JAHRBUCH DER GEOLOGISCHEN BUNDESANSTALT
Jb. Geol. B.-A. | ISSN 0016-7800 | Band 137 | Heft 2 | S. 345–363 | Wien, November 1994

The Early Alpine Orogeny in the Central Alps: A Discussion of Existing Data

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Zentralalpen
Alpidische Orogenese
Deformation
Strukturanalyse
P-T-Bedingungen
Geochronologie
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Die frühalpine Orogenese in den Zentralalpen: Eine Diskussion der vorhandenen Daten

Zusammenfassung

Strukturen, Verformungsdaten, Schersinnindikatoren und geochronologische Daten zeigen Hangend-nach-Westen gerichtete Bewegungen, schräg zum Gebirgsstreichen, in den untersten ostalpinen Decken und den darunterliegenden südpenninischen Einheiten während der frühalpinen Orogenese (Kreide bis mittleres Eozän) an. Diese Deformationen erfaßten die penninisch-ostalpine Grenzzone (Arosa-Zone), die südpenninischen ophiolitischen Einheiten (Zermatt-Saas und Antrona-Zone, Platta Decke, Averser Bündnerschiefer) und zumindest Anteile des Mittelpenninikums (Monte Rosa Decke und das Deckgebirge der Suretta Grundgebirgsdecke). Ob die mittelpenninischen Grundgebirgseinheiten (Suretta und Tambo Decke), Anteile der nordpenninischen Bündnerschiefer und die nordpenninische Adula Decke auch von den frühalpinen Deformationen erfaßt wurden, bleibt offen. Die frühalpinen Deformationen waren im allgemeinen mit einer Hochdruckmetamorphose verbunden (Ausnahmen sind die Arosa-Zone, die Platta Decke und Anteile der Combin-Zone). Diese frühalpine Hochdruckmetamorphose erfaßte auch die mittelpenninischen Grundgebirgsdecken (Suretta und Tambo), sowie die nordpenninische Adula und Cima Lunga Decke und Anteile der nordpenninischen Bündnerschiefer. Das läßt vermuten, daß auch diese Einheiten von der frühalpinen Orogenese erfaßt wurden. In den westlichen Zentralalpen fehlen eine vergleichbare Hochdruckmetamorphose und vergleichbare Deformationen in den nordpenninischen Decken unterhalb der Adula und Cima Lunga-Decke. In den östlichen Zentralalpen fehlen frühalpine Prägungen in der Schamser Deckgebirgsdecke und in Teilen der nordpenninischen Bündnerschiefer. In den zuletzt genannten Bündnerschiefern wurde bereichsweise bis in das Eozän Flysch abgelagert. Insgesamt zeigen diese Daten eine enge Nachbarschaft von Gebieten mit frühalpiner subduktionsgebundener Deformation und Metamorphose zu Gebieten, die von jeglicher frühalpiner Prägung verschont wurden, an.

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Paläomagnetische und sedimentologische Arbeiten zeigen, daß die Plattenkonvergenz in den Ost- und Zentralalpen sehr schräg war. Der Abtauchwinkel der jungen, und von daher wahrscheinlich warmen und auftreibenden südpenninischen Ozeankruste war vermutlich flach. Neuere paläotektonische Rekonstruktionen zeigen eine Reihe jurassischer Transformstörungen im ozeanischen penninischen Becken. Die Orientierung dieser Transformstörung war für eine Reaktivierung während der frühalpinen Konvergenz günstig. Diese Grenzbedingungen lassen eine großmaßstäbliche Aufteilung der Konvergenz in eine Subduktions- und eine Blattverschiebungskomponente vermuten. Eine solche Aufteilung kann erklären, warum Anteile der östlichen Zentralalpen subduktionsgebundene Deformation und Metamorphose erfuhren, während andere Gebiete jenseits der Blattverschiebungszonen gänzlich von subduktionsgebundenen orogenen Prägungen verschont blieben. Die schräge Plattenkonvergenz in den E–W-streichenden Ost- und Zentralalpen ließ vermutlich keine ausgedehnte Hochdruckmetamorphose zu, während die Subduktion in den Westalpen orthogonal zu den Plattengrenzen verlief und zu räumlich ausgedehnter Hochdruckmetamorphose führte.

Abstract

Structures, strain, rotational criteria, and geochronologic data reveal top-to-west directed thrusting highly oblique to the mountain belt in the lowermost Austroalpine and underlying South Pennine units in the eastern Central Alps, westernmost Eastern and northernmost Western Alps during Cretaceous to mid-Eocene (early Alpine) times. Deformation affected the Pennine-Austroalpine boundary zone (Arosa zone), the South Pennine ophiolitic units (Zermatt-Saas and Antrona zones, Platta nappe, Avers Bündnerschiefer), and, at least parts, of the Middle Pennine units (Monte Rosa nappe and the cover of the Suretta nappe). Whether or not the Middle Pennine Suretta and Tambo basement nappes, parts of the North Pennine Bündnerschiefer, and the North Pennine Adula nappe were also affected by early Alpine deformation remains an open question. Deformation was commonly accompanied by high-pressure metamorphism (exceptions are the Arosa zone, the Platta nappe and parts of the Combin zone). Early Alpine high-pressure metamorphism also affected the Suretta, Tambo, Adula and Cima Lunga nappes, as well as parts of the North Pennine Bündnerschiefer, suggesting that these nappes were also affected by the early Alpine orogeny. In the western Central Alps comparable high-pressure metamorphism and comparable deformation are largely absent in the North Pennine units underneath the Adula and Cima Lunga nappes. In the eastern Central Alps the Middle Pennine Schams cover nappe and parts of the North Pennine Bündnerschiefer also lack early Alpine orogenic imprints. In the latter flysch sedimentation continued until the Eocene. Overall, these data suggest a particular proximity of areas which suffered early Alpine subduction-related metamorphism/deformation to areas that were not affected by subduction during the early Alpine orogenic stage.

Paleomagnetic and sedimentologic work indicates that plate convergence in the E–W extending part of the Alps was highly oblique. The dip of the young, and therefore presumably hot and buoyant South Pennine oceanic crust was probably shallow. Recent paleotectonic reconstructions show a number of Jurassic transform faults in the Pennine realm which were favourably oriented for reactivation during the early Alpine convergent history of the Alps. Such features favour a large-scale partitioning of convergence into subduction and strike-slip and may explain why parts of the nappe edifice suffered deformation and metamorphism, while others, which were beyond the major strike-slip zones, escaped deformation and metamorphism. The highly oblique convergence in the E–W trending Eastern and Central Alps probably precluded widespread high-pressure metamorphism, whereas subduction in the Western Alps was almost orthogonal to the plate boundaries and caused a really extensive high-pressure metamorphism.

1. Introduction

Traditionally the E–W trending part of the Alps has been interpreted in terms of N–S directed plate convergence between Africa and Europe perpendicular to the former plate margins (e.g. TOLLMANN, 1977). Paleomagnetic data (e.g. SAVOSTIN et al., 1986), as well as modern sedimentologic and kinematic studies in the Eastern Alps (e.g. HESSE, 1981; WAIBEL & FRISCH, 1989; RATSCHBACHER et al., 1987, 1989; SCHMID & HAAS, 1988) demonstrate approximately E–W oriented crustal shortening during the Cretaceous, which are difficult to reconcile with interpretations of N–S directed plate convergence. RATSCHBACHER (1986) introduced a transpressional model to account for this inconsistency and to explain west directed thrusting during Cretaceous times in the Eastern Alps.

In the Central Alps, major deformation is generally attributed to meso-Alpine (Late Eocene to Early Oligocene) north moving nappes which proceeded under a regional Barrovian medium- to high-temperature metamorphism indicating a high geothermal gradient (Text-Fig. 1a; e.g. MILNES, 1974, 1978; MERLE et al., 1989; MERLE & GUILLIER, 1989). However, associated mineral isograds transect the nappe boundaries without being offset (FREY et al., 1974) indicating that the Barrovian metamorphism postdated nappe stacking. Furthermore, well known high-pressure relics in the Adula (indicating more than 17 kbar; HEINRICH, 1986) and Cima Lunga (indicating more than 20 kbar; ERNST, 1976; EVANS & TROMMSDORFF, 1978; HEINRICH, 1986) nappes of the Central Alps predate the medium- to high-temperature metamorphism (Text-Fig. 1a; NIGGLI, 1970; FREY et al., 1983; HEINRICH, 1986). Flysch sedimentation in parts of the North Pennine Bündnerschiefer trough in the vicinity of the Adula nappe commenced in mid-Cretaceous times (Tomül Flysch; PROBST, 1980; ISLER & PANTIC, 1980). These findings are considered to imply Cretaceous orogenic activity in the eastern Central Alps (OBERHÄNSLI, 1986; POLINO et al., 1990), but the significance of these data for the early Alpine tectonic evolution of the Central Alps remains enigmatic.

There has been considerable disagreement in recent years concerning the existence and the extent of an early Alpine orogenic event in the Central Alps and a critical reevaluation of the existing data is warranted. This contribution reviews early Alpine sedimentologic, metamorphic, isotopic and kinematic data from the Central Alps, the adjacent westernmost part of the Eastern Alps, and the northermost part of the Western Alps. Special emphasis, however, is devoted to the eastern Central Alps and deformation/metamorphism relationships and the timing of high-pressure metamorphism there. Furthermore, a general tectonic model for the early Alpine orogeny in the Central Alps is discussed. This model highlights the spatial distribution of early Alpine orogenic activity and should be regarded as a working hypothesis to be tested by future research.

In this contribution the term early Alpine will be used for the time interval between the Cretaceous and the pre Late Eocene (i.e. pre "meso-Alpine" in the sense of TRÜMPY, 1973). Therefore, all data summarised herein predate the main phase of mountain building in the Central Alps which is thought to have taken place in a relatively short time interval between the Late Eocene and the Early Oligocene, i.e. the "meso-Alpine" phase of TRÜMPY (1973, 1980). The term early Alpine as defined in this contribution should not be confused with the term "eo-Alpine" as defined by TRÜMPY (1980) for the Cretaceous orogenic evolution of the Alps. I consider the end of the early Alpine phase to imply a major change in the orogenic evolution of the Alps, because afterwards the Alps entered a phase of full continental collison (i.e. the "meso-Alpine" phase of TRÜMPY, 1973). The end of the early Alpine phase is related to a major change in the boundary conditions. The rate of subduction slowed down from perhaps 10 km/myr to approximately 4 km/myr which was accompanied by an increase in the thermal gradient that produced the "meso-Alpine" Barrovian metamorphism (PLATT, 1986).

2. Geologic-Tectonic Setting

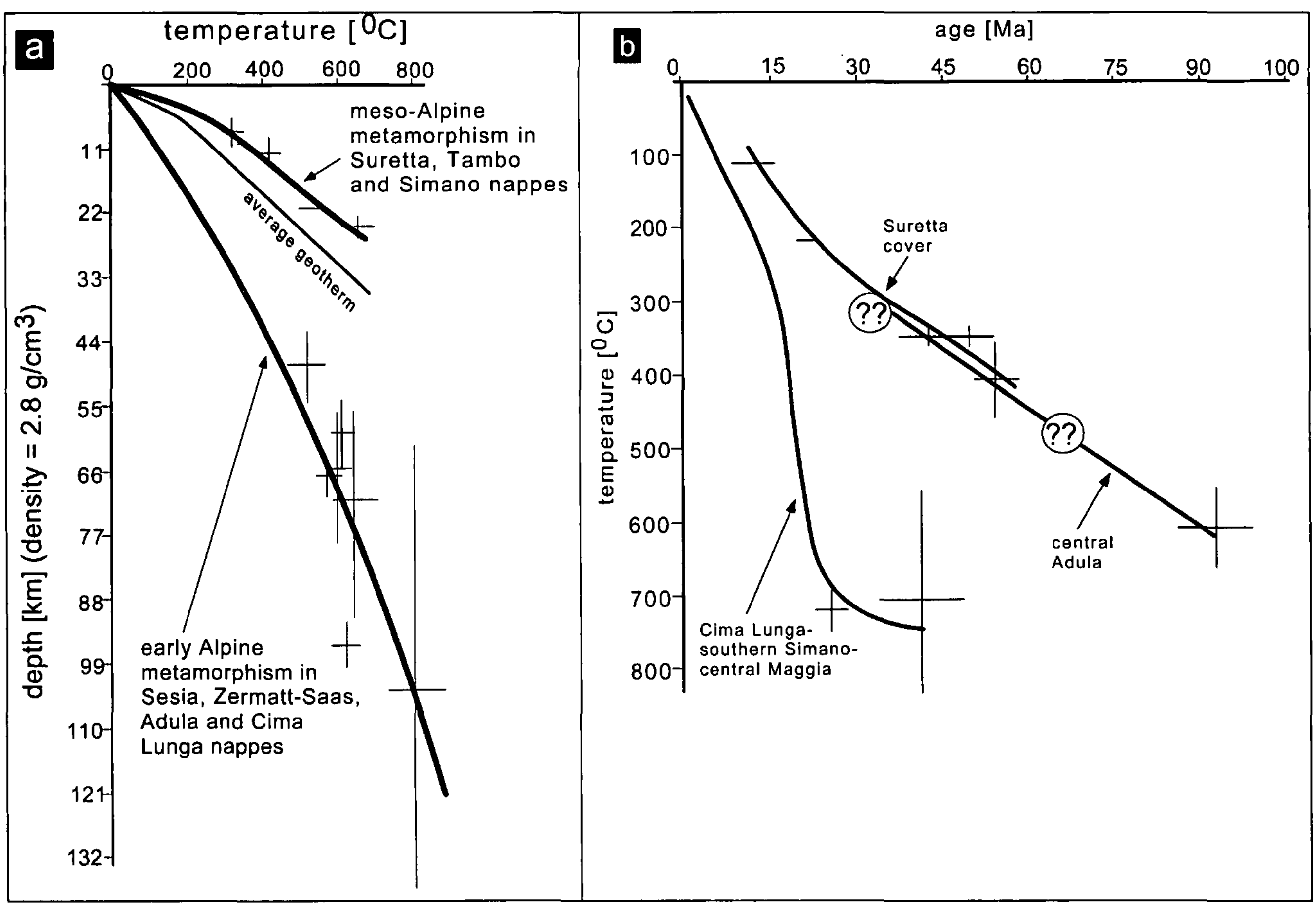
It is commonly assumed that the Adula nappe and the Cima Lunga nappe form one coherent tectonic unit (e.g. Tectonic Map of Switzerland, 1980).

