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SUMMARY: The Periadriatic Line and related lineaments formed as a result of post-collisional deformations which severely modified the Alpine chain. This post-late Oligocene deformation is the result of dextral transpression between the Adriatic sub-plate and the European foreland. Indentation of the western edge of the southern Alps caused uplift, related to backthrusting and associated deformations of the Lepontine region combined with E-directed escape of the central Alps. In the eastern Alps the response to dextral transpression is mainly by lateral escape along conjugate strike slip zones with minor or no vertical movements. Older deformations along this essentially late Alpine lineament can still be inferred locally and include: extension and transfer faulting in the late Palaeozoic to early Mesozoic, Cretaceous deformations, and Tertiary phases of compression (Eocene) and possibly extension (Oligocene). The geometry of crustal thinning associated with the formation of the passive continental margin of the southern Alps (associated with initial uplift of the Ivrea zone) has a profound influence on strain localization and the kinematics of movements along and north of the present day Periadriatic Line.

The polymorphism of the Periadriatic Line

The Periadriatic Line as the northern boundary of the southern Alps

Traditionally, the Periadriatic Line (Fig. 1a) is considered to mark a first order tectonic boundary between the southern Alps with only minor S-vergent thrusting and folding and the main body of the Alps with its W- to N-verging nappe structure. The change in tectonic style is very impressive across the western sector of the Periadriatic Line (Canavese and Tonale Lines) where this lineament separates the penetratively deformed area of the Lepontine region from the southern Alps (including the Ivrea zone) which lack an Alpine penetrative deformation. However, this contrast in tectonic style mainly reflects the metamorphic conditions during deformation. South-vergent backfolding also affected the central Alps (Argand 1916) and the 'minor' S-vergent thrusting in the southern Alps has recently been found to be rather impressive (Laubscher 1985), causing about 40 km shortening.

Further to the E the boundary between Austro–Alpine nappes and southern Alps was rather artificially drawn along the Pusteria and Gailtal Lines and S of the Drauzug (Fig. 1a) rather than N of the Drauzug and along the Defereggen–Anteselva–Vals (DAV) Line (see Bögel 1975 for an extensive discussion of the literature). Finally, the Periadriatic Line runs into the central zone of the bivergent Karawanken (Bauer 1984, Bauer & Schermann 1984), interpreted in terms of a flower structure by Laubscher (1983b). Thus, it seems that the notion of a major subdivision into southern Alpine and Austro–Alpine domains, each characterized by their own tectonic history and later juxtaposed along a first order tectonic boundary is misleading. Over most of its distance the Periadriatic Line transsects the crust of the southern continental margin (Fig. 1a) and it is merely a matter of definition as to where exactly (N or S of the Drauzug) one chooses to draw this 'first order' tectonic subdivision.

The Periadriatic Line as the southern limit of Alpine metamorphism

Ahrendt (1980) puts emphasis on another aspect of the Periadriatic Line, namely on that of a lineament which marks the southern limit of Tertiary metamorphism. Such a definition is very useful in regions with a strong metamorphic overprint (northern part of the Canavese Line and the western portion of the Tonale Line, Fig. 1b). However, as pointed out by Ahrendt (1980), it is rather the DAV Line which marks the southern boundary of Alpine biotite ages in the region S of the Tauern window than the Pusteria Line further to the S. Problems with this definition arise at the southwestern end of the Periadriatic Line as well. There, Zingg *et al.* (1976) report low grade metamorphism and Cretaceous ages from the cover of the southern Alps (Canavese zone s. str., Fig. 2), S of the

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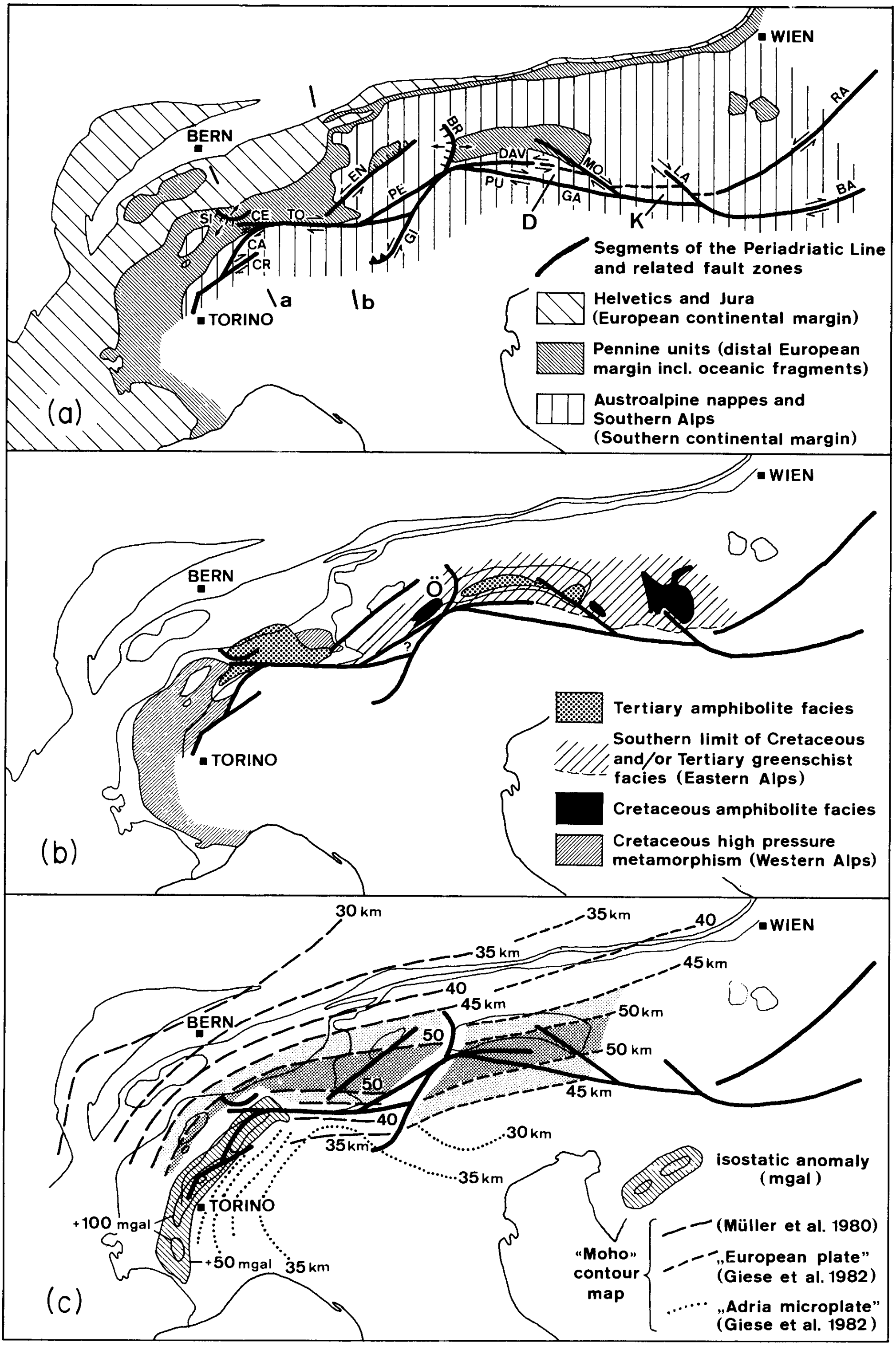

WIEN
BERN
TORINO
RA
BA
BR
EN
PE
GI
SI
CE
TO
CA
CR
DAV
MO
PU
GA
LA
D
K
a
b
(a)
Segments of the Periadriatic Line and related fault zones
Helvetics and Jura (European continental margin)
Pennine units (distal European margin incl. oceanic fragments)
Austroalpine nappes and Southern Alps (Southern continental margin)
Ö
?
(b)
Tertiary amphibolite facies
Southern limit of Cretaceous and/or Tertiary greenschist facies (Eastern Alps)
Cretaceous amphibolite facies
Cretaceous high pressure metamorphism (Western Alps)
30 km
35 km
40
35 km
45 km
40
45 km
50 km
50
50 km
50
45 km
40
30 km
35 km
35 km
+100 mgal
+50 mgal
35 km
(c)
isostatic anomaly (mgal)
«Moho» contour map
(Müller et al. 1980)
„European plate" (Giese et al. 1982)
„Adria microplate" (Giese et al. 1982)

Periadriatic Line. Two additional problems arise with this definition: (1) The impressive jump in radiometric ages ceases to exist east of the DAV Line; (2) the same lineament marks the southern and eastern boundary of Tertiary (Lepontine dome, Tauern window) as well as Cretaceous cooling ages (Sesia zone, eastern Alps). One feature emerging from inspection of Fig. 1(b) is highly conspicuous: Both the Lepontine dome and the Tauern window with their amphibolite grade Tertiary metamorphism are situated at the interference points of SW–NE and E–W-trending parts of the Periadriatic lineament. This geometry suggests a causal relationship between updoming and movements along the Periadriatic Line.

