe and Kalkalpine Randzone were deposited on the continental part of the convergent margin. For the highly dismembered Arosa and Walsertal zones we have no direct evidence. However, as the flysch sequences in the Arosa zone are typically associated with South Penninic elements, their derivation from the oceanic basin seems reasonable. The flysch sequences in the Walsertal zone are largely associated with Austroalpine distal continental margin lithologies and we may assume a continental basement for the sedimentary basin. The scarce ophiolitic rocks could have been incorporated by later tectonics.

We suggest that the flysches of the Arosa zone were deposited in the oceanic trench and slope environment, those of the Walsertal zone, the Kalkalpine Randzone and of the Allgäu- and Lechtal nappes in a continental foreland basin. These realms were probably separated by a foldthrust belt composed of oceanic, continental and convergence related metamorphic series shedding detritus to the adjacent basins (see later discussion and Fig. 20).

7. Heavy Minerals, High P-Metamorphism and Uplift

In several flysch sandstones detrital glaucophane and lawsonite were found (Fig. 15). The great variability of sandstone compositions suggests that they were not derived from one single sediment source. Their areal distribution show them to be related to flysch sediments deposited on the continental side of the convergent margin, because they only occur in the Allgäu- and external Lechtal nappe (Kalkalpine Randzone included) and in the Walsertal zone (WINKLER & BERNOULLI, 1986). Until now, they were not recognized in the Arosa zone (LÜDIN, 1987). The same distribution pattern is observed for detrital chloritoid that occurs together with some clinozoisite and epidote s. l. In the Arosa zone chloritoid was only observed in one minor flysch occurrence in its northern part (Rätschenjoch [LÜDIN, 1987) closely related to the Upper Austroalpine Madrisa imbricate.

Microprobe analysis (Table 9) shows the blue amphibole grains to be of glaucophane s. str. (7 grains), ferroglaucophane (7) and crossite (5) composition (Fig. 17, Table 9 and WINKLER & BERNOULLI, 1986). The chemistry of the glaucophanes and the occurrence of lawsonite clearly documents high-P/low-T metamorphic source terrains. Age and site of formation are uncertain. However, their provenance from the older Caledonian and Variscan basement is unlikely, because it has undergone several phases of higher grade regional metamorphism that would have eliminated these minerals, in particular Fe-glaucophane. MAGGETTI (1986) proposed that the Silvretta nappe during the Variscan orogeny suffered high-P metamorphism, which was overprinted during the Hercynian cycle by amphibolite grade metamorphism. We believe therefore that the low grade metamorphic source terrains were formed during Cretaceous convergence. The comparable distribution pattern of the low grade metamorphic minerals chloritoid and epidote suggests that during the same period also greenschist metamorphism occurred.

The detrital high-P/low-T metamorphic minerals occur over the entire Albian to Coniacian time interval. It is interesting to compare their occurrence with the radiometrically dated Early Alpine metamorphic events reported from the Central Alps (see Fig. 18). Radiometric age determinations of high-pressure metamorphism in the Alps is scarce, because it was overprinted in most cases by later greenschist and amphibolite metamorphism (MILLER, 1974). In the South Penninic oceanic units of the western Alps the oldest generation of glaucophane and blue-green amphiboles yields ages of 102–80 my (BOCQUET et al., 1974). K/Ar ages on phengites in oceanic radiolarites indicate cristallization at around 85 my (BONHOMME et al., 1980). More or less coeval high pressure metamorphism in the Austroalpine Sesia zone was determinded by HUNZIKER (1974) as 92 to 61,5 my old. In the South Penninic units of the eastern Alps, Cretaceous high-P metamorphism can be inferred from the occurrence of eclogites and blueschists in the Tauern window (MILLER, 1974), that, however, were overprinted by later high-T metamorphism. Cretaceous ages are obtained from medium-P assemblages on Mg-riebeckites, riebeckites and richterites in the South Penninic Platta nappe. Depending on the interpretations, ages of 90–70 my (PHILIPP, 1982) and 110–70 my (DEUTSCH, 1983) are proposed for the metamorphic event. In the Austroalpine basement nappes Cretaceous greenschist to amphibolite metamorphism is documented. For the Oetztal nappe, SATIR (1975) postulated an onset of metamorphism at 124 my but this datum is probably derived from mixed ages