Recent isotopic work by BECKER (1992), however, has revealed significantly different Sm/Nd garnet-pyroxene-whole rock metamorphic cooling ages for both nappes. Eclogites and garnet peridotites from the Cima Lunga nappe yielded Eocene ages, whereas eclogites from the Adula nappe yielded Cenomanian ages (see below). This pronounced discrepancy has led BECKER (1992, 1993) to question the assumption that both nappes form one coherent tectonic unit. Temperature versus time curves for both nappes also show marked differences (Text-Fig. 1b). For these reasons, the Adula and the Cima Lunga nappes are treated here as two independent tectonic units.

The main foliation in the Central Alps defines a complex dome structure, the deepest units of which are exposed in the centre of two subdomes (e.g. MILNES, 1978; PFIFFNER et al., 1990; Text-Fig. 2).

The eastern, Ticino subdome is floored by the Leventina and Lucomagno granitic gneiss (Le and Lu in Text-Fig. 2). To the east and south, tectonically higher, more internal, basement nappes are exposed, which are, from bottom to top, the Simano, Cima Lunga, Adula, Tambo and Suretta nappes. The Simano, Cima Lunga and Adula nappes represent North Pennine basement, separated from the overlying Middle Pennine Tambo and Suretta basement and the Schams cover nappes by ophiolitic mélange zones (Areua-Bruschghorn and Martegnas zones; SCHMID et al., 1990) which are tectonically intercalated with or lie on top of the North Pennine Bündnerschiefer.

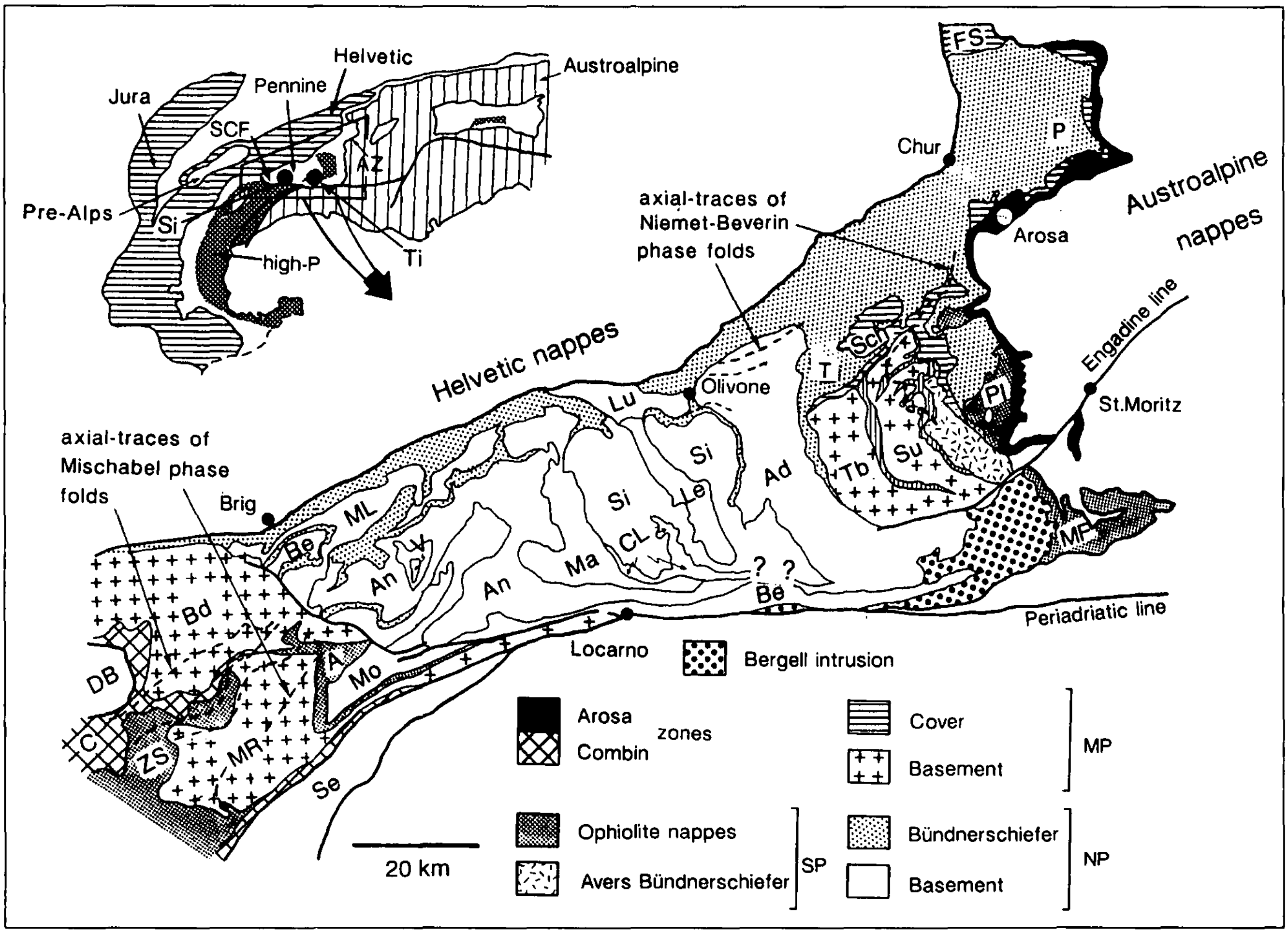
Geochemical work indicates that the North Pennine basin was, at least in part, floored by ridge-generated oceanic crust (DÜRR et al., 1993). Flysch sedimentation in the North Pennine basins lasted from the Cenomanian through the Eocene (ZIEGLER, 1956; TRÜMPY, 1980). Recent work in the Schams nappes by SCHMID et al. (1990) shows that the Niemet-Beverin fold (Text-Fig. 3a) is a large-scale backfold of Oligocene age, which has inverted the upper parts of the Suretta and Schams nappes and also parts of the North Pennine Bündnerschiefer. The ophiolitic Avers or South Pennine Bündnerschiefer, as well



Text-Fig. 1.

a) Composite metamorphic arrays for the early Alpine high-pressure metamorphism in the Sesia, Zermatt-Saas, Adula and Cima Lunga nappes and for the post high-pressure Barrovian metamorphism in the Simano, Adula, Tambo and Suretta nappes (data from FREY et al., 1980; BARNICOAT & FRY, 1986; HEINRICH, 1986; REINECKE, 1991; RING, 1992a).

b) Temperature versus time curves for various nappes in the eastern Central Alps (note, that curve for Cima Lunga, southern Simano and central Maggia nappe is composite) (data from HURFORD et al., 1989; HEINRICH, 1986; BECKER, 1992; RING, 1992a). Although the curve for the central Adula nappe is poorly constrained, the data suggest a rather similar evolution for the Suretta cover and the central Adula nappe, but indicate a different temperature-time evolution for the Cima Lunga-southern Simano-central Maggia nappe stack of the Central Alps.

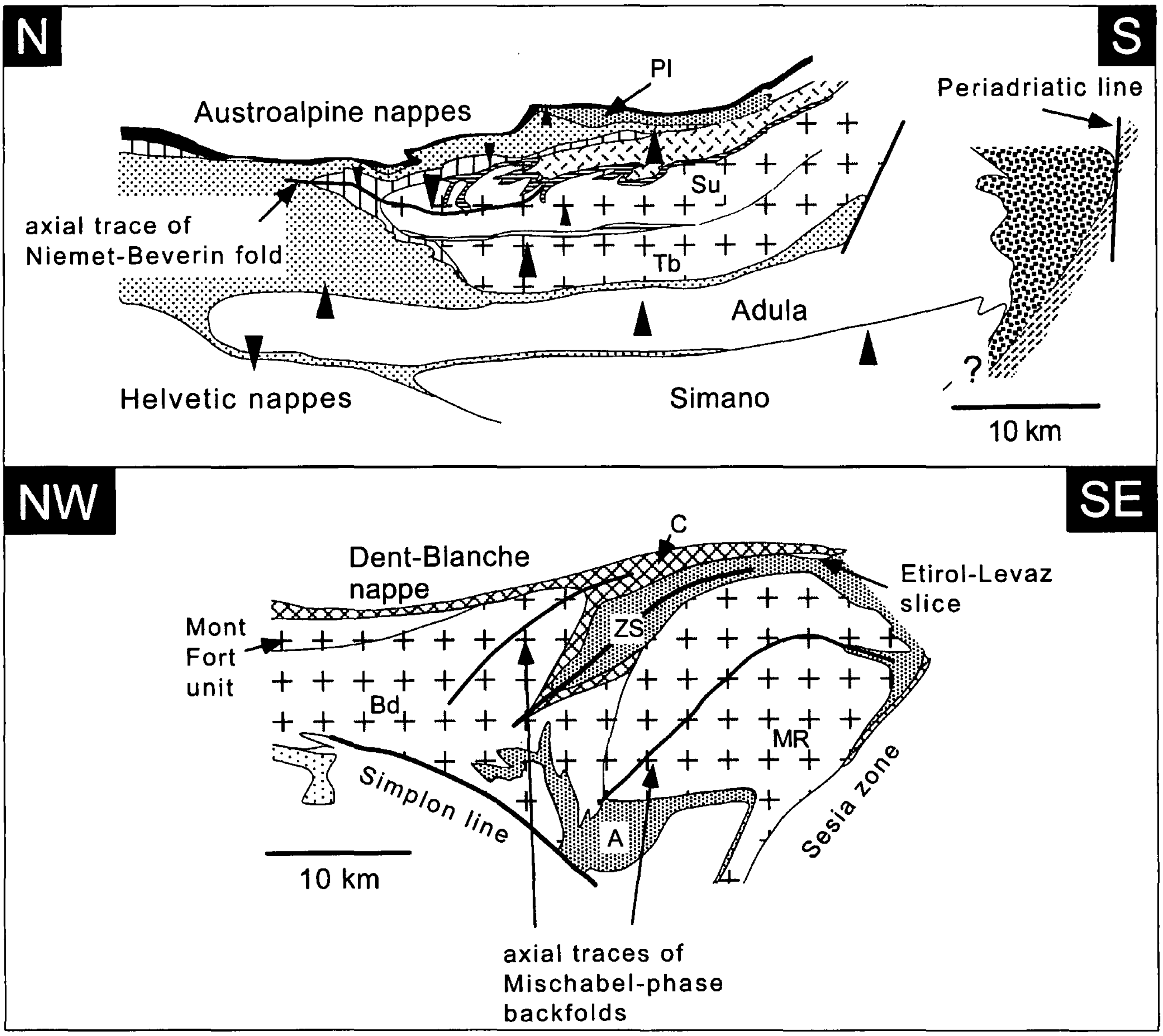


Text-Fig. 2.
Simplified map of the Alps showing Austroalpine unit (upper plate during Alpine orogeny and northern part of Adriatic subplate), continental and oceanic Pennine unit, and the European foreland (Helvetic nappes and Jura).
The Central Alps are situated between the Simplon line (SCF) and Arosa zone (AZ). Note the large area of high-pressure metamorphism (blueschist- and eclogite-facies) in Western Alps (S of Simplon line). Ti and Si indicate Ticino and Simplon subdomes within Central Alps. Main map: Tectonic sketch map of the Central Alps. The axial traces of Niemet-Beverin and Mischabel phase folds are shown according to MILNES et al. (1981) and SCHMID et al. (1990). Note, that the Schams nappe and parts of the North Pennine Bündnerschiefer were backfolded during the Oligocene (Niemet-Beverin fold) and that their upper, overturned limbs were brought into their present-day position between the Platta nappe and the Avers Bündnerschiefer not before the Late Oligocene. The nappes below (i.e. west) of the Adula nappe and below (i.e. east) of the Simplon line will be called Lepontine nappes in this article.
Legend: SP = South Pennine, MP = Middle Pennine, NP = North Pennine.
Map: FS = Falknis-Sulzfluh, Pl = Platta, MF = Malenco-Forno, Su = Suretta, Tb = Tambo, Sch = Schams, Ad = Adula, CL = Cima Lunga nappe, Si = Simano, Le = Leventina, Lu = Lucomango, Be = Bellinzona, Ma = Maggia, An = Antigorio, V = Verampio; ML = Monte Leone, Be = Berisal, Mo = Moncucco, Bd = Bernard, DB = Dent-Blanche, C = Combin, ZS = Zermatt-Saas, MR = Monte Rosa, A = Antrona, Se = Sesia, T = Tomül flysch, P = Prättigau flysch.
Niesen and Wägital flysch deposits crop out in the Pre-Alps and the Vorarlberg flysch belongs to the Eastern Alps.

as the Platta, Forno and Malenco zones represent remnants of the South Pennine ocean. The Pennine nappe edifice is separated from the overlying Austroalpine units by the Arosa zone which is a very heterogenous and disrupted unit containing ophiolitic South Pennine and continent-derived Austroalpine material and is interpreted as part of the main Alpine suture zone (e.g. WEISSERT & BERNOULLI, 1985; LÜDIN, 1987; RING et al., 1990).