The Periadriatic Line as the site of a root zone

A third aspect of the Periadriatic Line is related to the confusing notion of a 'root zone'. The Periadriatic Line marks the southern boundary of this so-called root zone, which is better referred to as the 'southern steep belt' (Milnes 1974), characterized by steeply N- and NW-dipping foliation planes. The term 'root' is misleading because it comprises both the vision of an origin for far-travelled nappes and at the same time the subvertical orientation of the nappe contacts. This old-fashioned concept of a highly squeezed root which runs in a subvertical orientation through the entire crust (as suggested in most classical cross sections through the Alps) led several authors to consider the Periadriatic Line as a suture zone (e.g. Dewey & Bird 1970). Mesozoic sediments along the Periadriatic Line (e.g. the Canavese) have classically been considered to represent the root of the Austro–Alpine nappes (Argand 1910), although they simply represent the cover of the southern Alps (Ahrendt 1980). In fact, the southern steep belt is genetically linked to late Tertiary post-nappe emplacement folding and backthrusting (Milnes 1974).

The Periadriatic Line as a strike-slip zone

Laubscher (1971a, b) placed emphasis on yet another aspect of the Periadriatic Line by postulating some 300 km dextral strike slip at or in the vicinity of this line. This postulate results from large scale kinematic considerations concerning the polarity of thrusting in the Alps, Dinarides and Appennines. As the Alpine belt swings into the N–S oriented strike of the western Alps the westward motion of the Adriatic sub-plate was held responsible for EW directed shortening in the western Alps including obduction of the Ivrea geophysical body (Laubscher 1984).

The Periadriatic Line in the light of geophysical data

Figure 1(c) suggests that the western sector of the Periadriatic Line marks the western edge of the Ivrea gravity anomaly. Kissling (1980, 1984) showed that the northwestern boundary of the Ivrea geophysical body is identical with the projection of the Periadriatic Line down to a depth of at least 10 km. Due to the NW-dip of the Canavese Line (as shallow as 40°–60° across the Valle d'Ossola) the gravity anomaly extends below the Sesia zone. The rather sharp bend into the E–W strike of the Tonale Line near Locarno coincides with the northeastern termination of this gravity anomaly. This suggests a causal relationship between the geometry of the Ivrea gravity anomaly and the position of the Periadriatic Line.

The same bend from a NNE–SSW into an E–W strike is noticable in the contour map for the Moho under the western and central Alps. Figure 1(c) incorporates older published data (Müller *et al.* 1980, Giese *et al.* 1982), and according to a more recent re-evaluation of seismic data (Ansorge, pers. comm.) this bend appears even more discrete. Thus, both the Canavese and Tonale Lines are situated S and

FIG. 1. The Periadriatic Line in the context of Alpine geology.
(a) The segments of the Periadriatic Line and related late Alpine faults. The segments of the Periadriatic Line are from W to E: CR–Cremosina; CA–Canavese; CE–Centovalli; TO–Tonale; GI–Giudicarie; PU–Pustertal; DAV–Defereggen–Anteselva–Vals; GA–Gailtal. Related faults are from W to E: SI–Simplon; EN–Engadine; PE–Pejo; BR–Brenner; MO–Mölltal; LA–Lavanttal; BA–Balaton; RA–Raba (Balaton and Raba lines after Kazmer & Kovacs 1985). D–Drauzug; K–Karawanken.
(b) Extremely simplified metamorphic map of the Alps (after Niggli & Zwart 1973, Frank 1987). Ö: thermal dome in the southern Ötztal nappe.
(c) Contour maps of the crust–mantle boundary (after Müller *et al.* 1980 and Giese *et al.* 1982) and isostatic anomalies of the Ivrea geophysical body (after Veccia 1968).

SE of the Moho trough. This close relationship is completely lost further to the E. For a short distance the axis of the Moho depression changes into the southern Alps. This suggests that the character of the Periadriatic Line changes rather drastically towards the E.

Terminology

Although it became customary to use the terms 'Periadriatic' and 'Insubric' synonymously we use the term 'Periadriatic' to denote the entire system of fault zones as depicted in Fig. 1(a). This figure also indicates the names used for various segments of the Periadriatic fault system. It is one of the aims of this contribution to show that portions of the Periadriatic Line accommodated different displacements at different times. The northeastern portion of the Canavese Line and the western sector of the Tonale Line play a rather well defined role during the uplift of the Lepontine region associated with backthrusting (Schmid *et al.* 1987), and following Spitz (1919) we reserve the term 'Insubric' to this portion of the Periadriatic Line which was active during the late Oligocene–Miocene postcollisional 'Insubric phase' in the sense of Argand (1916).

Dextral transpression during the Insubric phase and associated uplift of the Lepontine region

The Insubric mylonite belt south of the Lepontine region

A greenschist-facies mylonite belt of approximately 1 km thickness defines the NE portion of the Canavese Line which curves from a NNE–SSW into an E–W strike over a short distance (Fig. 2). The mylonites dip with values of 40°–60° to the NW across the Val d'Ossola. The dip angle increases towards the E as the mylonite belt swings towards an E–W strike (values around 70° are typical for the region around Locarno). The same mylonite belt can be followed further to the E along the Tonale Line (Wiedenbeck 1986, Heitzman 1987a,b). There, the mylonitic foliation dips at 60°–70° to the N or NNW. However, a late brittle fault (the Tonale Fault, which will be discussed below) is in a subvertical orientation and runs exactly E–W.

West of Locarno the mylonite belt comprises three types of protoliths (Schmid *et al.* 1987), being from the SE towards the NW: Ivrea-derived mylonites (mainly former paragneisses), Canavese sediments (Permo–Mesozoic cover of the southern Alps), and mylonites derived from the Austro–Alpine Sesia zone (which here lacks evidence for a high pressure Eoalpine event). East of Locarno mylonitization affects the Tonale zone (a characteristic association of lithologies which are part of the pre-Triassic basement of the Austro–Alpine nappes, Cornelius & Cornelius-Furlani 1931 Lardelli 1981) and parts of the tail of the Oligocene Bergell intrusion (Jorio tonalite, Fumasoli 1974, Heitzmann 1987b, Vogler & Voll 1981). In this region cover and basement of the southern Alps are only moderately overprinted by mylonitization but affected by cataclastic movements (Fumasoli 1974).

Manifestations of brittle faulting and cataclasis are rarely found within the mylonites of the Canavese Line W of Locarno. The E–W oriented Centovalli Line, however, represents a rather broad zone of cataclasis and fault breccias affecting the gneisses of the southern steep belt which lack signs of earlier mylonitization. Thus, it appears that the site of earlier ductile movements is spacially separated from the site of later brittle movements. This separation no longer exists E of Locarno. A system of dextral Riedel shears affects the southern steep belt of the central Alps (Fig. 2) including the mylonites along the Tonale Line (Fumasoli 1974, Heitzmann 1987a,b). A sharp brittle fault (Tonale Fault) forms the southern boundary of (i) the Riedel shears, and, (ii) the mylonites. This distinction between Tonale mylonite belt (N-dipping) and Tonale Fault (subvertical brittle fault) will turn out to be useful for later discussions of the kinematics of movements and the eastwards extension of the Periadriatic Line.

The kinematics of movement along the Canavese Line have recently been analysed (Schmid *et al.* 1987): mylonitized Canavese sediments with variably oriented stretching lineations separate an earlier formed, more northerly located mylonite belt which indicates backthrusting of the Sesia zone to the SE from a later, more southerly located mylonite belt formed during dextral shearing. The change in orientation of the stretching lineations from down-dip plunging to subhorizontal orientations is rather abrupt. However, overprinting relationships suggest that at least parts of the southern mylonite belt were previously affected by backthrusting as well.