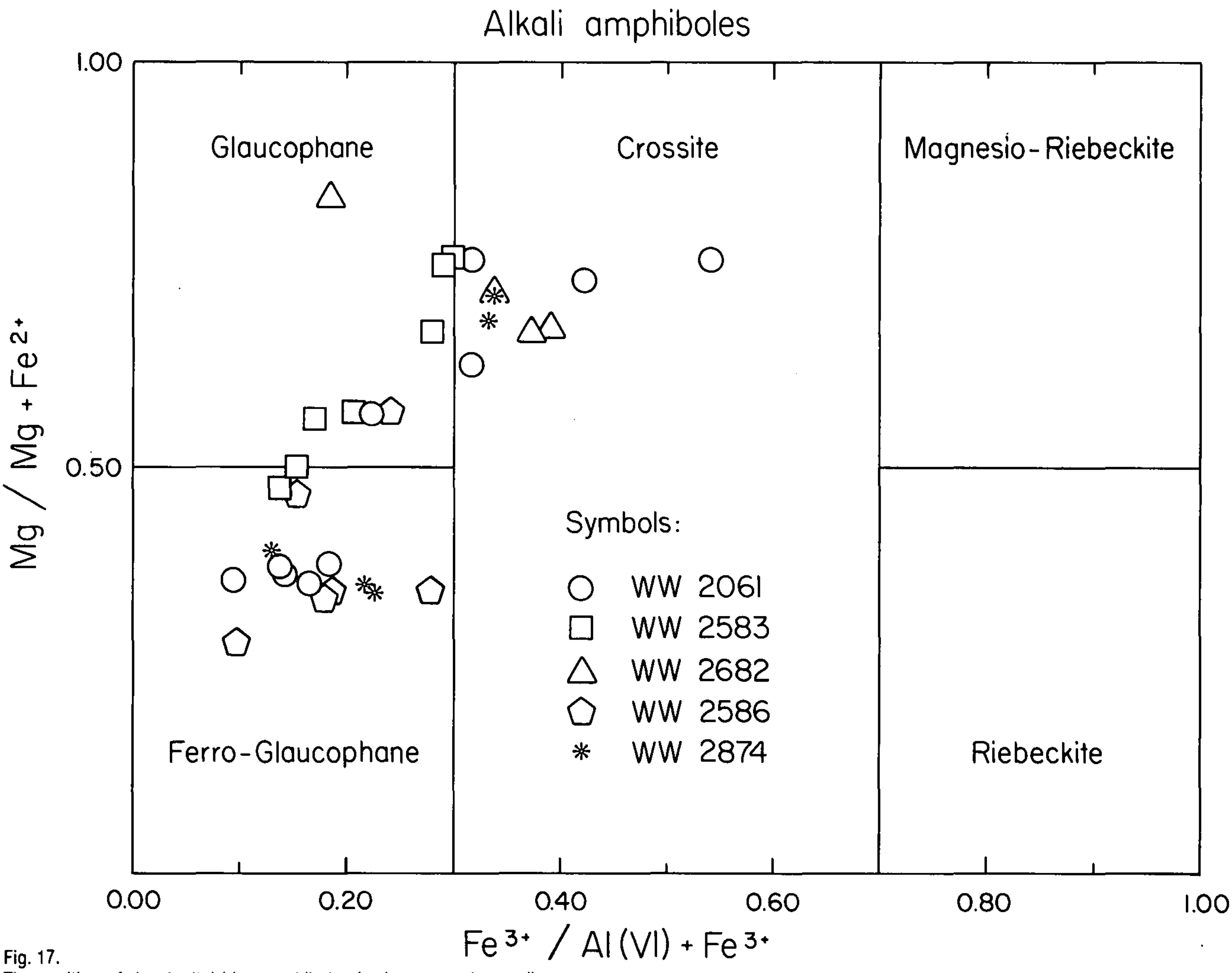


Fig. 17.
The position of the detrital blue amphiboles in the nomenclature diagram.
All measurements are plotted (for individual grain see Table 9).

Table 9.
Chemistry of detrital blue amphibole grains.
Analyst J. Albrecht; program of Bence & Albee (1968); standard deviation between brackets.

Glaucophane

	2583	2583°	2583	2583	2583	2586	2682
SiO_2	57.53	57.06	58.57	58.76	57.64	57.52	59.76
Al_2O_3	10.89	10.31	9.61	9.06	9.20	9.19	10.57
Cr_2O_3	0.00	0.00	0.00	0.00	0.11	0.00	0.00
TiO_2	0.04	0.93	0.00	0.00	0.12	0.00	0.07
FeO	15.40	14.39	11.76	11.66	13.48	15.28	7.89
MnO	0.06	0.04	0.09	0.00	0.12	0.00	0.00
MgO	7.12	8.14	10.76	11.09	9.88	8.20	12.47
CaO	0.10	0.05	0.00	0.05	1.01	0.00	0.09
Na_2O	7.27	7.41	7.50	7.46	6.91	7.41	7.68
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	98.41	98.33	98.29	98.08	98.29	97.60	98.53
Mineral formulas: atoms per 23 oxygens							
Si	7.961	7.883	7.943	7.979	7.897	8.009	7.970
Al	1.778	1.679	1.537	1.451	1.491	1.509	1.663
Ti	0.004	0.097	0.000	0.000	0.012	0.000	0.007
Fe^{3+}	0.313	0.364	0.605	0.611	0.540	0.472	0.371
Fe^{2+}	1.469	1.297	0.729	0.712	1.009	1.307	0.509
Mn	0.007	0.004	0.010	0.000	0.014	0.000	0.000
Mg	1.469	1.675	2.176	2.246	2.025	1.703	2.489
Ca	0.015	0.007	0.000	0.007	0.149	0.000	0.013
Na	1.950	1.985	1.972	1.964	1.841	2.000	1.986

Table 9 (continued).