The Simplon subdome in the western Central Alps is floored by the Verampio gneiss (V in Text-Fig. 2). The overlying basement nappes are surrounded by North Pennine Bündnerschiefer which rarely contain fragments of basic or ultrabasic rocks. The latter are restricted to the upper parts of the Bündnerschiefer. To the west tectonically higher basement nappes crop out. Those are the Antigorio, the Monte Leone and the Berisal nappe. The nappes of the western Central Alps represent the deepest tectonic units of the Pennine nappe edifice (Lepontine Nappes, Text-Fig. 2). They are separated from the structurally higher nappes of the Western Alps by the Simplon line (Text-Figs. 2 and 3b). The Simplon line is a late-Alpine low angle normal fault (MANCKTELOW, 1985).

The Bernhard basement nappe of the northern part of the Western Alps lies in the Middle Pennine zone and is overlain by the South Pennine Zermatt-Saas and Antrona ophiolite zones. The present-day position of the Monte Rosa nappe above the Antrona ophiolites and below the Zermatt-Saas oceanic complex can be interpreted as a mid-Tertiary doming and vertical intrusion of continental material into the dense oceanic rocks (RING & MERLE, 1992). This implies that the Monte Rosa nappe has a Middle Pennine position (compare the similar interpretation of the Dora-Maira unit of the Western Alps by BALLÈVRE et al., 1990). The Austroalpine nappes of the Western Alps (i.e. Sesia and Dent-Blanche nappes) are separated from the Zermatt-Saas zone by the highly disrupted and heterogenous Combin zone (e.g. BEARTHT, 1976; MARTHALER & STAMPFLI, 1989). The latter contains South Pennine ocean-



Text-Fig. 3.
Composite cross-section to illustrate present-day overall tectonic structure.
a) Eastern Central Alps (modified from SCHMID et al., 1990 and PFIFFNER, 1990; arrows indicate tectonic top).
b) Northern part of the Western Alps (modified from MILNES et al., 1983).

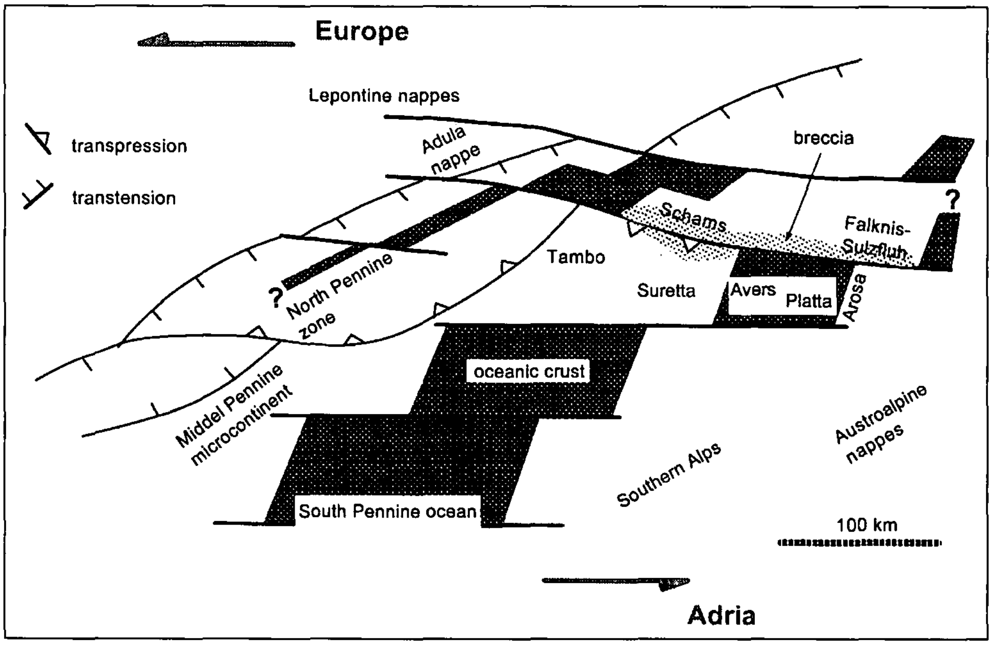
ic units as well as continent-derived rocks (CABY, 1981). Hence, at least parts of the Combin zone may be equivalent to the Arosa zone in the east (see also STAMPFLI & MARTHALER, 1990). Locally, Austroalpine slices are tectonically intercalated between the Zermatt-Saas and Combin zones (e.g. Etirol-Levaz slice, Text-Fig. 3b).

During the mid-Tertiary, large-scale refolding affected the northern part of the Western Alps (e.g. MILNES et al., 1981, Text-Fig. 3b) and caused inversion of parts of the nappe pile. These Mischabel-phase backfolds are correlated to the Niemet-Beverin folding phase (RING & MERLE, 1992). In both cases, large-scale backfolding occurred in greenschist-facies terrains, whereas the underlying amphibolite-facies terrains show no backfolding, suggesting that backfolding was controlled by thermal conditions.

The backfolding in the Pennine zone can be explained by differential, subhorizontal foreland movement of viscous material below a relatively rigid orogenic lid which is governed by frictional strength (Arosa-Platta units and Austroalpine nappes). Modelling work by MERLE & GUILLIER (1989) resulted in a similar relative transport velocity profile within a viscous medium (silicone putty) underlying an orogenic lid governed by Coulomb medium (sand). The relative transport velocity profile produced a line of no shear strain underneath which relatively high-grade metamorphic rocks were pushed faster towards the foreland than the lower grade rocks on top.

Therefore the shear criteria in the low grade rocks indicate a top-to-the-hinterland displacement with respect to deeper and faster forelandward moving viscous material, i.e. low grade rocks moved relatively backwards to the high-grade rocks below the line of no shear strain and caused the backfolding in the higher parts of the nappe stack (see MERLE & GUILLIER, 1989, for a general model of this backfolding event).

Jurassic paleotectonic reconstructions for the Pennine realm infer a transtensional setting (Text-Fig. 4; e.g. WEISSERT & BERNOULLI, 1985; DEWEY et al., 1989; SCHMID et al., 1990). Contractional motion commenced in about Early Cretaceous time (e.g. WINKLER, 1988) in the internal units



Text-Fig. 4.
Paleotectonic reconstruction of the Central Alps for the Jurassic (modified after SCHMID et al., 1990).
BS = Bündnerschiefer, FS = Falknis-Sulzfluh zone, Av = Avers Bündnerschiefer, Pl = Platta nappe.

and prograded to the foreland (e.g. FRISCH, 1979). Paleomagnetic work indicates a large component of sinistral strike-slip between the European and the African plates during the Cretaceous (SAVOSTIN et al., 1986; WESTPHAL et al., 1986). Left-lateral strike-slip between these two plates caused counterclockwise rotation of the Adriatic subplate between them. The Adriatic subplate moved independently from the African plate from at least 130 to 60 Ma (e.g. ZIJDERVELD et al., 1970), or perhaps throughout most of the history of the Alpine orogeny (PLATT et al., 1989).

3. Review of Data and Observations

3.1. Flysch Sedimentation

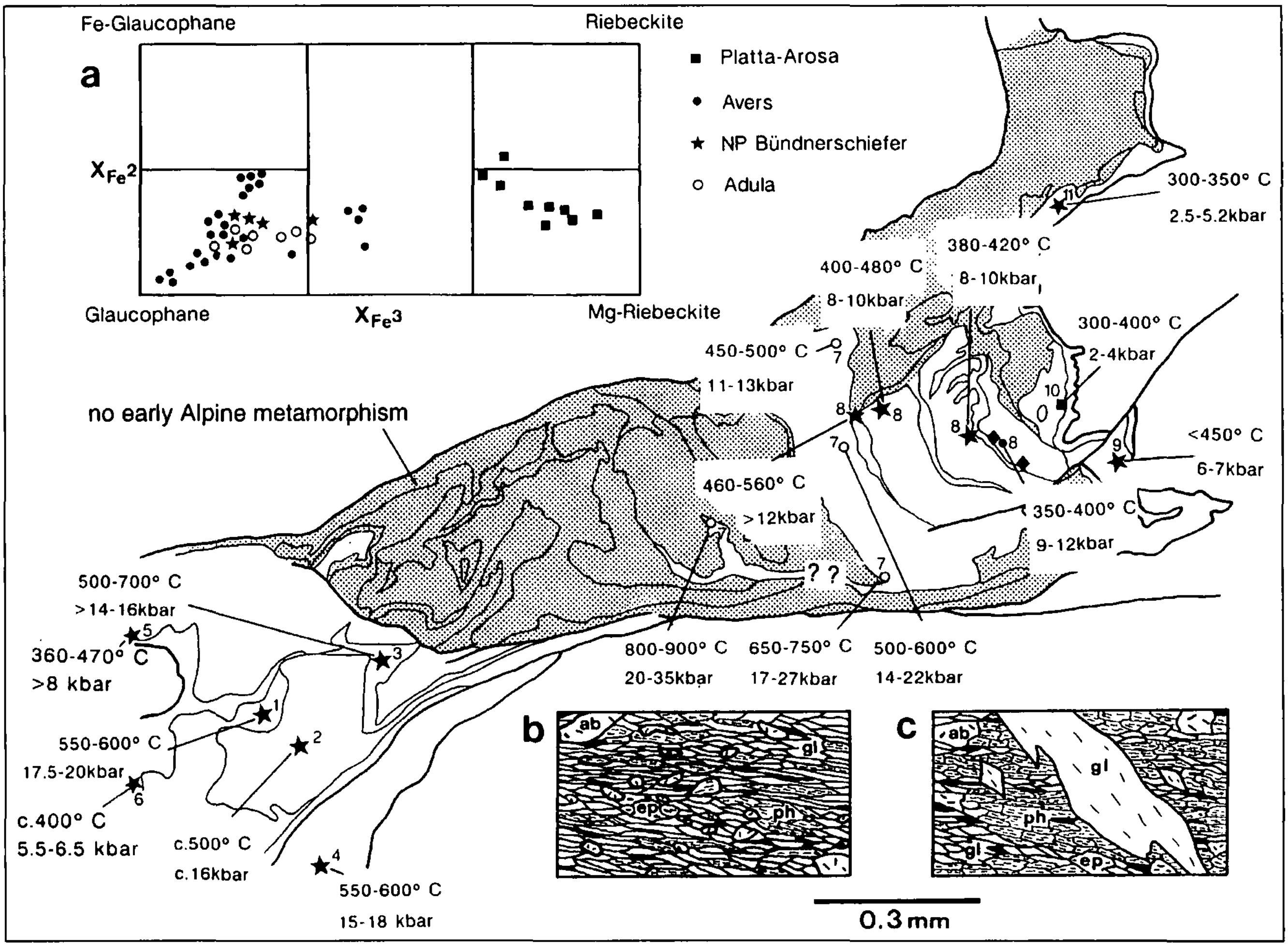
Flysch deposition in the South Pennine units is reasonably well understood and commenced in Aptian to Albian times (e.g. TRÜMPY, 1980; LÜDIN, 1987; WINKLER, 1988; MARTHALER & STAMPFLI, 1989). Relic glaucophane in mid-Cretaceous flysch from the Arosa-Zone is thought to reflect incipient orogenic activity already during the Early Cretaceous, prior to widespread flysch sedimentation (WINKLER & BERNOULLI, 1986).