The change in the orientation of stretching lineations is much more gradual E of Locarno. In the area of Passo S. Jorio (Fig. 2) the stretch-

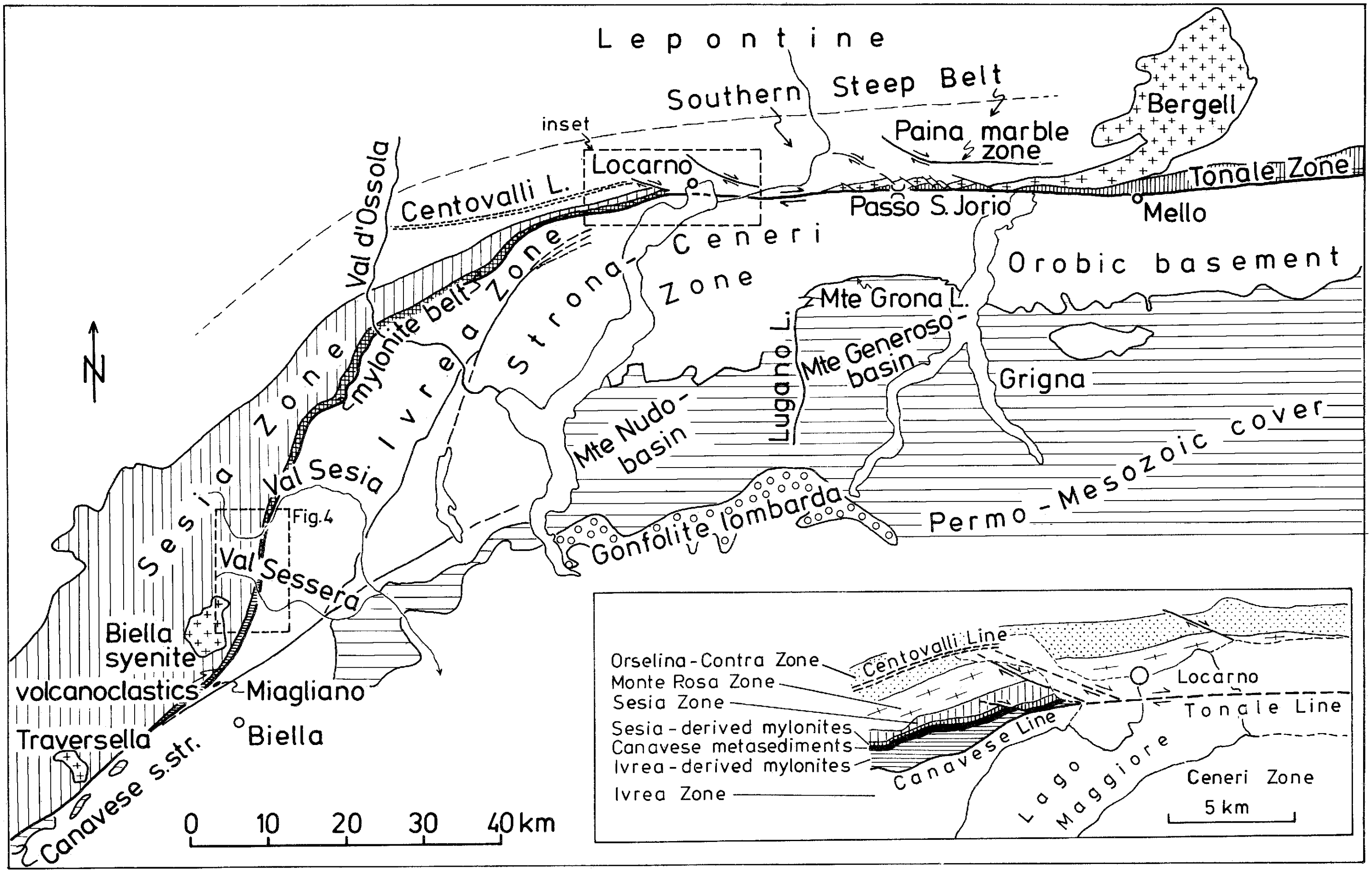

FIG. 2. Schematic map of the Canavese Line and its transition into the western Tonale Line indicating the location of geological and geographical names used in the text.

ing lineations are in a down-dip orientation (backthrusting) within the strongly deformed tonalites of the Bergell intrusion. Towards the S and within the mylonitized Tonale zone they gradually change from the same down-dip orientation to a pitch to the W (dextral combined with backthrusting movement) and finally into a subhorizontal orientation (dextral strike-slip, Vogler & Voll 1981, Heitzmann 1987a,b). This continuous change in the orientation of the lineation goes hand in hand with decreasing temperatures (from N to S) during the mylonitization event. Still further to the E and S of the main body of the Bergell intrusion (near Mello, Fig. 2) only subhorizontal stretching lineations indicating dextral shear are observed within the mylonitized Tonale zone (Wiedenbeck 1986).

Stretching lineations formed under conditions of simple shearing with a constant direction of shearing asymptotically approach the displacement vector. The above mentioned changes in orientation of the stretching lineations along and across strike suggest that the displacement vector changed in time and space. This leads to considerable difficulties in inferring the exact movement path because, strictly, the lineations merely record the finite stretch accumulated over some unknown duration in time at a given locality. Although Schmid *et al.* (1987) recognized two mylonite zones with distinct orientations of stretching lineation and sense of shear we interpret this configuration to indicate one continuous transpressive dextral strike-slip motion rather than two strictly separate events. Within the mylonite belt a volume of rock will first be affected by backthrusting to the SE and perpendicular to the NE–SW strike of the Canavese Line and it will then be either completely overprinted by dextral strike-slip movements (horizontal lineations in the southern mylonite belt), or it will be passively carried to the E due to later strain concentration within the southern mylonite belt (preserved steep lineations in the northern mylonite belt). The very gradual change in the orientation of the lineations within the Insubric mylonites as observed E of Locarno supports such a view. Additional arguments for a continuous movement during the Insubric phase will be given later when synchronous deformations outside the mylonite belt will be discussed.

Only during the final stages of deformation did dextral strike-slip outlast transpression. The brittle deformation within the Centovalli fault zone finds its eastward continuation in the Tonale Fault with its associated Riedel shears. This same event also caused strike slip deformation under greenschist facies conditions within more internal parts of the southern steep belt (Paina marble zone, Heitzmann 1987).

Formation of the southern steep belt and verticalization of the northwestern rim of the Ivrea zone

The contemporaneity of backfolding within the Monte Rosa and Sesia units with backthrusting within the Insubric mylonite belt was postulated in a section along the Val d'Ossola by Schmid *et al.* (1987). The rapidly and continuously decreasing amount of retrograde overprint towards the NW and away from the Insubric Line reflects a horizontal temperature gradient during backfolding and backthrusting. This gradient results from the rapid juxtaposition of a hot hangingwall (central Alps) over a relatively cooler footwall (southern Alps).

Verticalization is not restricted to the southern steep belt. Recent work in the Ivrea zone and along its contact to the Strona-Ceneri zone by Brodie & Rutter (1987) and by Handy (1986, 1987) indicates an Alpine age for late folding and tilting within the Ivrea zone around a NE–SW oriented axis. However, the sedimentary cover of the southern Alps, further to the S and E, was not affected by this verticalization. Thus, a hinge zone somewhere within the Strona–Ceneri zone or at the contact to the sedimentary cover has to be postulated.

Contemporaneity of backfolding and backthrusting N of the Insubric Line was also inferred for the region E of Locarno (Heitzmann 1987b). It is very tempting to also relate uplift of the Orobic basement S of the Tonale Line (De Sitter & De Sitter-Koomans 1949) to the same event. According to Bertotti (1987) this uplift can be interpreted to have tilted the northward continuation of Mesozoic normal faults, such as the Lugano Line, situated between the M. Nudo and Generoso basins. The continuation of the Lugano Line (the M. Grona Line) appears as a sinistral strike-slip zone in present day map view (see Figs 2 and 7 for localities). The age of thrusting in the Grigna mountains (Laubscher 1985) is still uncertain since Brack (1981) reports a pre-Adamello (Cretaceous?) phase of deformation further to the E.