Fe-glaucophane

	2061*		2583	2586°	2586°	2586	2874	2874°
SiO_2	55.32	(0.48)	57.20	55.87	56.06	56.51	56.72	55.83
Al_2O_3	11.39	(0.20)	11.32	10.49	9.58	10.02	11.37	10.31
Cr_2O_3	0.00		0.08	0.06	0.00	0.00	0.00	0.00
TiO_2	0.07	(0.07)	0.09	0.41	0.00	0.12	0.14	0.04
FeO	17.12	(0.37)	15.77	19.57	20.20	16.26	17.60	20.10
MnO	0.24	(0.04)	0.00	0.10	0.46	0.00	0.10	0.16
MgO	4.75	(0.16)	6.76	4.46	4.76	6.69	5.47	4.76
CaO	0.05	(0.05)	0.12	0.02	0.10	0.07	0.12	0.28
Na_2O	6.48	(0.07)	7.38	7.37	7.35	7.34	7.39	7.28
K_2O	0.00		0.00	0.00	0.00	0.00	0.00	0.00
Total	95.42	(0.28)	98.72	98.35	98.53	97.01	98.91	98.75
Mineral formulas: atoms per 23 oxygens								
Si	7.955		7.915	7.920	7.944	7.986	7.912	7.885
Al	1.933		1.848	1.754	1.601	1.670	1.871	1.717
Ti	0.008		0.009	0.044	0.000	0.013	0.015	0.004
Fe^{3+}	0.005		0.279	0.280	0.463	0.300	0.240	0.428
Fe^{2+}	1.737		1.545	2.039	1.930	1.621	1.812	1.944
Mn	0.030		0.000	0.012	0.056	0.000	0.012	0.019
Mg	1.019		1.395	0.943	1.006	1.410	1.138	1.002
Ca	0.008		0.018	0.003	0.015	0.011	0.018	0.042
Na	1.807		1.980	2.025	2.018	2.011	1.999	1.994

Crossite

	2061+		2061	2061	2682°	2874
SiO_2	56.36	(2.11)	56.49	56.35	57.90	58.05
Al_2O_3	8.08	(0.85)	7.53	8.78	8.13	8.75
Cr_2O_3	0.00		0.00	0.08	0.05	0.09
TiO_2	0.51	(0.06)	0.10	0.00	0.00	0.06
FeO	13.12	(1.75)	14.09	14.66	15.35	14.12
MnO	0.03	(0.05)	0.00	0.00	0.04	0.11
MgO	10.11	(0.17)	9.75	8.38	9.65	9.69
CaO	0.31	(0.20)	0.00	0.08	0.29	0.16
Na_2O	6.48	(0.08)	6.56	6.55	7.25	7.33
K_2O	0.00		0.00	0.00	0.00	0.00
Total	95.00	(0.30)	94.52	94.88	98.66	98.36
Mineral formulas: atoms per 23 oxygens						
Si	7.933		8.003	8.010	7.945	7.958
Al	1.341		1.258	1.472	1.314	1.415
Ti	0.055		0.011	0.000	0.000	0.006
Fe^{3+}	0.823		0.913	0.679	0.777	0.653
Fe^{2+}	0.723		0.755	1.063	0.982	0.965
Mn	0.004		0.000	0.000	0.004	0.013
Mg	2.123		2.060	1.776	1.972	1.981
Ca	0.047		0.000	0.012	0.043	0.023
Na	1.768		1.802	1.805	1.927	1.948

Standard deviations in parentheses.

Average of measurements per grain:

° 2 measurements
+ 3 measurements
* 5 measurements

Otherwise 1 measurement/grain.

(see e. g. THOENI, 1983). THOENI (1982, 1983) places the most important tectonic events for the Austroalpine basement between 100 and 85 my. Ages of 83 my and 78 my measured in biotites and white micas, respectively, in the Middle Austroalpine (Brenner) Mesozoic and basement are interpreted to represent the end of the general Early Alpine metamorphism (SCHMIDT et al., 1967; MILLER et al., 1967). From fine fraction (<2 µm) illite datings in Palaeozoic and Mesozoic sediment series of the Greywacke zone and Northern Calcareous Alps in the Salzburg area it appears that an Early Cretaceous nappe transport could have taken place (KRALIK et al., 1987).