The onset of flysch deposition in the Middle and North Pennine units is less well constrained. One reason is that uplift and erosion have destroyed most of the synorogenic deposits (TRÜMPY, 1973). However, there is distinct evidence that flysch sedimentation commenced in the Cenomanian, as indicated by the Niesen, Wägital, Tomül, Prättigau, and Vorarlberg flysch deposits (e.g. THUM & NABHOLZ, 1972; TRÜMPY, 1980; HOMEWOOD, 1983). Such a view seems to be corroborated by sedimentologic studies in the Schams nappe, where SCHMID et al. (1990) reported a Late Cretaceous unconformity which may reflect first orogenic events in the Schams nappe (SCHMID et al., 1990, p. 276), although SCHMID et al. place the first deformation event into mid-Tertiary times. KELTS (1981) reported redepositional processes (mud diapirs) from the Cenomanian Via Mala section of the North Pennine Bündnerschiefer and the Cenomanian Klus series of the Prättigau flysch which he attributed to Late Cretaceous orogenic activity. CARON et al. (1989) came to a similar conclusion and reported that flysch sedimentation in the Prättigau flysch commenced in Turonian times and was related to closure of the North Pennine basin. HOMEWOOD (1977) gave evidence for Cretaceous flysch sedimentation and melange formation in the North Pennine nappes of the Pre-Alps and suggested that this domain underwent continuous contractional deformation from Late Cretaceous to Eocene times which closed parts of the North Pennine basin. However, although closing of sedimentary basin apparently began in Late Cretaceous time, sedimentation in other parts of this basin occurred until the Eocene (ZIEGLER, 1956).

3.2. Early Alpine Metamorphic Conditions

The extent and distribution of high-pressure metamorphism in the Central Alps is still a matter of controversy. Nonetheless, there is growing evidence that large parts of the eastern Central Alps experienced high-pressure metamorphism (Text-Fig. 5).

Eclogitic parageneses in the Adula nappe formed by prograde reactions from blueschist-facies assemblages (HEINRICH, 1986; LÖW, 1987; Text-Fig. 6a). P-T estimates for the central Adula nappe (Trescolmen area) by various authors are fairly similar and range between 550–650°C and 15–22 kbar (HEINRICH, 1986, Text-Fig. 5) and 650–670°C and 18 kbar (SANTINI, 1992). Omphacite-glaucophane-magnetite parageneses in the overlying North Pennine Bündnerschiefer near the San Bernardino Pass immediately underneath the Tambo nappe also demonstrate high-pressure metamorphism. Reported P-T conditions are 465–630°C, 10–11 kbar (SANTINI, 1992) and 460–560°C, 12 kbar (RING, 1992a, Text-Fig. 5). High-pressure metamorphism in parts of the North Pennine Bündnerschiefer is corroborated by the occurrence of carpholite (indicating P>7 kbar and T>350°) in the Lugnez valley (north of the frontal part of the Adula nappe) and near Thusis (GOFFE & OBERHÄNSLI, 1992). Furthermore, EIERMANN (1988) reported glaucophane from the Martegnas melange zone of the uppermost part of the North Pennine Bündnerschiefer. Estimates for high-pressure metamorphic conditions in the overlying Tambo nappe show a rather broad scatter and range from 605–800°C and 14–16 kbar (SANTINI, 1992), 500–550°C and 10–13 kbar (BAUDIN & MARQUER, 1993) and 400–480°C and 8–10 kbar (RING, 1992a, Text-Fig. 5). A comparable scatter in high-pressure metamorphic conditions exists for the Suretta

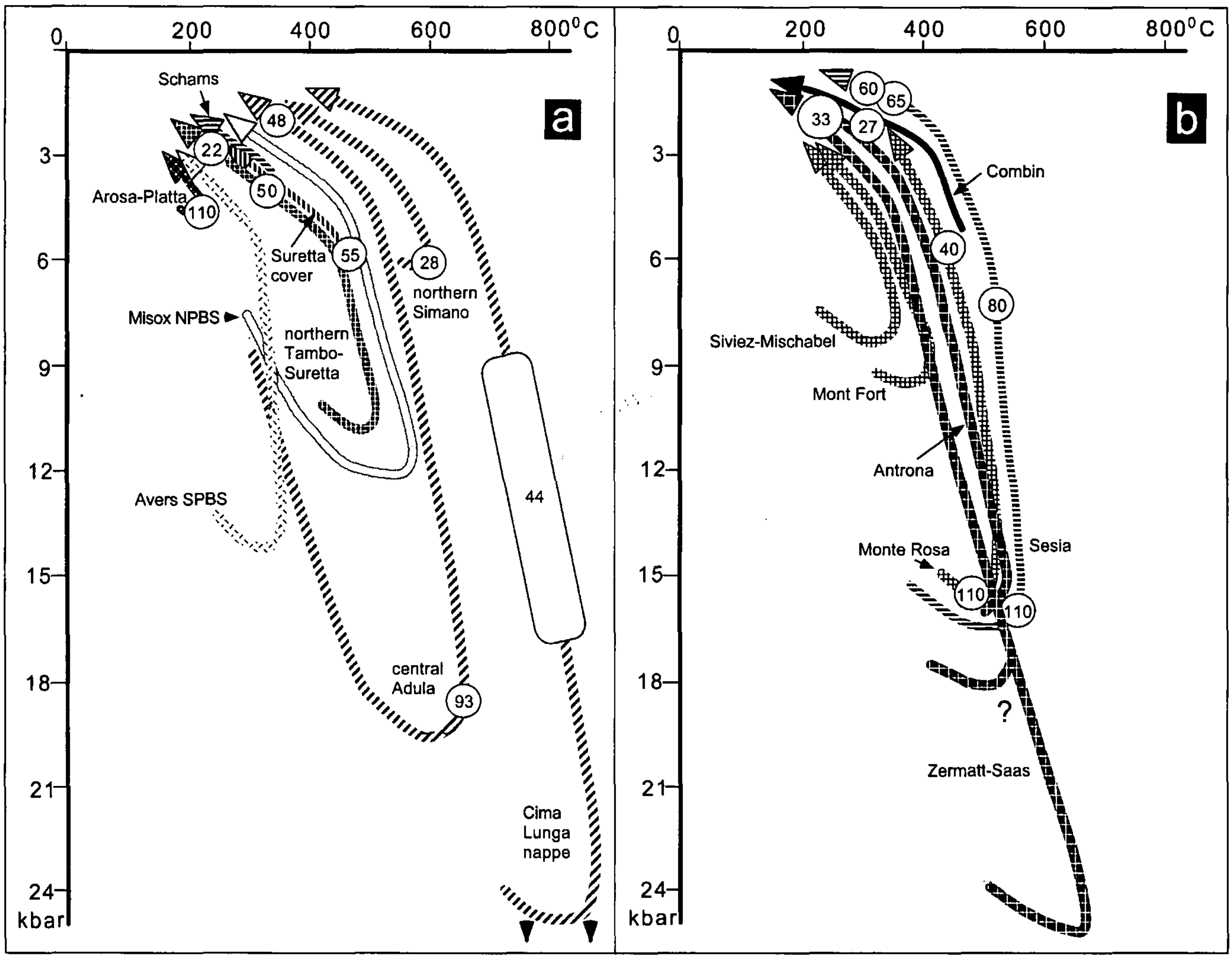


Text-Fig. 5.
Early Alpine P-T conditions for different nappes.
Data from 1 = BARNICOAT & FRY (1986), 2 = CHOPIN & MONIÈ (1984), 3 = COLOMBI & PFEIFER (1986), 4 = VUICHARD & BALLÈVRE (1989), 5 = WÜST & BAEHNI (1988), 6 = SPERLICH (1988), 7 = HEINRICH (1986), 8 = RING (1992), 9 = GUNTLI & LINIGER (1989), 10 = OBERHÄNSLI (1986), 11 = RING et al. (1989). For more data and further discussion see text.
a) Composition of blue amphiboles in the eastern Central Alps showing increase in glaucophane s.l. component to the west (see also OBERHÄNSLI, 1986, Fig. 4; data from OBERHÄNSLI, 1977; RING, 1992; $Fe^{2+} = Fe^{3+}$).
b) Glaucophane strongly sheared in foliation.
c) Glaucophane overgrowing foliation (both drawings are from microphotographs of rocks from the Avers Bündnerschiefer).
gl = glaucophane, ph = phengite, ep = epidote/clinozoisite, ab = albite. Riebeckites and Mg-riebeckites from the Arosa zone depict similar textural criteria as shown in (b + c) indicating that the early Alpine metamorphism outlasted deformation in the eastern Central Alps.

nappe. SANTINI (1992) estimated temperatures of 460–480°C for glaucophane amphibolites and temperatures of 560–750°C and pressures of 12–16 kbar for eclogitic rocks, whereas RING (1992a) proposed 380–420°C and 8–>10 kbar. The P-T estimates of RING (1992a) for the Suretta and Tambo nappes by means of garnet/phengite thermobarometry yielded low estimates, whereas the values of SANTINI (1992), especially those for the eclogitic rocks as deduced by garnet-pyroxene thermometry, gave high estimates. Blue amphiboles from the metasedimentary cover of the Suretta nappe near Cröt (Avers valley) have crossitic chemistry (RING, unpublished data) and suggest lower pressures than in the Suretta basement nappe. P-T estimates for the Avers Bündnerschiefer are 350–400°C and 9–>12 kbar (RING, 1992a, Text-Fig. 5). In general, the data indicate an overall decrease in pressure and temperature conditions towards the east (Text-Fig. 5; RING, 1992a). This is confirmed by the lower greenschist-facies metamorphism in the Platta nappe and the Arosa zone (Text-Fig. 5a).

Large portions of the North Pennine Bündnerschiefer and the Schams nappes (SCHREURS, 1990) apparently lack any evidence of high-pressure metamorphism. In the North Pennine basement nappes, there is unequivocal evidence for very high-pressure metamorphism (Cima Lunga nappe; HEINRICH, 1986, Text-Fig. 5) with pressure estimates of 20–35 kbar (HEINRICH, 1986) to 35–42 kbar (BECKER, 1993) and associated temperatures of 800–900°C (HEINRICH, 1986). A few probable high-pressure vestiges were reported from sparse basic and ultrabasic lenses within the Berisal nappe (STILLE & OBERHÄNSLI, 1987; Text-Fig. 5). Nevertheless, little evidence exists for this high-pressure event and this existing evidence is somewhat ambiguous, because garnets in the "eclogitic" rocks show very low pyrope and high almandine contents. Both, the Cima Lunga nappe and the Berisal nappe occupy a relatively high structural position within the North Pennine nappe stack. The deeper North Pennine nappes apparently show no evidence of a high-pressure event.

In the northern part of the Western Alps, eclogite-facies parageneses in the Zermatt-Saas zone and the Antrona ophiolites developed by prograde reaction from blueschist-facies assemblages (BARNICOAT & FRY, 1986). The



Text-Fig. 6.
Schematic P-T-time paths for Alpine high-pressure rocks in the eastern Central (a) and northernmost Western Alps (b).
Circled numbers indicate approximate ages in millions of years before the present. Curves for different units and age data after different authors as discussed in text.

Monte Rosa nappe underneath and the Austroalpine Sesia zone on top of the ophiolite zones shows a similar high-pressure imprint (e.g. HUNZIKER, 1970; CHOPIN & MONIÈ, 1984; VUICHARD & BALLÈVRE, 1988; Text-Fig. 5). P-T estimates for all of these nappes range between 15–20 kbar and 500–600°C (Text-Fig. 5); however, rare Mn-bearing metasedimentary lenses in the Zermatt-Saas zone in the Valtournanche yielded 26–28 kbar and 590–630°C (REINECKE, 1991). The decompression path of these metasedimentary rocks is very steep (Fig. 6b) and includes a second high-pressure metamorphic event at 13–15 kbar/500°C (REINECKE, 1991). It appears, that this second high-pressure imprint of the metasedimentary lenses is comparable to the high-pressure imprint for the rest of the Zermatt-Saas zone, as well as for the Monte Rosa nappe and Sesia zone.

However, the tectonic significance of the rare very high-pressure vestiges within the eclogite-facies rocks of the Zermatt-Saas zone are as yet not understood. Parts of the Bernhard nappe (Mont Fort and Siviez-Mischabel nappes; WÜST & BAEHNI, 1986; RAHN, 1991) and parts of the Combin zone (SPERLICH, 1988) show blueschist-facies metamorphism. However, other parts of the Bernhard nappe and the Combin zone as well as the upper unit of the Dent-Blanche nappe show no high-pressure imprint (e.g. BALLÈVRE et al., 1986; MAZUREK, 1988).