Both the southern steep belt and the Ivrea zone were also affected by dextral shearing but a clear sequence of backthrusting followed by dextral shearing cannot be established yet. Some of this dextral shearing within the southern steep belt occurred under amphibolite facies conditions (Steck 1984, Merle *et al.* this volume) whereas E of Locarno dextral shearing occurred under greenschist facies conditions (Heitzmann

1987). A large portion of the very complex deformation N of the southern steep belt can also be attributed to the Insubric phase (Merle *et al.* this volume).

The cooling history of the Lepontine region

Radiometric data from the Lepontine area are so numerous by now that the application of the cooling age concept allows for a rather precise evaluation of temperature vs time curves as depicted in Fig. 3. With K/Ar and Rb/Sr dating on biotite and white micas combined with fission track data on apatite and zircon, Hurford (1986) was able to constrain the cooling curves for 19 samples along a N–S profile through the Lepontine area N of Locarno to such detail that two periods of uplift can be distinguished. Within the southern steep belt rapid cooling (65°C/Ma corresponding to an uplift rate of about 2.2 mm/a) from 23 to 19 Ma was followed by significantly slower cooling (14°C/Ma corresponding to an uplift rate of around 0.4 mm/a) compatible with present day uplift rates. The same pattern is recorded for the flat-lying central and northern parts of the Lepontine except that the onset of rapid cooling becomes younger. Since the southern limit of this area of rapid cooling coincides with the Insubric Line, a correlation of the period of rapid cooling with uplift due to backthrusting along the steeply inclined Insubric Line is obvious. Because the onset of rapid cooling is expected to postdate the beginning of rapid uplift (Werner 1980), backthrusting along the Insubric Line may have

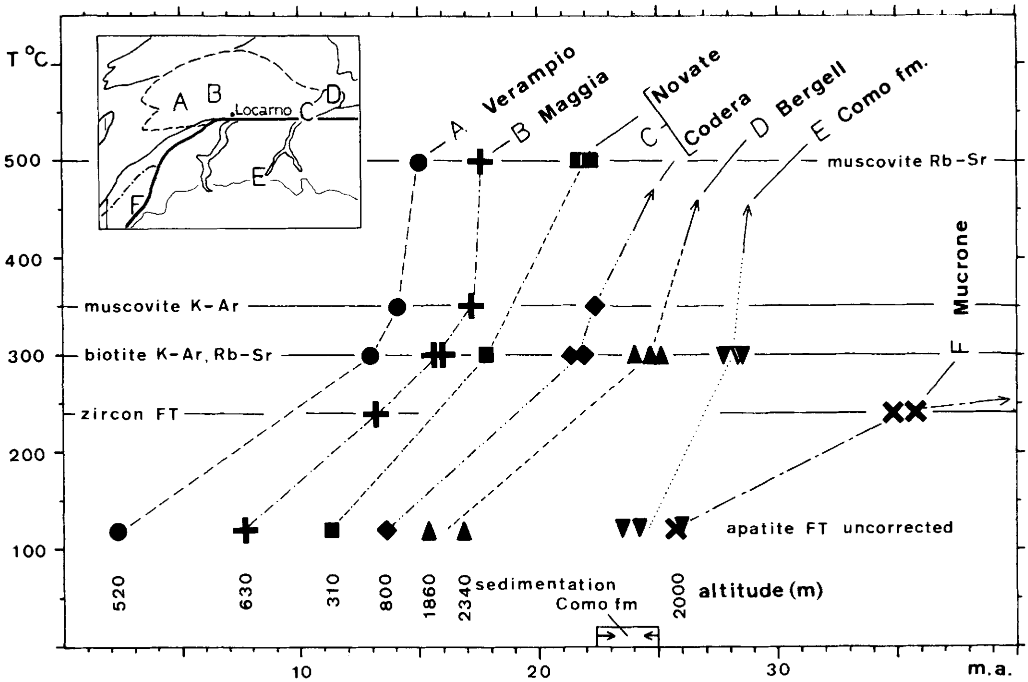

FIG. 3. Cooling history derived from published radiometric age determinations.
Tertiary amphibolite facies terrains: A and B Oligocene intrusions: C and D Bergell boulders from the Como formation: E. Cretaceous high pressure terrains of the Sesia zone: F.
A: Verampio (KAW 201), reference (2), (3), (4).
B: Maggia (KAW 1887), ref. (7).
C: Novate (KAW 132), ref. (2), (4).
Codera (KAW 553), ref. (3), (4).
D: Bergell (Z 6, BM 2, BM 3), ref. (1), (2), (5).
E: Como fm. (KAW 1003, 1004, 1005), ref. (4), (5).
F: Mucrone (KAW 987, 988, 989), ref. (6).
References: (1) Armstrong *et al.* (1966), (2) Jäger *et al.* (1967), (3) Purdy & Jäger (1976), (4) Wagner *et al.* (1977), (5) Wagner *et al.* (1979), (6) Hurford & Hunziker (1985), (7) Hurford (1986).

started somewhat earlier than 23 Ma ago. Based on an estimated amount of 9 km rapid vertical uplift during 4 Ma (Hurford 1986) a minimum shear strain rate of 8 x 10^{-14} sec^{-1} may be estimated during mylonitization. Later cooling and uplift affects both central Alps (14°C/Ma) and Ivrea zone (7°/Ma, Hurford 1986) and may partly be attributed to isostatic uplift.

The N–S age trend for the onset of rapid cooling (19 Ma vs 23 Ma for the southern steep belt and the northern and central Lepontine areas respectively) supports the idea of a substantial horizontal temperature gradient during backthrusting. This allows mylonitization under greenschist-facies conditions and along the Insubric Line to be contemporaneous with more distributed deformation under amphibolite-facies conditions further to the N.

The age differences along an E–W traverse N of the Insubric Line are much more pronounced. Cooling ages for most radiometric systems systematically decrease from the Bergell area in the E to the Verampio–Simplon area in the W (Fig. 3). From these data, combined with the pattern of mineral isograds which excludes simple tilting around a N–S axis it is clear that the Lepontine region cannot have been uplifted as a rigid block without contemporaneous internal ductile deformation (Merle *et al.* this volume).

This cooling pattern can be interpreted in the light of the earlier discussed concept of continuous dextral transpression with dominant backthrusting NW of the Canavese Line followed by dominant strike slip along and N of the Tonale Line. Thereby the Bergell region would have suffered its very rapid uplift at an early stage while positioned somewhere around Locarno whereas the Verampio area was uplifted while the Bergell area escaped sideways by dextral strike-slip. In fact, the displacement of the roof of the Bergell intrusion in relation to the 'Gonfolite lombarda' containing Bergell boulders (Gunzenhauser 1985) suggests dextral strike slip by some 60 km (Fumasoli 1974, Heitzmann 1987b) and is compatible with such an idea. Fission track data on these boulders (Fig. 3) suggest very rapid cooling and erosion (Wagner *et al.* 1977). The deposition of the Bergell boulders (latest Oligocene) predates most of the subsequent strike-slip movement. Later uplift of the area W of the Bergell intrusion was responsible for a considerable tilt of this intrusion around a N–S oriented axis resulting in a well documented contact aureole E of the Bergell batholith, while no such aureole can be observed in the western parts of the same intrusion (Trommsdorff & Nievergelt 1983). Based on hornblende geobarometry, Reusser (1987) determined a pressure difference of 2.5 kbar between eastern and western Bergell at the time of intrusion. This would correspond to a later differential uplift of the western parts of this intrusion in the order of 9 km.

Earlier deformations along the Canavese Line

Two mylonite belts along the southwestern portion of the Canavese Line

SW of the Valle Sesia the character of the Canavese Line and the adjacent zones changes significantly. The region considered is situated at the transition between the Upper Cretaceous high P–low T metamorphism and the Tertiary greenschist-facies metamorphism in the Sesia zone. The Ivrea zone consists of Palaeozoic granulite-facies rocks with a border of (Permian?) metatonalites and metagranites towards the Canavese Line (see Figs 4 and 5). Both Ivrea and Sesia zone show Oligocene magmatism. The Sesia zone was intruded by the Biella syenite. Along the Canavese Line remnants of related andesites and tuffites are found in a steeply dipping position. Boulders of Upper Cretaceous high-pressure rocks, found within the tuffite, indicate that this volcano–sedimentary series represents the cover of the Sesia zone (Bianchi & Dal Piaz 1963). Its Oligocene age has been confirmed by K–Ar age dating (Scheuring *et al.* 1974). This cover is now at the same topographic level as the intrusives. In the Ivrea zone an Oligocene tonalite was found near Miagliano (Carraro & Ferrara 1968) and mafic dykes of inferred Tertiary age are observed in the granitoid rim of the Ivrea zone in the Valle Sessera region.