On stratigraphic grounds it is generally assumed that the subduction was initiated in Aptian/Albian times (e. g. OBERHAUSER, 1978; FAUPL, 1978 by southward underthrusting of the South Penninic oceanic crust beneath the Austroalpine continental margin (LAUBSCHER, 1970; ERNST, 1971). From the early occurrence of the detrital high-P/low-T metamorphic minerals in Austroalpine units it must be assumed that convergence started earlier and the radiometric ages derived from

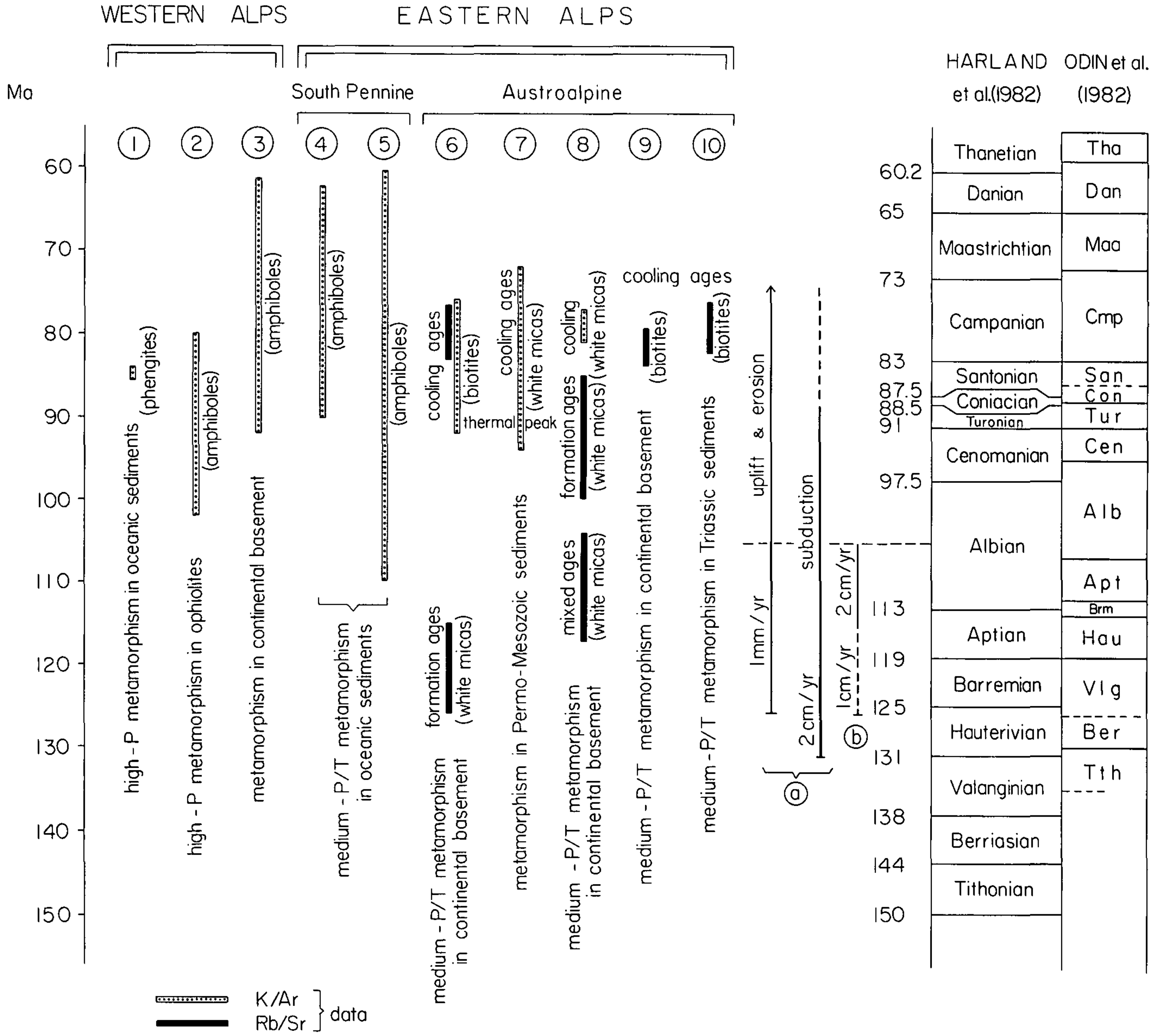


Fig. 18.
Radiometric ages of Early Alpine metamorphic events compared with the first occurrence of detrital blue amphiboles in Early to Middle Albian flysch sandstones.
After: 1 = BONHOMME et al. (1980); 2 = BOCQUET et al. (1974); 3 = HUNZIKER (1974); 4 = PHILIPP (1982); 5 = DEUTSCH (1983); 6 = SATIR (1977); THÖNI (1982); 8 = THÖNI (1983); 9 = SCHMIDT et al. (1967); 10 = MILLER et al. (1967).
Uplift rates calculated after a) PAVLIS & BRUHN (1983) and b) CLOOS (1982).

the Austroalpine basement do not date the earliest orogenic movements.

Since simple isostatic uplift would have been too slow, alternative tectonic mechanisms must be envisaged to bring up these rocks from about 20 km depth (TURNER, 1981) within a rather short time interval. Models for rapid uplift essentially based on the "corner flow" concept of COWAN and SILLING (1978) have been proposed by CLOOS (1982) and PAVLIS & BRUHN (1983). PAVLIS & BRUHN (1983) have argued that subduction, decollement and underplating of the descending sediments at depths greater than 20 km would result in strong thickening of the accretionary wedge and rapid uplift would occur. In this way high-P/low-T metamorphic rocks could be uplifted at a rate of 1 km/Ma. Considering that the metamorphism should have been preceded by a certain time of subduction to establish the metamorphic regime and assuming that subduction proceeded at a rate of 2 cm/a, subduction could have started in about Hauterivian times (see Fig. 18).