3.3. Radiometric Data

Radiometric age data constraining subduction-related high-pressure metamorphism from the Pennine-Austroalpine boundary region in the northern part of the Western Alps cluster around 130–110 Ma, and cooling ages fall into the range of between 80–60 Ma (Text-Fig. 6; HUNZIKER, 1974; RUBIE, 1984; OBERHÄNSLI et al, 1985; STÖCKERT et al., 1986). Age constraints from frontally accreted low to very low grade rocks in the eastern Central Alps (e.g. Arosa zone, Platta nappe) show a wide range of isotopic ages between 110–60 Ma (DEUTSCH, 1983; RING, 1989).

MONIÈ (1985) carried out a detailed Ar/Ar study on white mica in the Monte Rosa nappe. He interpreted weakly-defined plateau ages of 110 Ma to reflect the high-pressure metamorphic event and well defined plateau ages of ca. 40 Ma to date the main greenschist-facies overprint. Minor plateau ages of 27 Ma are thought to indicate a second greenschist-facies event. MONIÈ's data in conjunction with the data from the Penninic-Austroalpine boundary zone are thought to indicate a prolonged history of Cretaceous subduction, accretion and exhumation. Exhumation commenced in the Austroalpine units (Sesia zone) and progressed downwards.

Cooling of the Monte Rosa nappe occurred considerably later than cooling in the Sesia zone (Text-Fig. 6). Recent isotopic studies show more scattered ages which are considered, in part, to indicate a Tertiary age for high-pressure metamorphism in the Pennine zone (MONIÈ & PHILLIPOT, 1989; BARNICOAT et al., 1991). However, BALLÈVRE & MERLE (1993) argue that the scattered ages only occur in units which show a substantial greenschist- to amphibolite-facies overprint and may therefore reflect mixed ages.

K/Ar age determinations on the E–W-aligned blue amphiboles from the cover of the Suretta nappe near Cröt yielded ages of 49–55 Ma (HURFORD et al., 1989). The significance of this event is not understood. HURFORD et al. (1989) regard it as a crystallisation age, but, alternatively, it can be regarded as a metamorphic cooling age. ONSTOTT & PEACOCK (1987) have proposed a closure temperature of 450–550°C for argon in amphibole, but the closure temperature for blue amphibole is not well constrained. Unfortunately, no P-T data exist for the cover rocks of the Suretta nappe and temperatures for the underlying Suretta basement show a large spread (see above). Temperatures for the overlying Avers Bündnerschiefer are between 380–420°C and P-T conditions in the cover of Suretta nappe apparently never reached amphibolite-facies grade. Therefore, it seems likely that peak metamorphic temperatures for the high-pressure metamorphic event in the Suretta cover rocks did not exceed 450–550°C by very much. In this case, the age of 49–55 Ma should in fact be close to the age of crystallisation, if the above closure temperature for amphiboles is assumed to be the same as for blue amphiboles. Then a Late Paleocene to Early Eocene age for the blue amphiboles appears to be likely. Since the crossitic chemistry of the blue amphiboles from the cover of the Suretta nappe differs from the glaucophanitic chemistry of blue amphiboles in eclogitic lenses in the underlying Suretta basement nappe and the metabasalt of the overlying Avers Bündnerschiefer, the Late Paleocene to Early Eocene age must not necessarily be representative for the peak of high-pressure metamorphism in this region.

Phengite Rb/Sr ages from the Suretta nappe show a large spread beetween 23 and 45 Ma and an age of 35–40 Ma has been interpreted as a phengite crystallisation age (STEINITZ & JÄGER, 1981). Furthermore a Rb/Sr whole rock isochron of 118 Ma may represent a Cretaceous metamorphic event (STEINITZ & JÄGER, 1981); however, HURFORD et al. (1989) suggested that STEINITZ & JÄGER's Cretaceous Rb/Sr isochron may be an artefact of mixing. Because of the difficulty in interpreting the Rb/Sr phengite-whole rock data from the Suretta nappe, any interpretation of these data will be avoided here. K/Ar phengite ages of STEINITZ & JÄGER (1981) fall into the range of 38 to 50 Ma. These data are probably best interpreted to reflect cooling below 350–360°C (WIJBRANS et al., 1993). Although peak metamorphic temperatures for the high-pressure event show a rather huge spread (see above), they are higher than the K/Ar blocking temperature in phengite and therefore high-pressure metamorphism is older. For K/Ar in phengite, this closure temperature is, however, very close to the temperature conditions of the subsequent greenschist-facies metamorphic event in the Suretta nappe (RING, 1992a), and may thus approximately date the greenschist-facies metamorphic phase.

The age of the high-pressure metamorphism in the Adula nappe (Cretaceous or Tertiary?) is still controversial (e.g. SCHMID et al., 1990). Nonetheless, the high-pressure metamorphism reflects a lower than average geothermal gradient (Text-Fig. 1a) and indicates subduction to considerable depth. Thermal relaxation of thickened crust with time results in a high geothermal gradient and usually the time span for complete thermal relaxation in a thickened crust undergoing steady-state subduction is thought to be in the range of 30 to 60 Ma (GLAZNER & BARTLEY, 1985). Furthermore the exhumation of rocks from a depth of up to ca. 80 km (as inferred from the high-pressure data in the central Adula nappe) to a depth of approximately 25 km (as deduced from the mid-Tertiary metamorphic conditions, [HEINRICH, 1986]) may need some 27.5–55 Myr, using exhumation rates of 1 to 2 mm/a. However, the ages for high-pressure metamorphism in the Cima Lunga nappe and subsequent amphibolite-facies metamorphism in the immediately underlying Simano nappe (see below) suggest that exhumation and thermal relaxation have occurred at faster rates. SANTINI (1992) reported Ar/Ar phengite ages from the northern and central Adula nappe. Three samples from the northern part of the nappe yielded ages of between 31 and 40 Ma, whereas another three samples from the central part of the nappe gave ages of 34 to 48 Ma (note, that these Ar/Ar ages are similar to the K/Ar ages from the Suretta nappe). These ages appear to represent cooling below an isotherm of 350–360°C (WIJBRANS et al., 1993). Given that the amphibolite-facies overprint of the eclogite-facies metamorphism in the central Adula nappe took place at P-T conditions of 500–620°C (HEINRICH, 1986), the Ar/Ar data of SANTINI (1992) should be interpreted to reflect cooling after the amphibolite-facies event. This implies, however, that the amphibolite-facies event is older than 48 Ma, and that the preceding high-pressure event is considerably older than 48 Ma. According to this reasoning, a Late Cretaceous age for the high-pressure metamorphism in the Adula nappe seems to be most likely, although an earliest Paleocene age can not strictly be ruled out. A Late Cretaceous age is in accordance with a few Sm/Nd age determinations of BECKER (1992), which have yielded an age of 92.5 Ma.

Sm/Nd mineral ages of garnet peridotites and eclogites from the Cima Lunga nappe have yielded ages of between 37.5 and 43.9 Ma (BECKER, 1993). These ages are considered to be cooling ages. The closure temperatures for Sm/Nd in slowly cooled garnet from granulite-facies complexes has been estimated to be ca. 600±30°C (MEZGER et al., 1992). BECKER (1993) gave evidence for a relatively high cooling rate, and, therefore, he suggested, that his ages are close to the peak of eclogite-facies metamorphism, assuming that the above closure temperature for garnet remains the same in both highly and slowly cooled rocks. This assumption, however, may not be valid. Another line of reasoning for considering the Sm/Nd ages as being close to the peak of high-pressure metamorphism stems from the high closure temperature for Sm-diffusion in diopside (>850°C). The clinopyroxenes in BECKER's samples certainly have a high jadeite component and BECKER (1993) gave no evidence whether diopside and jadeite-rich pyroxene have a similar Sm-diffusion behaviour. Nevertheless, it appears to be reasonable to assume that the peak of high-pressure metamorphism probably has occurred in Late Paleocene to Middle Eocene times, prior to rapid cooling. It should be noticed, that GEBAUER et al. (1992) proposed an U/Pb zircon age of 28.5 Ma for the peak of eclogite-facies metamorphism in the Cima Lunga nappe. Their age is in marked contrast to the age of BECKER (1993), especially when the U/Pb monazite ages of 28 Ma for amphibolite-facies metamorphism (3–5 kbar, 650–700°, FREY et al., 1980) in the Simano nappe (KÖPPEL & GRÜNENFELDER, 1975) immediately underneath the Cima

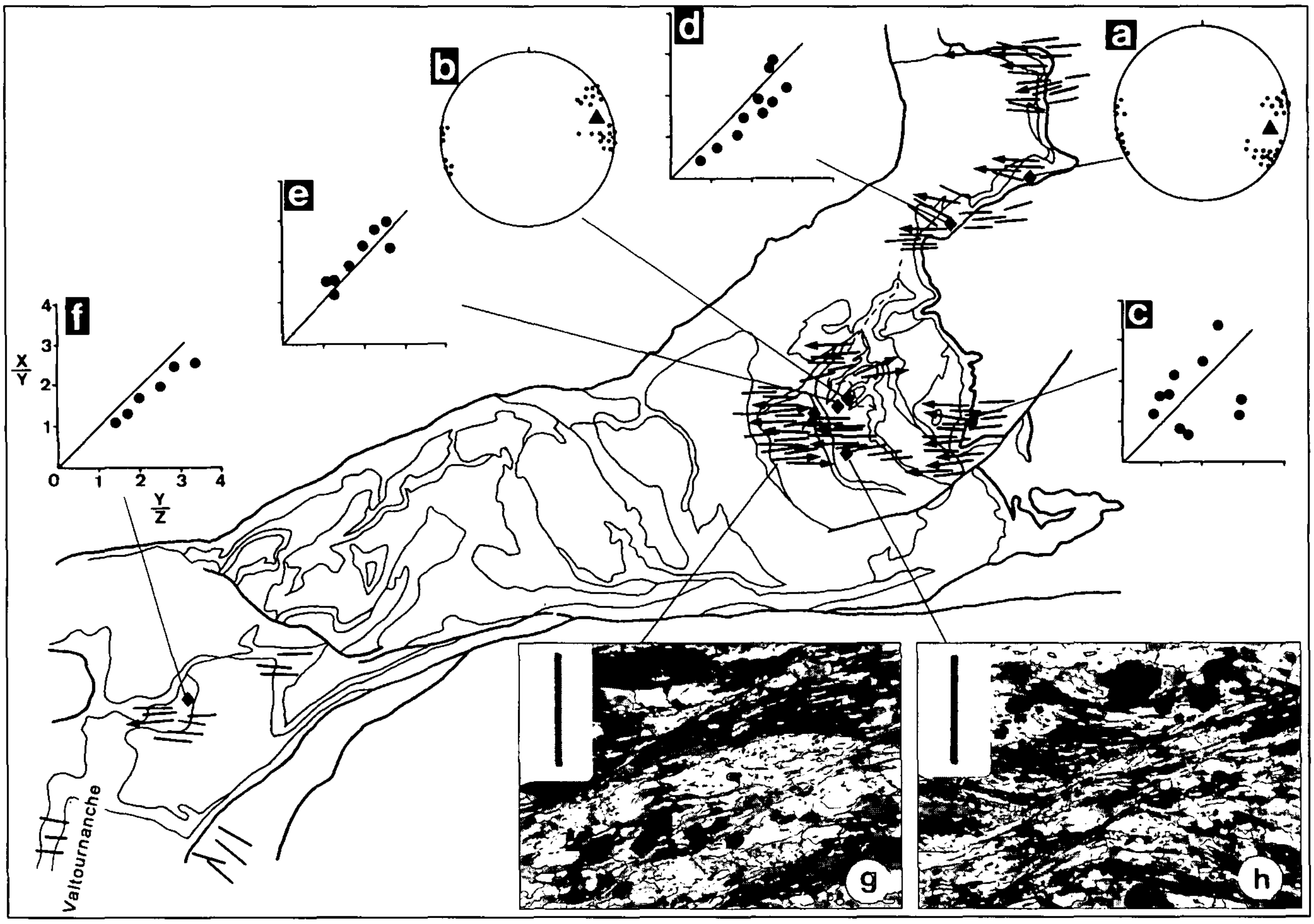
Lunga nappe are considered. This amphibolite-facies overprint also affected the Cima Lunga nappe and because associated isograds cut the nappe boundaries (FREY et al., 1980) it may be reasonable to assume, that both nappes have largely been juxtaposed by mid-Oligocene time. GEBAUER et al. (1992) unfortunately gave no data in support of their age and interpretation, and the relation of zircon growth to the peak of high-pressure metamorphism remains unclear. Therefore, the ages of BECKER (1993) are favoured here.

3.4. Early Alpine Kinematics and their Relation to Metamorphism

Early Alpine kinematic data for the Pennine-Austroalpine boundary zone appear to be much less controversial than those for the Middle and North Pennine units. In the latter nappes the major point of controversy is the succession of deformation events and their relation to the high-pressure metamorphism. Since there is general agreement between various authors that north to northwest directed thrusting in the Central Alps occurred in Late Eocene to Early Oligocene time (TRÜMPY, 1973, 1980; MILNES, 1974, 1978; MILNES & SCHMUTZ, 1978; MERLE et al., 1989; SCHMID et al., 1990; among others), this tectonic event will serve as a relative time marker in the following discussion.