In the region between the Valle Sessera and the Valle Sesia (Figs 2 and 4) the Canavese Line swings into a SSW–NNE strike. At the same time the inclination increases to about 70° to the WNW. Further to the SSW, a steep ESE dip is observed, possibly as a consequence of interference with the younger Cremosina Line (Fig. 1). Two mylonite belts can be distinguished. The earlier mylonitization affects the tonalitic rim of the Ivrea tectonic unit. This earlier mylonite belt (belt 1) also contains tectonically emplaced slivers of Canavese sediments. Based on sense of shear criteria this mylonite belt 1 indicates a relative uplift of the Ivrea zone combined with a dextral component of shear (Fig. 4). Mafic dykes of inferred Oligocene age

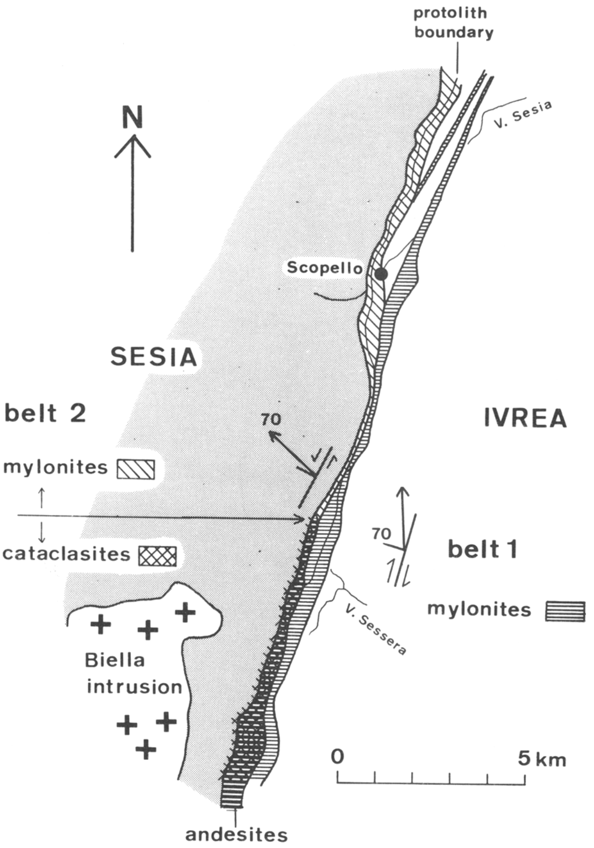

FIG. 4. Sketch map of the southwestern part of the Canavese line

intrude the western margin of the Ivrea zone and mylonite belt 1 and they are clearly seen to postdate mylonitization.

Granitic rocks (Sesia zone) and the above mentioned Oligocene andesite bearing formation are affected by later mylonitization and/or cataclasis within mylonite belt 2. It is only this post-Oligocene mylonite belt 2 which represents the continuation of post-late Oligocene backthrusting movements along the Insubric Line, as discussed in the previous chapter. Sense of shear criteria within mylonite belt 2 indicate a relative uplift of the Sesia zone in respect to the Ivrea zone, combined with a minor sinistral strike-slip component. South of the Sesia valley the tectonites of the post-late Oligocene mylonite belt 2 pass through the transition from crystal plasticity into cataclasis. This indicates that shallower levels of the post-Oligocene Periadriatic Line are exposed in this region and that the amount of post-Oligocene backthrusting and uplift is minor. This view is supported by the cooling path deduced by Hurford & Hunziker (1985).

Palaeomagnetic evidence for a large scale rotation of Ivrea and Sesia units near the Canavese Line

The remanent magnetism of 26 specimens taken from 4 mafic dykes intruding the mylonitized rim of the Ivrea zone (belt 1) was measured. The results of these investigations are plotted in Fig. 6 together with other data taken from the literature. A 60° rotation of the palaeopoles around a horizontal axis with a strike parallel to the Canavese Line (N20E) in an anti-clockwise sense viewed to the north brings these poles into a position near to that of stable Europe in the Oligocene. A similar rotation has to be applied to the data obtained from the Oligocene intrusion of Traversella, the mafic dykes found in the internal part of the Sesia zone and the andesites of the Sesia cover, whereas the mafic

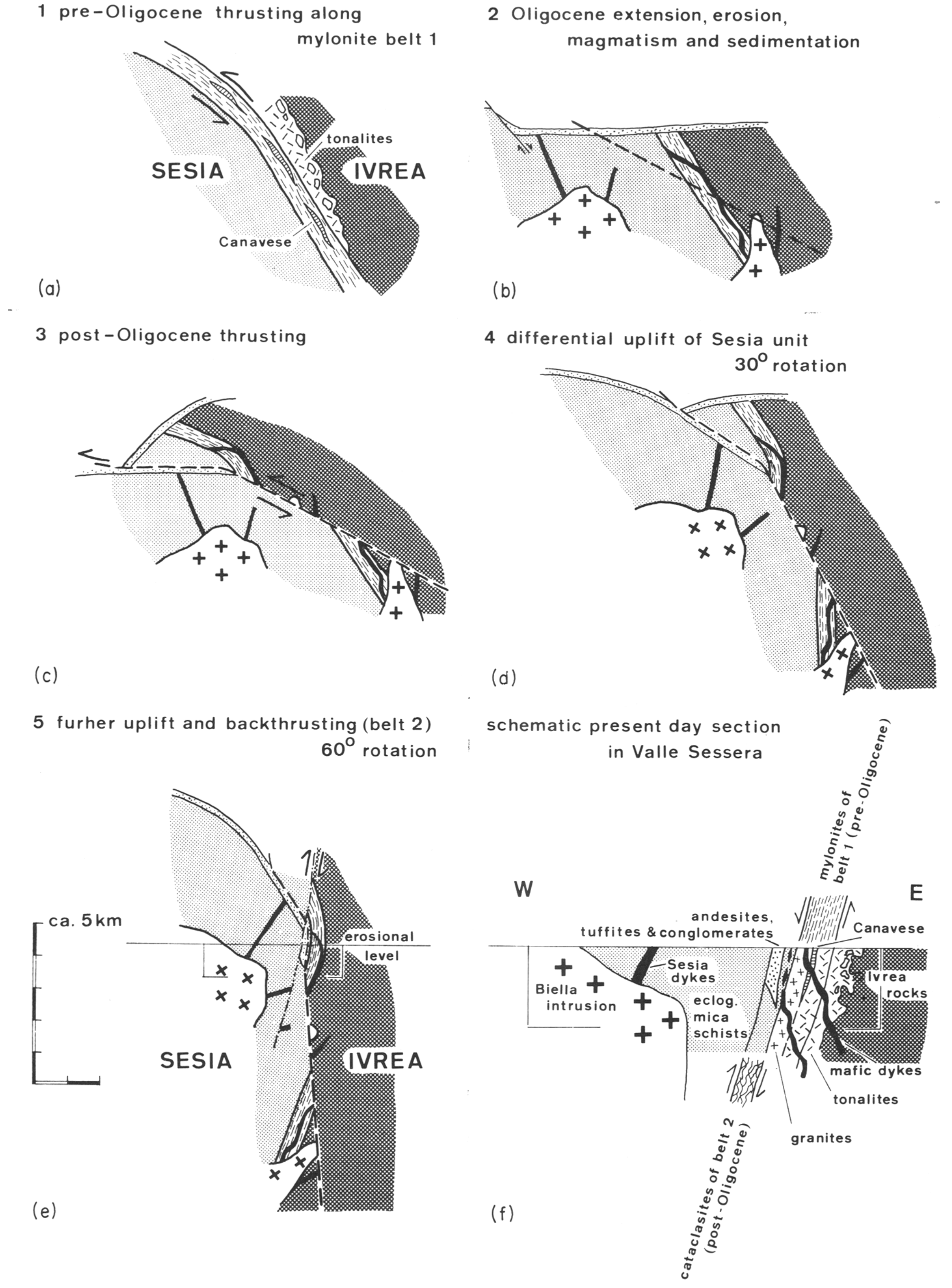

FIG. 5. A possible kinematic reconstruction (a–e) for the profile across the Canavese Line in the Valle Sessera (f). For further explanations see text.

dykes of more external parts of the Sesia zone require a smaller amount of rotation (Lauza, 1977). After this backrotation the palaeopoles cluster with other measurements from the Piemonte and the central Alps.