The "flow melange" model of CLOOS (1982) would suggest even more rapid uplift rates. In a V-shaped ductile flow complex, open towards the oceanic basin, oceanic basement and sediments are transported to great depth by subduction and subsequently uplifted by ductile matrix flow. The model proposes that the uplift rate is proportional to the subduction rate, but a theoretical Newtonian behaviour of the matrix has to be assumed. Considering rapid subduction rates (2 cm/year and more, see Fig. 18) this model could be in line with the supposed Aptian/Albian onset of subduction. However, the early occurrence of chromite from oceanic basement in Barremian–Aptian (this work), Early Cretaceous Palombini Shales (LÜDIN, 1987) and Barremian (HAGN, 1982) sediments anyway suggests earlier convergent movements (Tab. 8).

We think that both models do not fit the present situation and mineral distribution. These models, and in particulad the "flow melange" concept would imply that very low grade metamorphic detritus is supplied to the oceanic basin (Arosa zone) and probably to a smaller extent to the "fore-arc" area. In our case, we observe these minerals together with greenschist metamorphic grains redeposited exclusively in the Austroalpine foreland basins. In addition, these models would also suggest the presence of an early accretionary prism for which we have no direct evidence, and in line with recent examples of accretionary prisms, the probability of ophiolitic, and in particular serpentinite (for chromite) accretion must be considered to be low. To explain the high frequency of chromite during the earliest stages of convergence we therefore suggest early obduction of oceanic basement.

To illustrate the situation, the Eocene–Oligocene convergence documented in the Papua New Guinea orogeny may be used as a model. After DAVIES & SMITH (1971), DOW (1977) and PIETERS (1978) the scenario can be sketched as follows: During the Eocene, Jurassic-Cretaceous oceanic crust and sediments of the Pacific plate were overthrusted southward along a low-angle fault onto the Australian continental crust. The Australian continent extends as a pronounced promontory toward the north and underneath the ophiolite nappe. Stratigraphic data indicate that the main orogeny took place between the Middle/Late Eocene and the latest Oligocene (42–27 my [DOW, 1977]), whereas most radiometric datings fall between 27 and 22 my (DOW, 1977). The obducted complex today is represented by the Mobile Belt and the Papuan Ophiolithic Province. The Mobile Belt is characterized by non- metamorphosed sedimentary to mainly greenschist metamorphic pelitic rocks. Glaucophane schists and glaucophane-lawsonite rocks locally are included in greenschist series. The mechanism of this high-P/low-T metamorphism is not well understood, but it is suggested that oceanic crust of the Australian promontory was first subducted northeastward under the Pacific plate. This process was accompanied by high-P metamorphism. Shortly afterwards the Australian continent collided with the Pacific plate and obduction of Pacific crust and lithosphere occurred. Independent from the question where the high-P/low-T metamorphism took place, it is interesting to note that glaucophane/lawsonite-bearing clasts are reported from Middle Miocene sandstone and conglomerate sequences (MONTGOMERY, 1930; Chiara Formation, BROWN, 1977; ROGERSON, personal communication, 1986) situated in front (to the south) of the Mobile Belt. The time lap between the initiation of convergence and the redeposition of this material, can tentatively be estimated to be about 30 Ma.

During the main orogeny the convergence zone was mostly submerged supplying only little detritus to the adjacent basins. During this period also no remarkable igneous activity is recognized in the closer vicinity of the orogen.

In Oman in Late Cretaceous obduction of ophiolites on the continental margin and synorogenic metamorphism occurred. The metamorphic series are underlying the obducted oceanic slab and consist of glaucophane-bearing (glaucophane s. str. and crossite) high-P/lower-T and greenschist respectively amphibolite grade metamorphic rocks. It is suggested by LIPPARD (1983) that during obduction the very low grade metamorphism took place in the vicinity of cool distal continental margin crust whereas the higher grade metamorphism occurred near the base of the upthrusted hot oceanic crust and mantle.

The Papuan example can also serve as a geometric model for the Cretaceous South Penninic–Austroalpine orogeny. The scale of the whole convergence belt respectively Australian promontory is in the order of the hypothetical Apulian promontory/Adriatic microplate. It offers an explanation why in spite of the necessarily earlier onset of convergence, this is not strongly reflected in the South Penninic and Austroalpine Early Cretaceous sedimentary record, except for some minor or local terrigeneous detritus. The Oman model can explain how the metamorphism took place and how uplift could have worked. If we assume that glaucophane/lawsonite-bearing metamorphic rocks could also be formed at shallower depth (OBERHÄNSLI, 1986) obduction alone can accout for the formation of the metamorphic minerals.