3.4.1. Pennine-Austroalpine Boundary Zone in the Eastern Central Alps and South and Middle Pennine Nappes of the Northern Part of the Western Alps

Stretching lineations from the Pennine-Austroalpine boundary region in the eastern Central Alps and the adjacent Eastern Alps (LINIGER & GUNTLI, 1988; BIEHLER, 1990; DÜRR, 1992; RING et al., 1988, 1989) and in the Zermatt-Saas zone, the Antrona ophiolites and the Monte Rosa nappe of the northern part of the Western Alps (STECK, 1989; RING & MERLE, 1992) are approximately E–W oriented (Text-Fig. 7). In the eastern Central Alps, large-scale folding during the mid-Tertiary was in general subparallel to the orientation of these stretching lineations and did therefore not substantially reorientate the Cretaceous stretching trajectories as shown in Text-Fig. 7. In the northern part of the Western Alps, however, mid-Tertiary folding did in fact reorientate the early Alpine stretching lineations in the upper, inverted parts of the large-scale backfolds (see RING & MERLE, 1992). Therefore, only the unre-



Text-Fig. 7.
Early Alpine stretching lineations.
Data from STECK (1989), BIEHLER (1990), DÜRR (1992), RING et al. (1989), RING (1992b), RING & MERLE (1992).
Origin of arrows indicate measurement location. Early Alpine age is suggested by radiometric dating of deformation-related minerals (e.g. CHOPIN & MONIÉ, 1984; DEUTSCH, 1983; RING et al., 1989; HURFORD et al., 1989). The stretching lineations in the Suretta and Tambo nappes are not dated, but the foliation on which they occur can be traced into the Avers Bündnerschiefer, the Platta nappe and the Arosa zone, for which age data exist.
a+b) Stereographic projections (lower hemisphere) showing orientation of stretching lineations (stars) around large-scale folds (triangles). These plots indicate that the stretching lineations were not considerably reoriented by folding.
c–f) Finite strain data (Flinn, 1962) indicating slightly oblate to apparent plane strain conditions, data in (c) from DÜRR (1992).
g–h) Shear bands indicating top-to-the-west thrusting, west is to the left.

oriented stretching lineations from the upright parts of the folded nappe stack are shown in Text-Fig. 7. Finite strain estimations using the Rf/Φ- (DUNNET, 1969), the FRY- (FRY, 1979), and the AMS-methods (anisotropy of magnetic susceptibility; KLIGFIELD et al., 1981; HROUDA, 1982) indicate slightly oblate to apparent plane strain conditions (Text-Fig. 7c,d,f). Kinematic indicators, such as shear bands, rotated minerals, and oblique quartz-c-axis patterns, supply evidence for non-coaxial deformation and are fairly consistent in the lowermost Austroalpine nappes (LINIGER & GUNTLI, 1988), as well as in the upright parts of the Arosa zone (BIEHLER, 1990; DÜRR, 1992; RING et al., 1988, 1989), the Zermatt-Saas zone, the Antrona ophiolites and the Monte Rosa nappe (STECK, 1989; RING & MERLE, 1992). In parts of the nappes which have been overturned during mid-Tertiary folding the early Alpine kinematic indicators have been inverted (BIEHLER, 1990; RING et al., 1989; RING & MERLE, 1992). Blue amphiboles in the southern Arosa zone and in parts of the Zermatt-Saas zone are either aligned parallel to the E–W trending stretching lineation and are sheared in the accompanied foliation or overgrew both foliation and lineation, respectively. Therefore, at least some of the structures in the Arosa and Zermatt-Saas zones have probably been formed during the loading stage of subduction-related metamorphism.

These kinematic indicators occur in mylonitic zones at tectonic boundaries, such as the Pennine-Austroalpine boundary zone, and within the interiors of nappes. The kinematic indicators and their relation to the metamorphic evolution are interpreted as the result of top-to-the-west directed nappe stacking during subduction-accretion. Nappe stacking apparently led to penetrative deformation that affected the thrust zones between the nappes and, also, the interiors of the nappes.

In the Combin zone, no structures associated with the early Alpine mildly blueschist-facies metamorphism have been observed (see also BALLÈVRE & MERLE, 1993). Subsequent greenschist-facies structures in the Combin zone display a pervasive northwest trending stretching lineation. Associated sense of shear indicators seem to be equivocal. They are either thought to demonstrate a consistent top-to-the-SE tectonic transport (J.R. PORTER, pers. comm., 1991), or, alternatively, a uniform top-to-the-NW directed sense of shear (LE GOFF, 1986; BALLÈVRE & MERLE, 1993). RING (unpublished data) found alternating top-to-the-E/SE and top-to-the-W/NW kinematic indicators in the Combin zone immediately above the Zermatt-Saas zone in the Zermatt area, and more uniformly top-to-the-SE directed sense of shear in the eastern Valtournanche area (middle part of the Combin zone). The Etirol-Levaz slice of the Sesia zone, which is sandwiched between the Combin and Zermatt-Saas zones in the western Valtournanche valley (Text-Fig. 3b), shows an overall top-to-the-E sense of shear at its top, and a top-to-the-W sense of shear at its base (RING, unpublished data). For the immediately underlying, uppermost Zermatt-Saas zone high-pressure structures yielded also ambiguous results. VOGLER (1987) reported a uniform top-to-the-SE sense of shear, whereas BALLÈVRE & MERLE (1993) reported alternating top-to-the-W and top-to-the-E kinematic indicators.

These kinematic data from the Combin zone and the contact between the Combin and Zermatt-Saas zones are hard to interpret. One possibility might be a large component of coaxial deformation which is manifested in a pattern of distributed non-coaxial flow with variable senses of shear.

3.4.2. Avers Bündnerschiefer and Suretta Nappe

In the South Pennine Avers Bündnerschiefer and in the cover rocks of the Middle Pennine Suretta nappe, an E–W oriented mineral stretching lineation is defined by preferred orientation of glaucophane and crossite, respectively. The blue amphiboles are highly sheared and now lie in the foliation planes (Text-Fig. 5b, 8a). In the Avers Bündnerschiefer, this high-pressure foliation is overgrown by blue amphiboles (Text-Fig. 5c) of almost similar composition (RING, 1992a). Therefore, some of these structures probably formed during the loading stage of high-pressure metamorphism. The association of the structures to high--pressure metamorphic minerals and, the fact that those structures do not overprint earlier structures suggest, that they are related to an early Alpine subduction-related tectonic event. The foliation, in which the E–W oriented high-pressure minerals are aligned, can be traced into the Suretta basement. There, an E–W oriented mineral and aggregate stretching lineation is also associated with this foliation; however, the relation of both the foliation and the stretching lineation to the high-pressure metamorphic fabric is not straightforward (RING, 1992a). Nonetheless, this foliation is overprinted by NW/NNW displacing shear zones (Text-Fig. 8b), the latter are usually attributed to Late Eocene/Early Oligocene orogenic activity (MILNES & SCHMUTZ, 1978; SCHREURS, 1990; RING, 1992b). MILNES & SCHMUTZ (1978) also described an early Alpine tectonic event (Avers phase) that predated north to northwest directed thrusting (Ferrera phase) in the Suretta nappe. Thus, it is tempting to correlate the above described foliation, and the accompanied E–W trending stretching lineation, with the Avers phase of MILNES & SCHMUTZ (1978).

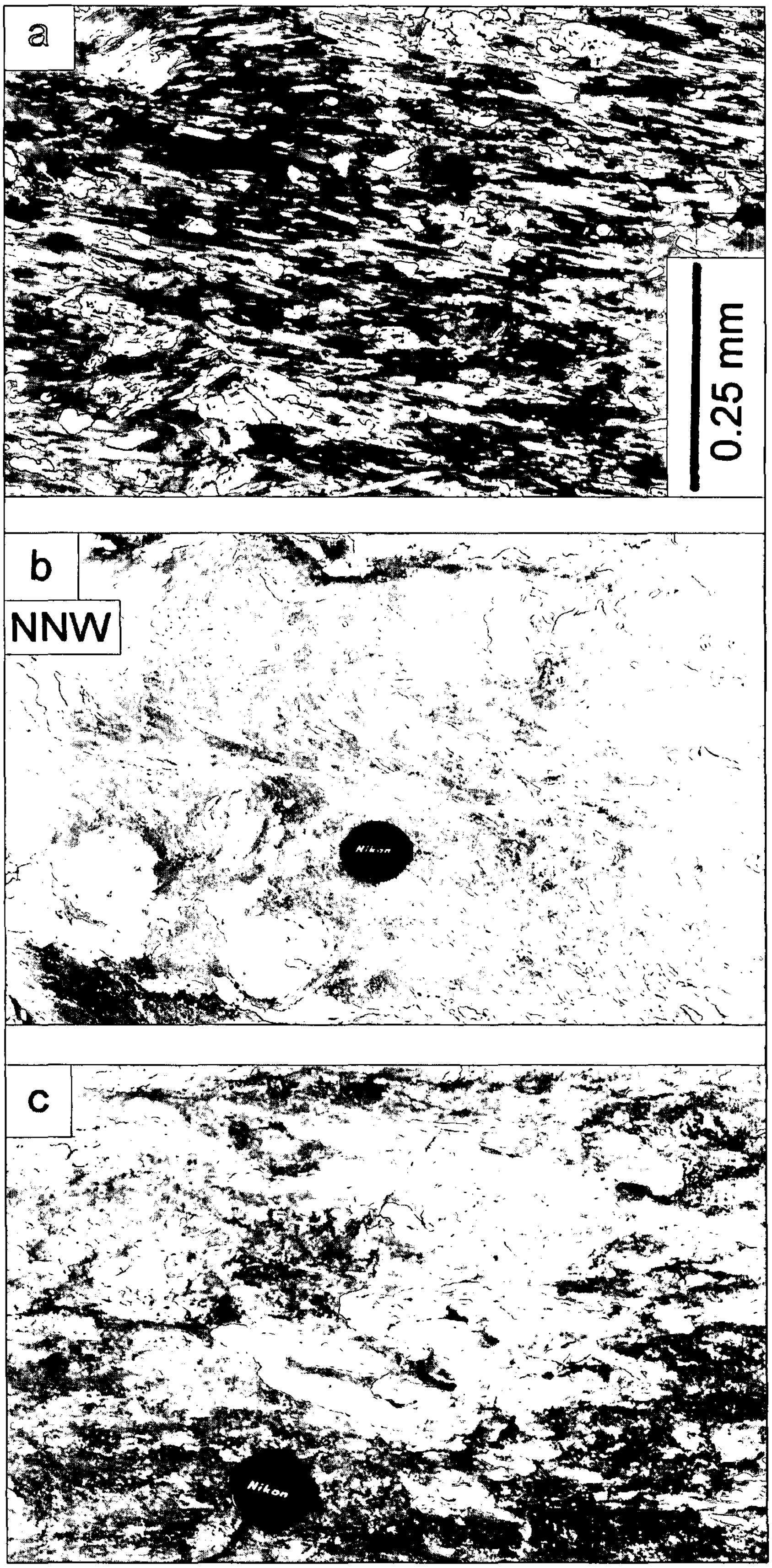
Sense of shear indicators associated with the E–W trending stretching lineation are, in general, less consistent in the Middle Pennine units than along the Pennine-Austroalpine boundary zone in the eastern Central Alps. In the lower, upright part of the Suretta nappe, the kinematic indicators are mainly top-to-the-west, although some top-to-the-east shear sense indicators can be observed locally. In the upper, inverted part of the Suretta nappe, shear sense indicators associated with the stretching lineations are top-to-the-east, indicating inversion of the shear sense due to later folding (Niemet-Beverin fold) with a fold-axis subparallel to the early stretching lineation and overprinting of early sense of shear indicators by later folding (RING, 1992b). The same inversion is observed in the inverted parts of the Mischabel fold of the northern Western Alps (RING & MERLE, 1992).

The structures from the contact between the Suretta nappe and the Avers Bündnerschiefer are interpreted to reflect west directed thrusting of the South Pennine Bündnerschiefer onto the Middle Pennine microcontinent under high-pressure conditions.