These findings very strongly support the idea of post-Oligocene verticalization of the Ivrea zone during the Insubric backfolding event, so far based on rather circumstantial evidence (Handy 1987, Schmid *et al.* 1987). Since the mafic dykes intrude mylonite belt 1, a backrotation has to be applied to this mylonite belt as well in order to restore the pre-Oligocene situation depicted in Fig. 5.

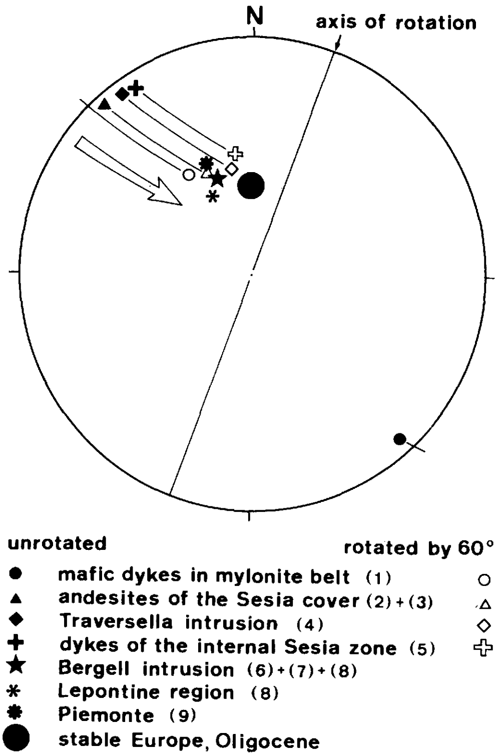

FIG. 6. Summary of a palaeomagnetic data suggesting a 60° rotation around a horizontal pole positioned N20°E (lower hemisphere). References: (1) new data, (2) Lanza (1979), (3) Heller & Schmid (1974), (4) Lanza (1984), (5) Lanza (1977), (6) Heller (1971), (7) Heller (1973), (8) Heller (1980), (9) Van den berg (1979).

A kinematic model for the southwestern part of the Canavese Line

Figure 5 (f) shows the present-day configuration. Although the kinematic evolution is not completely constrained, the following episodes can be reconstructed combining palaeomagnetic and structural data: pre-Oligocene dextral strike-slip combined with thrusting of Ivrea rocks in a northwesterly direction lead to the formation of mylonite belt 1 (Fig. 5a). This mylonite belt contains slivers of Canavese sediments and mainly affects the (Permian?) tonalitic rim of the Ivrea zone. Both Canavese sediments and tonalites are interpreted to represent shallow crustal levels of the southern Alps, strongly tectonized and overridden by the rest of the Ivrea zone during thrusting and dextral strike slip (Figs 4, 5a). Both subduction and exhumation of the high pressure Sesia rocks to the W of mylonite belt 1 occurred in Cretaceous times (Hurford & Hunziker, 1985, report mica ages suggesting 300°C at 60 Ma ago). Mylonite belt 1 cannot be held responsible for subduction (lack of high pressure overprint) nor exhumation (opposite sense of shear in Fig. 5a) of the Sesia high pressure rocks. Thus, movements along mylonite belt 1 are interpreted to postdate exhumation. Tentatively we relate these movements to the Mesoalpine collision event of the western Alps, but the regional significance of these movements remains enigmatic.

Oligocene magmatism is very widespread all along the Periadriatic Line and Laubscher (1983b) relates these intrusions to a scenario of extension affecting a large region all around the Alps. Although direct evidence for such an extensional event has not yet been found along this lineament, this scenario could well explain rapid erosion and redeposition (Fig. 5b) of huge Sesia boulders well exposed NW of Biella near Sordevolo (Bianchi & Dal Piaz 1963).

In order to explain the sandwiching of Oligocene andesites between the erosional surface of the Sesia zone and mylonite belt 1 a second post-Oligocene thrusting event is required (Fig. 5c). Subsequently, the Insubric phase produces large scale rotation of both the internal Sesia zone and the western rim of the Ivrea zone (Fig. 5d, e). The component of backthrusting must have been minor. This explains the above mentioned transition into cataclastic deformation along mylonite belt 2.

Although the local geology is not yet fully understood the following conclusions can be drawn from the observations in the Sessera area:

(1) Pre-Oligocene deformations are documented in mylonite belt 1.
(2) There is a lateral transition from crystal plasticity into cataclastic deformation along belt 2 in post-Oligocene times, i.e. during the Insubric phase.

(3) Palaeomagnetic data indicate post-Oligocene rotation and verticalization of the Ivrea zone and the internal part of the Sesia zone.

In the next section a possible model will be discussed which helps to explain this rapid change in amount and direction of shearing along the Insubric Line.

A model of indentation and sideways escape of the Lepontine region during the Insubric phase

In an attempt to understand the complexity of late to post-Oligocene movements along the Insubric Line and the associated deformation within central and southern Alps the role of the Ivrea zone (and its extension to depth, the Ivrea geophysical anomaly) as a rigid buttress with restricted internal deformation has to be emphasized. Schmid *et al.* (1987) interpret the vertical uplift of this slice of deep continental crust and upper mantle to result essentially from crustal thinning culminating in the early Jurassic (possibly starting in the late Palaeozoic, Handy 1986 1987, Brodie & Rutter 1987) combined with Cretaceous subduction. Radiometric data from the Ivrea zone (McDowell & Schmid 1968, Hunziker 1974) indicate temperatures at around 300°C 180 Ma ago. Hence mantle material whose rheology is dominated by olivine, and in addition, deeper crustal levels dominated by feldspar rheology, were present in shallower crustal levels and before the onset of orogenesis. This had severe consequences for later compressional movements in that the rheology of the Ivrea rocks must have been dominated by the flow properties of olivine and feldspar. Both these minerals are significantly harder to deform at shallow depth than quartz, the mineral which will determine the rheology of upper crustal levels under normal circumstances (see Ranalli & Murphy 1987 for a compilation of depth vs strength curves).

The mylonites of the Insubric Line closely follow the pre-existing northwestern margin of the Ivrea zone. Their localization is the product of a pre-existing configuration created by Mesozoic rifting (Fig. 7), i.e. a NNE–SSW oriented axis of spreading offset by E–W running transfer faults (Weissert & Bernoulli 1985) modified by Cretaceous subduction and underplating of the Sesia zone (Schmid *et al.* 1987). We interpret the relatively sharp bend of the Canavese Line into the E–W strike as it merges with the Tonale Line to be predetermined by a former transfer fault. No deep crustal or upper mantle rocks are preserved along the continuation of this passive continental margin into the Lower Austro–Alpine units of eastern Switzerland. The exceptionally good preservation of a passive continental margin in the southern Alps, including lower crust and upper mantle is attributed to another anomaly, namely the subduction and exhumation of continental crust in the form of the Sesia zone. The quartz-bearing Sesia zone acted as a buffer inhibiting the deformation and subduction of the deeper parts of this continental margin at its western edge during collision.

Dextral transpression during the Insubric phase led to highly variable amounts of uplift related to a very complex displacement path along the curved Insubric Line (Fig. 7) and in front of a rigid indenter in the form of the Ivrea zone which is bounded by a transfer fault in the north. The lateral escape of the central Alps occurred almost entirely in an eastern direction because, (i) the southwestern Canavese Line (mylonite belt 2) acommodates only minor amounts of backthrusting and sinistral strike-slip, (ii) a substantial component of dextral strike-slip is recorded along the Canavese Line northeast of Valle Sesia, i.e. in a region where this line strikes NE–SW and perpendicular to the inferred direction of indentation (Fig. 7), and (iii) further to the E and S of the Bergell intrusion the component of backthrusting rapidly decreases in favour of dextral strike-slip which clearly outlasts backthrusting (Heitzmann 1987b).