8. Palaeotectonic Interpretation

The Austroalpine/South Penninic continental margin was situated along the northern edge of the African promontory (CHANNELL & HORWATH, 1976; HORWATH & CHANNELL, 1977) respectively Apulian plate (BIJU-DUVAL et al., 1977). It is generally assumed that from the Late Triassic onwards its relative motion is controlled by the drift of Africa with respect to Eurasia. Widespread occurrence of Middle- to early Late Cretaceous flysch deposits in the Austroalpine and South Penninic nappe edifice and elsewhere (Apennines, Carpathians) document convergent generally northward/northwestward directed movements of Apulia with respect to Eurasia during this time. This however, does not appear in earlier plate-tectonic reconstructions (DEWEY et al., 1973; CHANNEL & HORWATH, 1976; HORWATH & CHANNEL, 1977; BIJU-DUVAL et al., 1977). For this time interval general left lateral movements were considered between Africa and Eurasia. For a joint movement of Adria with Africa serious space problems arise. For this reason FRISCH (1979) suggested that the Apulian plate in the Early Cretaceous was decoupled from Africa and moved independently.

Recent reconstructions based on re-examined kinematic parameters (SAVOSTIN et al., 1986; DERCOURT et al., 1986) better fit with our timing of tectonic events along the Austroalpine/South Penninic margin in the Cretaceous as suggested here. From palaeomagnetic data WESTPHAL et al. (1986) infer that Apulia in Early Cretaceous exercised a 20° anti-clockwise rotation with respect to Africa, but in late Cretaceous again was magnetically parallel to it. This is interpreted to document a timely limited independence of Apulia relative to Africa between 130 and 80 my (see Fig. 19). Although there are many uncertainties in this kind of reconstruction, the postulated right lateral transpressive movement of Apulia relative to Eurasia between 130 and 110 my is in good accordance with our interpretation of the tectonic timing. From our data it appears plausible that along the South Penninic/Austroalpine margin compression started in the Valanginian/Hauterivian. Of course, the correlation of radiometric ages