3.4.3. Tambo Nappe

In the Tambo nappe the most penetrative structural element is, again, an E–W oriented stretching lineation (Text-Fig. 8c), however, the tectonic significance and the relative age of this stretching lineation is debatable. MAYERAT (1989), followed by BAUDIN et al. (1993), attributed it to a young tectonic event postdating the Late Eocene/Early Oligocene north to northwest directed thrusting and proposed a top-to-the-E sense of shear. BAUDIN & MARQUER (1993) gave evidence that top-to-the-E motion occurred during a drop from high (10 kbar) to medium (5 kbar) pres-

Text-Fig.8.
a) Highly sheared glaucophane crystals within an early Alpine foliation in the Avers Bündnerschiefer.
b) Penetrative foliation in the Suretta nappe is overprinted by small-scale, NNW-translating shear zones.
c) Penetrative E–W-oriented stretching lineation in gneiss of the northern Tambo nappe.



sures and related the penetrative E–W-oriented stretching lineation to initial exhumation of the Tambo nappe. On the other hand, RING (1992b) attributed penetrative E–W- stretching to an old, early Alpine event predating N/NW-directed thrusting. He reported kinematic indicators showing top-to-the-east and top-to-the-west sense of shear. Therefore, bulk coaxial stretching has been suggested for large parts of the Tambo nappe. Because top-to-the-E-directed kinematic indicators appear to prevail in the lower Tambo nappe at the contact to the North Pennine Bündnerschiefer, RING (1992b) suggested an increasing top-to-the-E simple shear component at the base of the Tambo nappe. RING (1992b) also reported a top-to-the-east tectonic event postdating north to northwest-directed thrusting and attributed it to tangential stretch in the eastern Central Alps caused by Late Oligocene/Early Miocene uplift in the Ticino area of the Lepontine dome.

BAUDIN & MARQUER (1993) showed that north to northwest-directed thrusting is accompanied by the high-pressure metamorphism in the Tambo nappe and that the peak of high-pressure metamorphism occurred at the end of this thrusting event (BAUDIN et al., 1993, p. 551). Given the aforementioned Late Eocene/Early Oligocene age for N/NW vergent thrusting, their findings imply an Oligocene age (< about 35 Ma) for the peak of high-pressure metamorphism in the Tambo nappe. Such an age is considerably younger than the peak of high-pressure metamorphism in the underlying Adula nappe and even younger than the age for the high-pressure metamorphism in the notably more external Cima Lunga nappe (BECKER, 1992, 1993). Furthermore, it suggests, that structures due to north-directed thrusting may be overgrown by high-pressure minerals. These implications are at variance with the study of SCHREURS (1990) in the Schams nappe. At least parts of the Schams nappe were situated underneath the Tambo nappe before and during NW/NNW-directed thrusting. Due to this tectonic position, the Schams nappe should have also suffered extensive high-pressure metamorphism. SCHREURS (1990) reported that white mica and stilpnomelane constitute structures due to north to northwest-directed thrusting, and he related lower greenschist-facies metamorphic conditions to N/NW directed thrusting in the Schams nappe. MAYERAT (1989) also suggested that greenschist-facies mineral parageneses in the northern part of the Tambo nappe postdate the N/NW-directed thrusting event, although she admits, that the relation of mineral growth with respect to the Alpine structural evolution remains largely unclear and that certain minerals might represent pre-Alpine relics.

The fairly consistent K/Ar phengite cooling ages of between 35–50 Ma for the overlying Suretta (STEINITZ & JÄGER, 1981) and the underlying Adula nappes (SANTINI, 1992; see above) also cast doubts on an Oligocene age for high-pressure metamorphism in the Tambo nappe.

If, however, penetrative E–W-stretching was in fact younger than N/NW vergent thrusting, it should penetratively overprint N/NW vergent structures in the Misox and Splügen mylonite zones, because these shaly and carbonate-rich, highly deformed units should be susceptible to reactivation and are thought to represent zones of localised top-to-the-E normal shearing (BAUDIN et al., p. 546). The data of SCHREURS (1990, p. 137 and p. 140) and RING (1992b) show abundant E–W-oriented stretching lineations in the hanging walls of both zones, but do not show pervasive E–W-stretching within both zones. This suggests, that mylonitic N/NW vergent thrusting obliterated the pervasive E–W-trending stretching lineations within both zones, and that the penetrative E–W-stretching lineation survived only within the less highly deformed interiors of the Suretta and Tambo basement nappes on top of both the Misox and Splügen zones. Consequentely, pervasive E–W-oriented crustal stretching should represent the earliest Alpine deformation event, similar to the deformation history in the Mesozoic cover of the Suretta nappe and the nappes overlying the latter. Since E–W-stretching can be linked to early Alpine nappe stacking in the overlying units, I assume that it is related to thrusting of the Tambo nappe, although the E–W-trending lineations can not be directly related to the nappe bounding mylonite zones.

3.4.4. Adula Nappe

In the Adula nappe, no structures attributable to early Alpine E–W-directed stretching have been detected (LÖW, 1987; MEYRE & PUSCHNIG, 1993; RING, 1992a,b). Moreover, the relation of the high-pressure metamorphism to tectonic events remains largely unkown.

LÖW (1987) analysed the tectonometamorphic evolution of the northern Adula nappe and describes a first deformational event (Sorreda phase) taking place under high-pressure metamorphic conditions, but predating the peak of this metamorphism. This event is thought to have caused imbrication of the Adula basement with its Mesozoic cover and the North Pennine Bündnerschiefer. A second event (Zapport phase of LÖW, 1987) produced a penetrative N–S to NW–SE-oriented stretching lineation. The foliation in which this stretching lineation developed is composed mainly of old, reoriented phengite and paragonite and represents a composite foliation (LÖW, 1987, p. 26). Eclogitic rocks are boudinaged in this foliation and show retrogression and/or brittle deformation (LÖW, 1987, p. 18). Although LÖW (1987, p. 60–61) attributes part of the Zapport deformation to the peak of high-pressure metamorphism, the main phase of this deformation obviously took place during retrograde high-pressure metamorphism and/or after the high-pressure metamorphic event. This is in accordance with findings of RING (1992a, b), who reported that north/northwest-directed thrusting in the Adula nappe postdates the high-pressure metamorphism.

In a recent study, MEYRE & PUSCHNIG (1993) studied the metamorphism and deformation of the central Adula nappe. They reported two early deformation phases which took place under high-pressure metamorphic conditions. The kinematics of both events remain unkown. They relate their third event (D2b of MEYRE & PUSCHNIG, 1993), which probably represents the main phase of nappe transport, to the Zapport phase of LÖW (1987) and attributed a top-to-the-north-directed sense of shear to it. During this third phase clinozoiste overgrows zoisite and MEYRE & PUSCHNIG (1993) attribute this transformation to amphibolite-facies overprint of the earlier eclogite-facies assemblage, suggesting that N/NW-directed thrusting postdated high-pressure metamorphism or at least the peak of high-pressure metamorphism.

3.4.5. Western Central Alps

Recently, MERLE et al. (1989) gave a comprehensive study of the kinematic evolution of the western Central Alps. They describe a Late Eocene to Early Oligocene N/NW-directed thrusting event that occurred under amphibolite-facies metamorphic conditions. Early Alpine tectonic events have not been detected. A later E–W-trending stretching lineation is attributed to successive updoming of the Central Alps and associated lateral gravitational escape of rocks (MERLE et al., 1989).

The early deformation history and kinematics of exhumation of the Cima Lunga nappe are as yet not understood. The rocks of the Cima Lunga nappe developed a pervasive foliation during high-pressure metamorphic conditions. From the isotopic data, the amphibolite-facies metamorphic overprint (which is similar to that of the Simano nappe), and its structural position on top of the latter, it appears, that the Cima Lunga nappe must have been thrust on top of the Simano nappe in Late Eocene to Early Oligocene time. However, the process by which this happened is as yet largely unknown. The first stage of exhumation of the continental material of the Cima Lunga nappe may have been entirely controlled by buoyancy forces which could explain their rise from within the mantle (the high-pressure metamorphic data suggest depth of approximately 80–150 km) to the base of the crust.

4. Discussion

The scarce sedimentologic data seem to support orogenic activity in the Central Alps during the Late Cretaceous. Some of the flysch basins show obvious relationships to synsedimentary tectonic activity (TRÜMPY, 1980) and it seems reasonable that flysch deposition is related to contraction in adjoining areas (TRÜMPY, 1973).

The metamorphic data reveal two important relationships. First, they show a tectonic juxtaposition of nappes with subduction-related high-pressure metamorphism next to units which apparently lack any subduction-related metamorphism (Text-Fig. 5). The extent of the high-pressure metamorphism in the Central Alps has recently been reviewed by PFEIFER et al. (1991). Although these authors proposed that probably the whole Central Alps suffered a high-pressure imprint, their figures 1–3 suggest, like Text-Fig. 5 of this study, that large parts of the western Central Alps (beneath the Simplon line, Text-Fig. 2) remained unaffected. However, if it turned out, that calcite-dolomite-diopside-zoisite assemblages and pseudomorphs of chlorite after garnet are in fact high-pressure relics, as suggested by PFEIFER et al. (1991, p.447), the extent of high-pressure metamorphism in the western Central Alps would be larger than indicated in Text-Fig. 5.

Second, the metamorphic data show that nappes which were affected by early Alpine metamorphism show abrupt increases in metamorphic grade downward across their tectonic boundaries (i.e. contacts between Platta nappe – Avers Bündnerschiefer, Tambo – Adula nappes and Combin – Zermatt-Saas zones, Text-Figs. 5 and 6). Between the Platta nappe and the Avers Bündnerschiefer about 30–40 km of crust has been removed. The metamorphic gap between the Tambo nappe and the underlying Adula nappe indicates that between 7–37 km of crust are missing between the two units and approximately 30–50 km of crust must have been excised between the Combin and the Zermatt-Saas zones. From the work of NIEVERGELT et al. (1991), it can be concluded that 2–3 km of the missing crust between the Platta nappe and the Avers Bündnerschiefer were excised during Oligocene low-angle normal faulting along the Turba mylonite zone. RING (1992a, b) reported that the Misox zone between the Adula and Tambo nappes also was affected by mid-Tertiary extensional faulting. This suggests, that parts of the crust were eliminated during the mid-Tertiary orogeny, however, by far most of the crust must have been excised during the early Alpine stage of subduction, because the whole nappe pile was affected rather uniformly by the meso-Alpine Barrovian-type metamorphism (see below).

The review of isotopic ages suggests that subduction-related high-pressure metamorphism commenced in Early Cretaceous times in the lowermost Austroalpine units and the subjacent South Pennine units (Pennine-Austroalpine boundary zone). The scarce age determinations from the underlying Middle and North Pennine units suggest that subduction progressed towards the foreland and affected the lower units in Late Cretaceous and Early Tertiary time. BECKER (1993) proposed, that the high-pressure metamorphism in the Cima Lunga nappe is related to the collision of the Adriatic plate with the European plate, and not to subduction of the Pennine oceanic basins. However, according to TRÜMPY (1980), the North Pennine basin was eliminated in earliest Oligocene time indicating the time when the European continental margin entered the convergence zone and deformation commenced in the Helvetic unit. The onset of deformation in the Helvetic domain is generally regarded as the time of continental collision (MILNES, 1978; PLATT, 1986). Therefore, continental collision postdates the peak of high-pressure metamorphism in the Cima Lunga nappe. Continental collision, however, may have played a role in the later stages of exhumation of the Cima Lunga nappe within the crust. The early stages of exhumation may have been achieved by buoyant rise within the upper mantle. The isotopic data seem to imply that buoyant rise occurred at a fast rate (approximately 3–10 mm/a as deduced from the metamorphic and isotopic data). Thermal gradients for high-pressure metamorphism are between 6 and 17°/ km for the Adula nappe, 6–7°/ km for the Cima Lunga nappe and 7–11°/ km for the Pennine-Austroalpine boundary zone in the northern part of the Western Alps. Those estimates were made assuming an average rock density of 2.8 g/cm^3. Since some of these high-pressure rocks were subducted into the mantle, the geotherms for such rocks are slightly too low. Nonetheless, the thermal gradients show, that the thermal profile remained fairly constant throughout the period of subduction. This might have been achieved by continuous underthrusting of cold material which prevented equilibration of the disturbed thermal structure (e.g. DAVY & GILLET, 1986). Because the peak of high-pressure metamorphism progressed towards the foreland, the thermal profile was probably also transported in the same direction.

Another interesting feature is evident from the isotopic data. The Ar/Ar and K/Ar phengite cooling ages from the Adula and Suretta nappes of SANTINI (1992) and STEINITZ & JÄGER (1981) suggest an age > about 50 Ma for the Barrovian metamorphism in the Adula and Suretta nappes. The U/Pb monazite ages from the southern part of the Simano nappe, which underlies the Adula nappe, are <28 Ma (KÖPPEL & GRÜNENFELDER, 1975) and have been interpreted as monazite crystallisation ages at temperatures at, or very close to, the peak of amphibolite-facies metamorphism (650–700°C, BECKER, 1993). This seems to indicate that the Barrovian metamorphism in the Central Alps also progressed, like the earlier high-pressure metamorphism, in time and space towards the foreland. This suggests that deeper units suffered high-pressure metamorphism while higher tectonic units were undergoing thermal relaxation.