The complex cooling history of the Lepontine region with the earlier mentioned migration of late Tertiary cooling and uplift from E to W (Fig. 3) can now be readily explained by this model which suggests a point of indentation somewhere at the northwestern edge of the Ivrea body. Parts of the central Alps which were previously uplifted and backthrusted at this northwestern edge of the Ivrea zone would successively move to the E. Extension across the Simplon Line (Mancktelow 1985) postdates most of the backthrusting and backfolding. These movements along the Simplon Line indicate a substantial tangential stretch in front of the indenter during the closing stages of dextral transpression. For a more detailed discussion of the internal deformation within the Lepontine dome the reader is referred to Merle *et al.* (this volume).

Viewed in cross section (Fig. 8) the modification of the Insubric movements to the previously existing Alpine edifice are impressive.

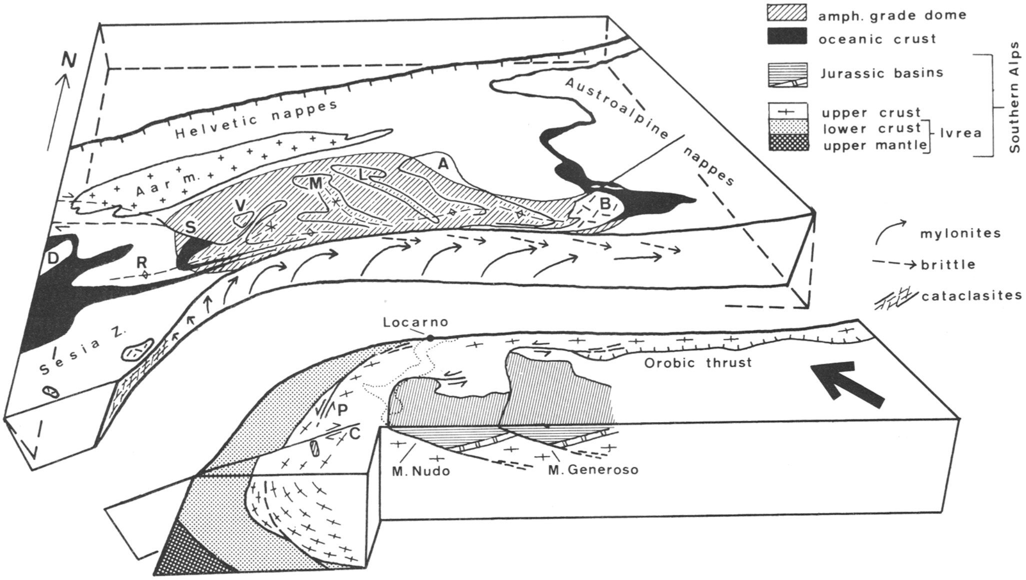

FIG. 7. Three-dimensional sketch illustrating the model of asymmetric escape of the Lepontine region as a result of indentation of the passive continental margin in the Southern Alps (Ivrea geophysical body in particular). Arrows indicate the displacemant path of the central Alps in relation to the southern Alps as inferred from the analysis if stretching lineations (Insubric mylonites) and slickensides (brittle overprint of the Insubric line by the Tonale fault).

Backthrusting and backfolding in the south are largely contemporaneous with the age of major nappe transport and folding in the Helvetic nappes as given by Trümpy (1969) and Pfiffner (1986). Pfiffner (1985) pointed out that some 15–30 km displacement are still required as far back as point X in Fig. 8(b) along the Garvera thrust, which accomodates part of the 50 km displacement along the Glarus thrust. Two solutions are possible for the continuation of this thrust: it either runs down into the Moho as a ductile shear zone or it has to be kinematically connected with backthrusting along the Insubric Line. We prefer the second option which would imply that the central Alps form an asymmetric wedge or orogenic lid (Laubscher 1983a) with complete decoupling between lower and upper crust. The asymmetry of the shape of this wedge, i.e. low angle thrusts in the Helvetics and steeply inclined backthrusting along the Insubric Line is also reflected in a similar but less pronounced asymmetry of the northern and southern slope of the Moho (Figs 1c, 8b). It thus appears that the present day topography of the Moho is closely related to and caused by post-collisional shortening during the Insubric phase. The question as to whether post-collisional subduction during the Insubric phase and below the central Alps is needed (as depicted in the model of Laubscher 1984) or not cannot be decided before a serious attempt in volume balancing is made under consideration of the amount of syntectonic erosion.

Whereas Laubscher envisaged a similar geometry during the Eocene collision (fig. 16b in Laubscher 1983a) we prefer a model of S-sloping subduction during the Eo- and Mesoalpine stages. We propose that the Insubric backthrust merely displaces the suture between Austro–Alpine and Pennine units and that the same suture extends further to the S and under the southern Alps. This reasoning can be supported by the following arguments:

(1) The density inversion at the base of the Ivrea geophysical body (Fig. 8a) is readily explained by Eoalpine subduction of an originally much larger volume of continental crust as compared to the present-day Sesia zone (Schmid *et al.* 1987).

(2) The palaeomagnetic results presented earlier give firm support for late or post-Oligocene verticalization of the Ivrea zone. On the other hand most of the cover of the southern Alps further to the S and E remained in a subhorizontal attitude. This