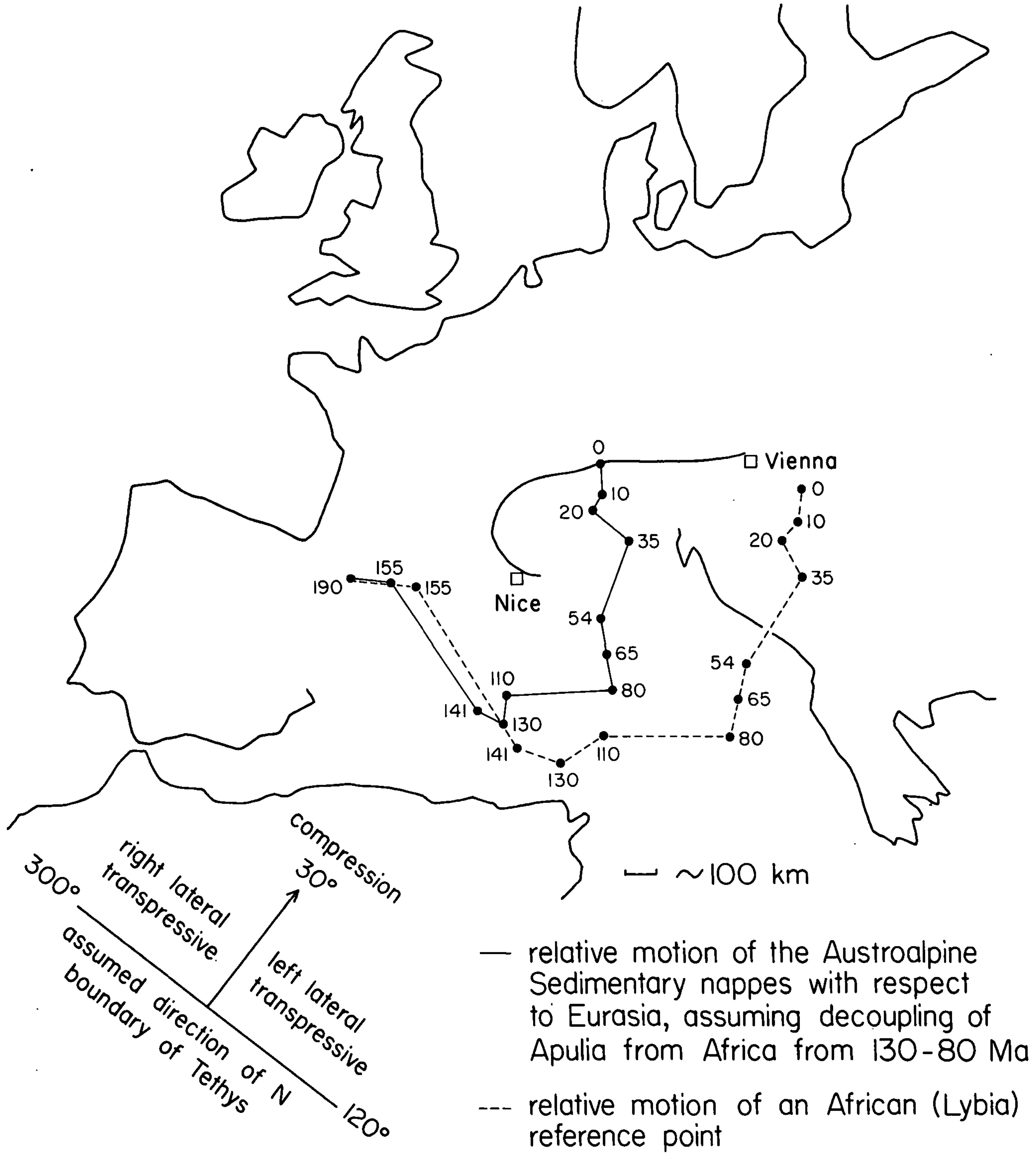


Fig. 19.
Relative motions of the Apulia margin and an African (Lybia) reference point with respect to Europe (after SAVOSTIN et al., 1986).
The latter flow line representative for a joint movement of Apulia and Africa indicates serious space constraints.

with geological stages depends on the scale adopted. The time scale of HARLAND et al. (1982) is based on high-temperature minerals mainly and we correlate the onset of subduction at 130 my with the early Hauterivian (see Fig. 18). According to the time scale of ODIN et al. (1982) the compression should have started at the Jurassic/Cretaceous boundary, but this would be difficult to reconcile with the general sedimentary evolution.

In line with these general plate-tectonic considerations the Cretaceous tectonic evolution of the South Penninic/Austroalpine margin may tentatively be interpreted as sketched in Fig. 20. Because of the probably transpressive movements between Apulia and Eurasia along the convergent continental margin, considerable lateral displacements could have taken place, however, for the moment, they cannot be located specifically or quantified.

The Jurassic situation was characterized by oblique spreading between the Apulian plate and the southern margin of Eurasia (Fig. 20a), giving rise to the formation of oceanic crust and lithosphere in the South Penninic realm. Along the distal continental margins distension is reflected by breccia and turbiditic sandstone formations to the north (Middle Penninic Breccia nappes) and to the south of the Tethys (Lower Austroalpine). In latest Jurassic and earliest Cretaceous times uniform pelagic limestone sedimentation (Calpionella Limestone) prevailed, indicating relatively quiet tectonic conditions.

In Valanginian–Hauterivian an about south-directed obduction of South Penninic ophiolithic series on distal parts of the Lower Australpine margin could have occurred (Fig. 20b). It can be speculated that a serpenti-