The kinematic data seem to indicate overall top-to-the-W crustal-scale nappe stacking in the lowermost Austroalpine and in the South Pennine units and can therefore be correlated to the Cretaceous kinematics of the Eastern Alps (see summary in RATSCHBACHER et al., 1989), although the data from the Combin zone remain difficult to interpret. In the Middle Pennine nappes of the eastern Central Alps no clear picture emerges from the existing data. However, at least the cover of the Suretta nappe appears to unequivocally support early Alpine E–W oriented crustal stretching. There is also evidence, that syn-high-pressure deformation occurred in the Adula nappe, but related structures are too strongly overprinted to allow for any tectonic interpretation. Nevertheless, it seems apparent that the major phase of top-to-the-N/NW transport postdated high-pressure metamorphism, or at least the peak of high-pressure metamorphism. North to northwest-directed nappe transport during greenschist- to amphibolite-facies metamorphism is compatible with published data from the western Central Alps (see references in MERLE et al., 1989), with the data from the Schams nappe (SCHREURS, 1990), and the data from the South Pennine and Austroalpine nappes. Moreover, there is evidence that most of the nappes of the western Central Alps, portions of the North Pennine Bündnerschiefer (in which sedimentation continued until the Eocene, see above), and the Middle Pennine Schams cover nappe lack structures that can be associated with early Alpine E–W oriented crustal stretching (e.g. MERLE et al., 1989; SCHMID et al., 1990; SCHREURS, 1990).

The kinematics of the tectonic boundary zones along which large amounts of crust have been excised in early Alpine times are not well constrained. The dynamics of subduction-accretion complexes have recently been analysed by PLATT (1986), who demonstrated, that, if the boundary conditions and mechanical properties of orogenic wedges remain unchanged and erosion is neglected, they will suffer shortening or extension until a critical taper is achieved. Processes leading to changes in the wedge shape will perturb the system and, therefore, change the stability of the wedge. Underplating of heterogenous oceanic and continental material to the underside of the orogenic wedge tends to thicken the wedge and causes it to extend locally, and probably periodically, to reestablish a stable taper. Such a scenario may cause a large-scale component of coaxial deformation and may explain excision of considerable segments of crust between tectonic units as described in this study. Alternatively, excision and apparent attenuation of the crust can be achieved by out-of-sequence thrusting (either towards the fore- or hinterland) (RING & BRANDON, 1994). Therefore, kinematic indicators and the original orientation of the associated tectonic boundary, and an analysis of the deformation history are of primary importance for distinguishing between extensional deformation or out-of-sequence thrusting.

For the Platta nappe/Avers Bündnerschiefer contact no early Alpine kinematic data have been reported so far. For the contacts of the Tambo and Adula nappes, and the Combin and Zermatt-Saas zones, the kinematic indicators are uncertain.

The kinematic data of BAUDIN et al. (1993) from the Tambo nappe argue for thrusting of the latter onto the Misox zone and the underlying Adula nappe followed by an east-directed extensional exhumation of the Tambo nappe. The underlying Adula nappe depicts a similar deformation history as the Tambo nappe with pronounced top-to-the-E extension following top-to-the-N/NW vergent thrusting.

However, both MERLE et al. (1989) and RING (1992a, b) gave evidence, that top-to-the-E extension occurred during retrogression of amphibolite-facies metamorphism and is caused by doming of the Ticino dome in the Central Alps (Text-Fig. 2, insert), which is at variance to the findings of BAUDIN et al. (1993). RING (1992b) suggested, that excision of large amounts of crust between the Tambo and Adula nappes may be explained by bulk coaxial extension with an increasing component of top-to-the-E vergent non-coaxial deformation at the base of the Tambo nappe. Therefore, it is thought, that the Tambo nappe was exhumed by extensional shearing.

For the contact between the Combin – Zermatt – Saas zones the data are even more ambiguous, mainly because no early Alpine structures have been detected in the Combin zone so far. If an extensional exhumation of the Zermatt-Saas was favoured, it would have lasted until the meso-Alpine orogenic events as shown by the greenschist-facies kinematic indicators.

Another point of discussion in Alpine geology is the relation of nappe transport directions, as deduced from stretching lineations and associated kinematic indicators, to plate motions (e.g. PLATT et al., 1989; FRY, 1989). PLATT et al. (1989) argued, that nappe transport directions reflect an interplay between the direction of plate motion and local body forces. Gravity is the only body force and its direction depends on topographic gradients. PLATT et al. (1989) assumed in their model that gravity forces are directed arc-normal, i.e., directed towards the forelands of the orogen.

Nonetheless, there is ample evidence in the Alps that gravitationally-driven movements took place parallel to the Alpine arc (e.g. MERLE et al., 1989; RATSCHBACHER et al., 1989; RING & MERLE, 1992), which have probably been controlled by intraplate processes.

If it was assumed, however, that stretching lineations reflect the motion of the overriding plate when acquired before the peak of subduction-related metamorphism and during the process when a rock unit is transferred from the footwall to the hanging wall of an orogenic wedge (when gravity forces are assumed to be at a minimum), the data discussed here for the Pennine-Austroalpine boundary zone and for the region of the Avers Bündnerschiefer and the cover of the Suretta nappe, would indicate west-directed motion of the Adriatic subplate during early Alpine times.

5. A Subduction-Related Strike-Slip Model

The above outlined data are interpreted to imply a close vicinity of units which suffered early Alpine subduction-related metamorphism and deformation to units which were not affected by early Alpine orogenic activity and in which sedimentation continued. This situation results in a space problem which can be solved by introducing strike-slip zones to the early Alpine convergence history.

5.1. Arguments in Favour of Subduction-Related Strike-Slip Faults

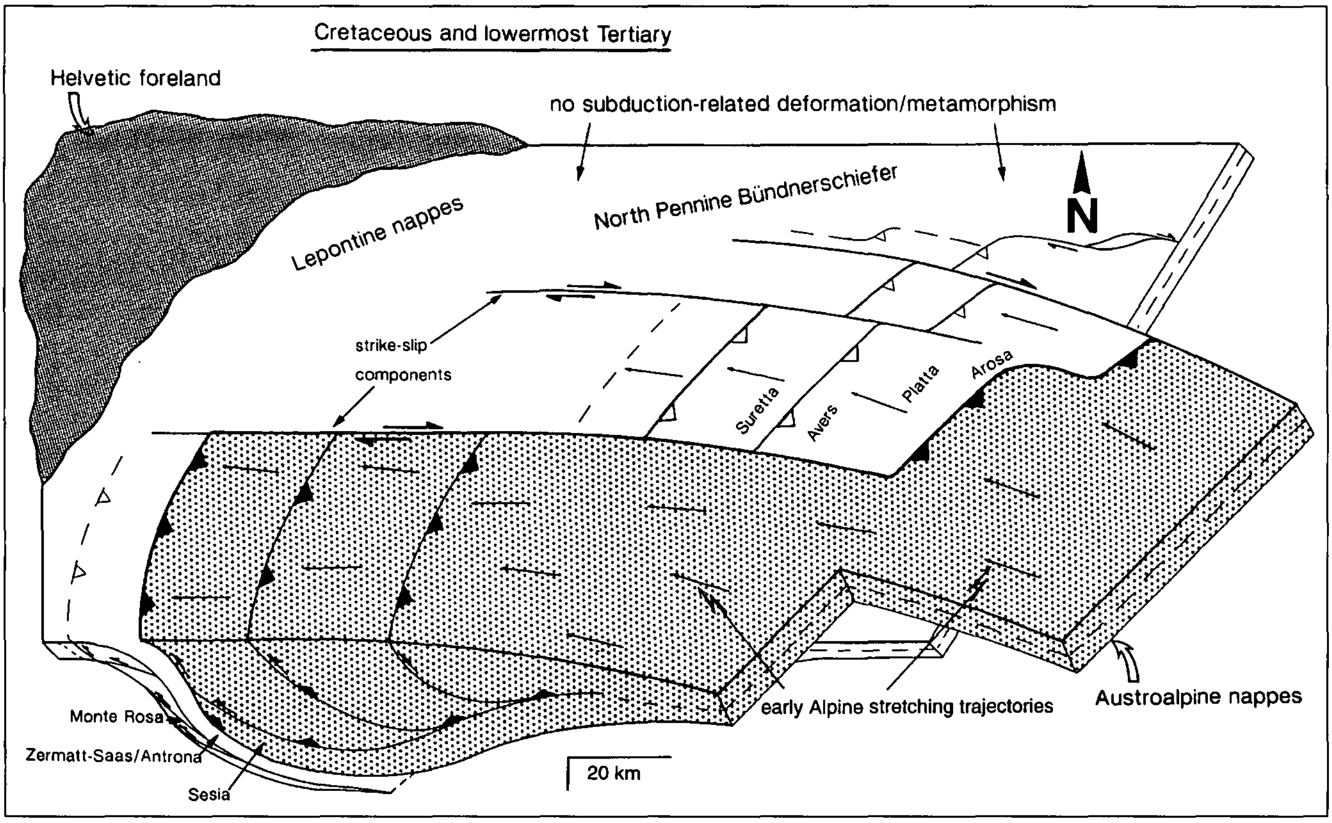
According to BECK (1986), three major factors control the initiation of transcurrent faults during oblique subduction:

1) *Oblique plate convergence* is suggested by the long duration of sedimentation in the Rhenodanubian and other flysch basins (from the Early Cretaceous through the Eocene). This implies a large component of lateral convergence between Adria and Europe (e.g. HESSE, 1981). Sedimentological studies by WAIBEL & FRISCH (1989) in the Lower Engadine window also suggest a highly oblique convergence during Cretaceous times. Paleomagnetic work (e.g. WESTPHAL et al., 1986; SAVOSTIN et al., 1986) show a counterclockwise rotation and west-directed motion of Adria relative to Europe during the early covergence history of the Alps. This is confirmed by structural work (PLATT et al., 1989).
2) *A shallow dip of subduction* is suggested by subduction of young and buoyant oceanic lithosphere. Spreading of South Penninic oceanic crust commenced in about Middle to Late Jurassic times (ca. 160 Ma, PETERS & STETTLER, 1987) and initial consumption of this crust already took place in the Early Cretaceous (ca. 130 Ma, WINKLER, 1988). This proves subduction of a very young oceanic crust and favours a shallow near surface dip of the subducting slab. Furthermore, the arrival of other buoyant fragments (e.g. a seamount edifice or relatively light continental fragments) also promote at least temporary shallowing of the dip of subduction. Seamounts in the South Pennine domain have been proposed by OBERHÄNSLI (1977) and continental fragments which arrived at the subduction zone are the Margna nappe (LINIGER & GUNTLI, 1988; SCHMID et al., 1990) and the Middle Pennine vestiges of the Central Alps (Tambo – Suretta microcontinent of SCHMID et al., 1990).
3) *Relatively easy slip on the decoupling strike-slip fault* may have been attained by the reactivation of the aforementioned favourably oriented Jurassic transform faults during the Cretaceous convergence.

All outlined arguments are interpreted in favour of a partitioning of convergence into zones where subduction occurred and simultaneously operating strike-slip zones.

5.2. The Model

The cartoon in Text-Fig. 9 illustrates the model. The anticlockwise rotation of the overriding Adriatic subplate in Cretaceous times caused oblique subduction of the South Pennine ocean underneath the Austroalpine continental crust. Convergence was partitioned into dextral



Text-Fig. 9.
Proposed subduction-related strike-slip model.
West directed overriding of the Austroalpine units (irregular northern part of Adriatic subplate) caused west vergent crustal stacking along approximately N–S oriented segments. Along roughly E–W trending segments strike-slip prevailed. Strike-slip faults are thought to have developed simultaneously with subduction.

strike-slip motion along the E–W oriented segments of the irregular Pennine-Austroalpine plate margin and west directed thrusting along its N(NE)-S(SW) trending sections (see RATSCHBACHER et al. [1987] and RING et al [1989] for the Eastern Alps).

Subduction-related strike-slip can explain the close proximity of high-pressure metamorphism and continuing sedimentation in the North Pennine realm. According to this model large parts of the later Lepontine nappes and their cover were situated beyond a major strike-slip segment and escaped thorough Cretaceous deformation.

The oblique plate convergence excluded prevalent high-pressure metamorphism in the E–W trending part of the Alps (i.e. Eastern and Central Alps), whereas the Western Alps suffered subduction almost orthogonal to the plate boundaries, which resulted in a really extensive high-pressure metamorphism (insert Text-Fig. 2).

Acknowledgements

A discussion of this kind reflects the author's passions and prejudices, while overlooking some favourites of others. I hope at least to have been thought provoking. Also, my thanks to colleagues who have tried to encourage some sense of balance in my thinking over the last years, especially Olivier MERLE, Stefan SCHMID, Wolfgang FRISCH, Lothar RATSCHBACHER, Sören DÜRR and Bernhard BECKER. Obviously, they cannot be faulted for omissions, misinterpretations or other flops here. Mark BRANDON provided a pre-submission review.

The Deutsche Forschungsgemeinschaft provided financial support (Ri 538/1-2).

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Manuskript bei der Schriftleitung eingelangt am 20. März 1994