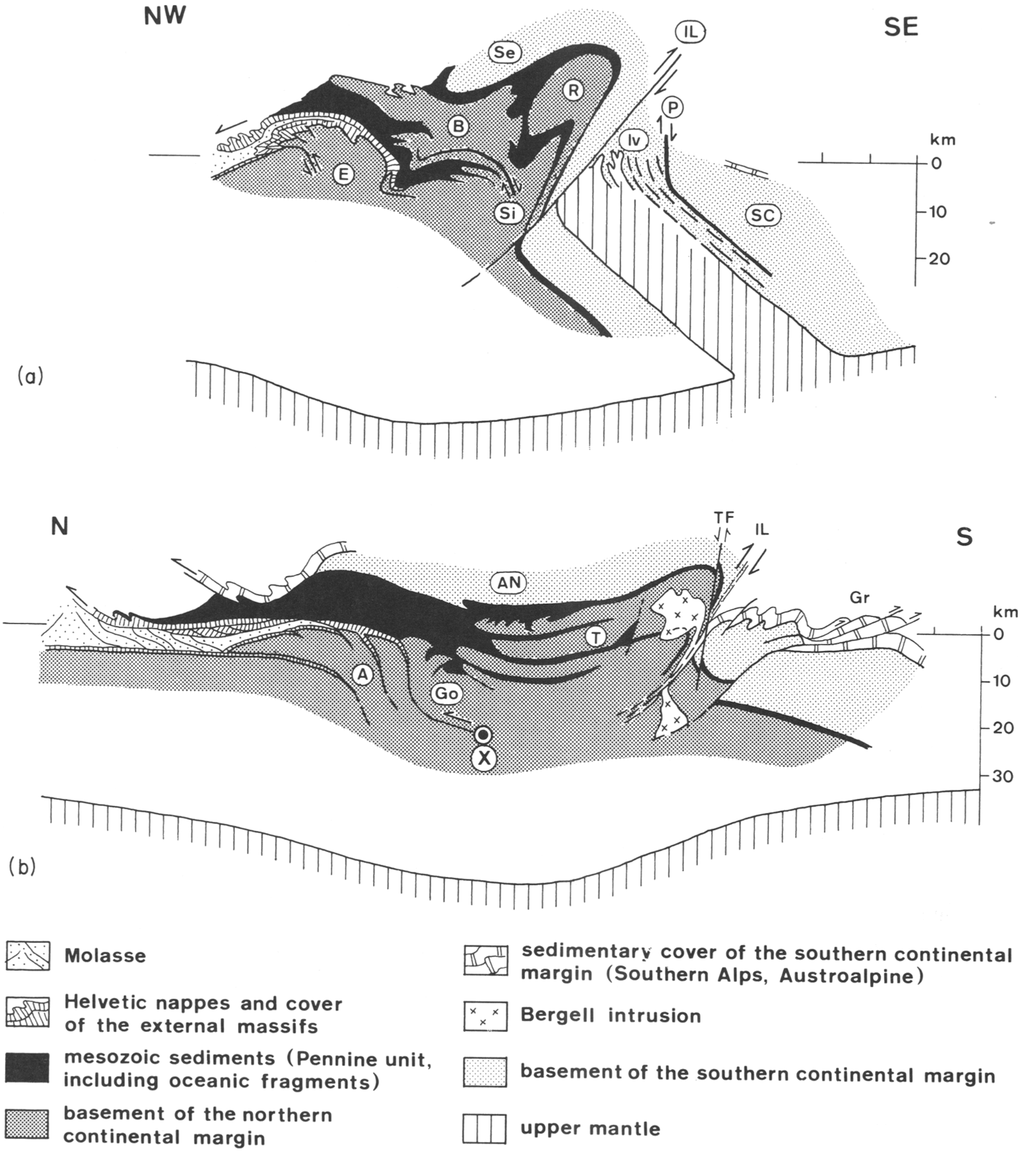

FIG. 8. Two scaled profile sketches through the Alps (profile trace indicated in Fig. 1a).
(a) Profile through the Simplon area (after Kissling 1980, Schmid *et al.* 1987, Escher *et al.* 1988). E–external massifs; B–Bernhard nappe; R–M Rosa nappe; Se–Sesia–Dent Blanche nappe; Iv–Ivrea zone; SC–Strona Ceneri zone; Si–Simplon Line; IL–Insubric Line; P–Pogallo Line. (b) Profile through eastern Switzerland (after Trümpy 1985 and Pfiffner 1985). A–Aar Massif; Go–Gotthard 'Massif'; T–Tambo nappe; AN–austro–Alpine nappes; Gr–Grigna mountains; TF–Tonale fault (brittle); IL–Insubric Line (mylonites); X–see text.

situation calls for a hinge zone somewhere SE of the Periadriatic Line (Fig. 7). Thus, it is tempting to bring the suture back into a moderately S-dipping orientation as shown in Fig. 8(b).

(3) Müller *et al.* (1980) provide evidence for a deep seated lithospheric root S of the Periadriatic Line, and Giese *et al.* (1982) interpret their seismic section through a region further to the E in terms of crustal doubling.

(4) In the absence of substantial vertical displacements across the Periadriatic lineament further to the E (Gailtal Line) a major subdivision into Austro–Alpine nappes and southern Alps becomes rather dubious, at least in profile view (we will discuss possible strike-slip components later).

The Periadriatic Line and related lineaments in the eastern Alps

The following discussion is largely based on reviewing the literature. Considerable uncertainties about the kinematics of movements still exist because of the paucity of modern microstructural work eludicating the sense of shear. The increasing importance of Cretaceous deformations and metamorphism in the eastern Alps is another complicating factor.

The exact nature of interference between Giudicarie and Tonale Lines is still unknown. A simple offset of the Tonale and Pustertal Lines by the Giudicarie Line can be ruled out because of the non-existence of an extension of the Giudicarie Line into the central Alps. It is possible that the eastern parts of the Tonale Line only take up the cataclastic components observed along the Tonale Fault and that the mylonite belt, which takes up most of the 60 km dextral shear continues along the Pejo Line where Andreatta (1948) described greenschist-facies mylonites.

The Giudicarie Line runs immediately to the W and parallel to a palaeogeographic boundary between the Trento swell and the Lombardian basin (Castellarin 1972). This boundary persisted from the early Jurassic into the Eocene and forms the eastern edge of deposition of upper Cretaceous flysch deposits (Bernoulli *et al.* 1981). Furthermore, Brack (1981) showed that N–S compression within the southern Alps west of the Giudicarie Line predates the Eocene Adamello intrusion. Further to the E it appears that this pre-Eocene (Cretaceous?) deformation is transformed into sinistral transpression along the Giudicarie Line. All this suggests that this line may have acted as a transpressive sinistral strike-slip zone in Cretaceous times, although it certainly was also active after the Oligocene (Castellarin & Sartori 1979).

Cretaceous movements along or in the vicinity of the northern segment of the Giudicarie Line are indicated by east directed thrusting of the Oetztal nappe (Schmid & Haas 1987), contemporaneous with Cretaceous amphibolite grade metamorphism (Thöni 1981, 1986). This thermal dome within the southern Oetztal nappe (Fig. 1b) must have rapidly cooled during Cretaceous times (Thöni 1986). Pre-Alpine radiometric ages (Del Moro *et al.* 1982) are found in a region S of the Oetztal nappe but still N of the traditional location of the northern branch of the Guidicarie Line. All this suggests a scenario of backthrusting and westward escape of the Oetztal nappe in Late Cretaceous times, associated with movements along or in the vicinity of the Periadriatic Line (i.e. the northern Giudicarie Line).

Renewed compression during the Insubric phase produced tangential stretching along the Brenner fault (Behrmann 1987, Selverstone 1988) combined with updoming of the Tauern window (Fig. 1a). The localization of tangential stretching and updoming in front of an indenter (southern Alps E of the Giudicarie Line) is very similar to what is observed at the western edge of the Lepontine dome. There, tangential stretching is recorded along the Simplon Line (Mancktelow 1985, Merle *et al.* this volume) and in front of the indenting Ivrea zone (Fig. 1a).

Based on a modern microstructural and textural analysis of the greenschist-facies mylonites along the DAV line, Kleinschrodt (1987a, b) demonstrated sinistral strike-slip movements combined with a minor component of uplift north of the DAV line, responsible for an age jump in terms of biotite ages (Borsi *et al.* 1978). These biotite cooling ages and the deformation of dykes associated with Oligocene intrusives in that region date these movements to be contemporaneous with the Insubric phase. Additionally, Stöckhert (1984) provides evidence that the same lineament was also active during the Cretaceous. Dextral movements along the Pusteria and Gailtal Lines are indicated by a series of large scale Riedel shears: the Mölltal and Lavanttal Lines (Fig. 1a).

Thus, we are faced with evidence for both dextral and sinistral strike-slip movements forming at a very acute angle during post-Oligocene times. Palaeogeographic evidence can substantiate such strike-slip movements. Bechstädt (1978) calls for a very substantial amount of strike-slip between the northern calcareous Alps and the Drauzug based on palaeogeographic arguments. Kleinschrodt (1987a) proposed the DAV Line as a possible site for such sinistral movements. On the other hand there are considerable facies differences across the Gailtal Line between Drauzug and the southern Alps

(Prey, in Oberhauser 1980 and Bechstädt 1978) calling for compression and/or dextral strike-slip.

In a recent attempt to reconstruct the palaeogeography of a very large region including the Transdanubian central ranges (Bakony, Hungary) Kazmer & Kovacs (1985) postulate lateral escape of Drauzug and Bakony unit to the E between the DAV and Raba Lines operating sinistrally and the Gailtal and Balaton Lines operating dextrally (Fig. 1a). Although these authors date this lateral escape of some 450 km to have taken place from middle Eocene to late Oligocene times, the closing stages of this escape may still coincide in time with the Insubric phase of the western Alps. The fact that the Mölltal and Lavanttal Lines dextrally transect a large area to the N of the Gailtal Line and the younger age for transpression in the Karawanks (late Miocene, Laubscher 1983b) may indicate that dextral transpression outlasted this continental escape.

We regard the total amount of dextral strike-slip movement N of the Adriatic sub-plate (300 km) to be rather well constrained by the arguments of Laubscher (1971a). However, recent structural work in the Austro–Alpine nappes (Ratschbacher 1986, Schmid & Haas 1987) calls for a regime of dextral transpression already during Cretaceous orogeny of the eastern Alps. It thus appears that a large portion of the 300 km total strike-slip predates the post-late Oligocene movements along the Periadriatic Line.

In summary, it appears that the response of the eastern Alps to post-Oligocene dextral transpression is of a fundamentally different nature as compared to the western Alps: lateral escape between conjugate strike-slip zones rather than substantial uplift associated with foreland thrusting (Helvetic nappes) and backthrusting (Insubric Line). As shown in Fig. 1c the Moho trough no longer follows the direction of the Periadriatic Line E of the Tonale Line and its topography seems to be unrelated to and unaffected by Giudicarie, Pusteria and Gailtal Lines.

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