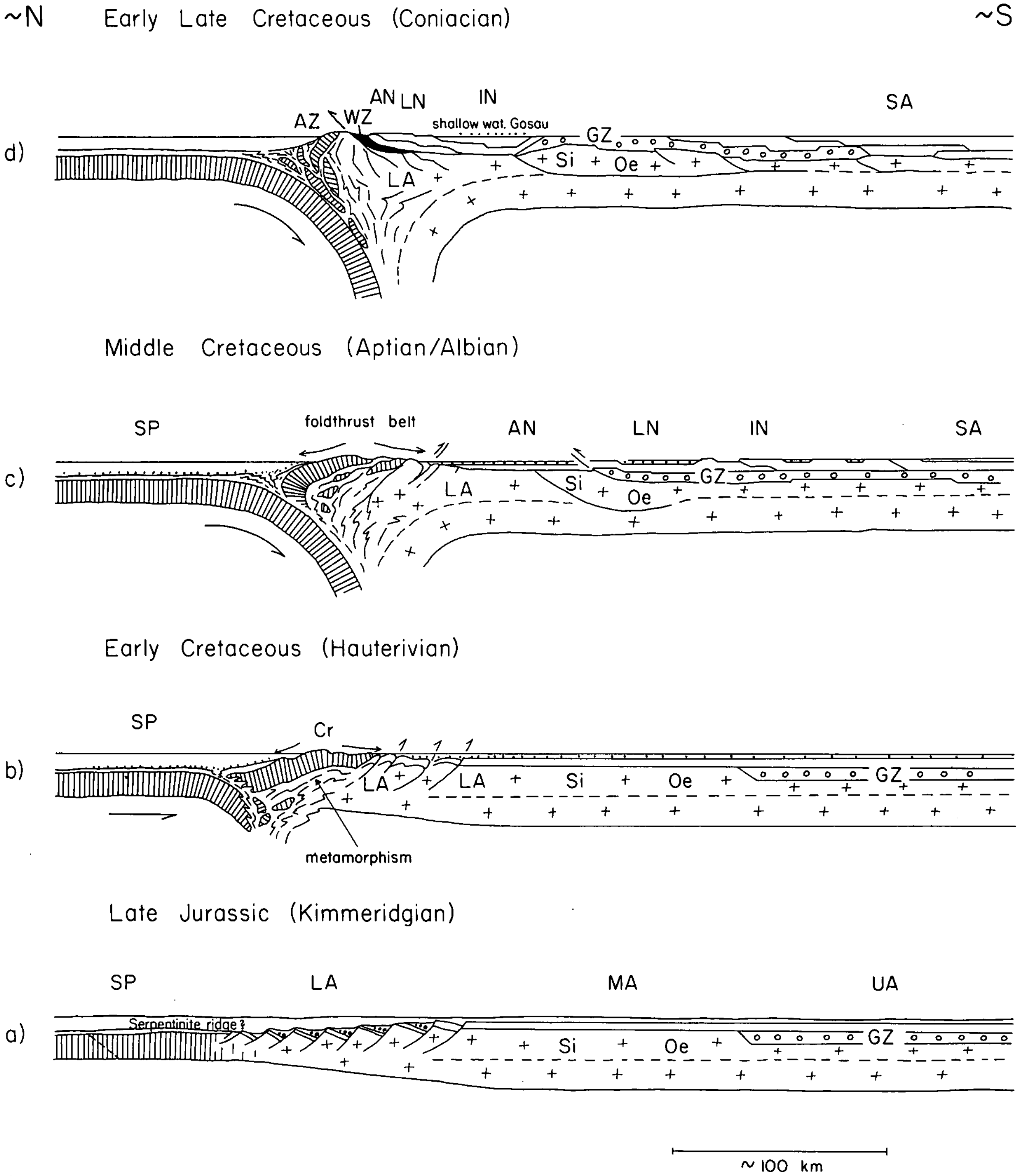


Fig. 20.
Interpreted Cretaceous palaeotectonic evolution of the South Penninic/Austroalpine margin .
SP = South Penninic; LA = Lower Austroalpine; MA = Middle Austroalpine; UA = Upper Austroalpine; Si = Silvretta nappe; Oe = Oetztal nappe; GZ = Grauwacken zone; SA = Southern Alps; AN = Allgäu nappe; LN = Lechtal nappe; IN = Inntal nappe; AZ = Arosa zone; WZ = Walsertal zone; Cr = chromite.

nite ridge, as observed today off Galicia (BOILLOT et al., 1985) could have represented a mechanically weak portion in the oceanic margin where decoupling took place. The internal parts of the Lower Austroalpine realm could have been deformed by inversion of the listric faults originated during rifting of the margin (BALLY, 1984). The first compressive phase obviously was not recorded by frequent and coarse grained clastic deposits. But the turn from Calpionella Limestone sedimentation to the more terrigeneous Palombini and Lavagna Shales in the South Penninic realm could record this event. Sparse detrital intercalations in the Palombini Shales of the Arosa zone yield chromite (LÜDIN, 1987). If blue amphiboles of the described composition can also be formed at shallower depth under suitable pressure/temperature ratios (OBERHÄNSLI, 1986), low grade metamorphism could also have taken place along the base of the obducted oceanic slab.

Continued, now left lateral compression (Fig. 19) and subduction resulted in further imbrication and uplift of oceanic and continental margin series in a complex south vergent foldthrust belt supplying progressively detritus to flysch basins to the north and south (Fig. 20c). The proposed geometry is supported by the observed one-sided redeposition of the metamorphic detrital minerals towards the continental foreland basins. Internal parts of the Lower Austroalpine realm were part of the foreland basin domain, because sedimentary sequence range up in age to Cenomanian/Early Turonian? (RÖSLI, 1944). Radiometric data from the Oetztal and Silvretta nappes indicate that in the Middle and also Upper Austroalpine basement from Late Albian till Coniacian/Santonian metamorphism and shortening occurred (THÖNI, 1983; see Fig. 18). These movements obviously imply detachment of the upper crust from the lower crust and mantle. From volumetric constraints we therefore must assume that the lower crust was considerably thickened or subducted along the convergence zone as proposed by LAUBSCHER (1983). The rugged topography of the external Lechtal nappe, reflected by the inhomogeneous Mid- to early Late Cretaceous sedimentation pattern indicates that it was a tectonically active site of erosion and sedimentation related to the shortening of the upper crust. For the Allgäu- and internal Lechtal nappe rather continuous sedimentary conditions can be assumed in Aptian–Albian and probably Cenomanian times.

A major tectonic event must have affected the continental margin at the Turonian/Coniacian boundary or in the Coniacian (see Fig. 20d). This is inferred from the stratigraphic range of the flysch formations included in the Arosa and Walsertal zone. For the Arosa zone we suggest that parts of the obducted oceanic slab were downbended by the subducting oceanic plate during this event, dismembered and tectonically mixed, giving rise to the formation of various melange types composed of South Penninic/Lower Austroalpine basement and sedimentary elements and South Penninic flysch deposits (Fig. 20d). To the other hand the Walsertal zone was probably formed by tectonic imbrication of foreland basin flysch with Austroalpine sequences. The Allgäu nappe appears to have been eliminated definitively as a site of deposition during this period. In parts of the Lechtal nappe (WEIDICH, 1984b) and in the Inntal nappe (shallow water Gosau Beds) sedimentation continued or was re-established. From the presence of detrital chromite in shallow water Gosau Beds (WOLETZ, 1963; WILDI, 1985) and in the Coniacian deposits of the external Lechtal nappe (this work) we can assume that the previous source are to the north was still undergoing erosion during this time. In Early Campanian, with the onset of the deep water turbiditic Gosau Beds this clastic source seems to have become inactive, as the sediments generally are devoid of chromite (WOLETZ, 1963; WILDI, 1985).

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