Journal of Structural Geology, Vol. 14, No. 10, pp. 1203 to 1213, 1992
Printed in Great Britain

0191-8141/92 $05.00+0.00

Deformation partitioning during polyphase oblique convergence in the Karawanken Mountains, southeastern Alps

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(*Received* 15 *January* 1992; *accepted in revised form* 28 *May* 1992)

Abstract—The Karawanken Mountains of southeastern Austria straddle the Insubric Line, a major fault zone that corresponds to the Austroalpine–South Alpine border of the eastern Alps. They display polyphase structural patterns that resulted from deformation partitioning at shallow crustal levels. Following a poorly constrained late Cretaceous deformation history, Paleogene contraction produced NW–SE-trending fold–thrust structures and possibly related sinistral (?) cross faults. Miocene deformation produced both NW- and SE-directed thrust faults and NW-striking high-angle dextral cross faults which merged with or displaced the W-striking Insubric Line. Distributed dextral strike-slip displacements of the order of 30–40 km and thrust displacement of 4–5 km along the northern Karawanken front initiated subsidence of a small foreland basin north of the Karawanken Mountains. Recent regional deformation seems to be concentrated along cross-cutting NNW-striking dextral faults within a shifting system of seismogenic transfer faults that probably merge with the convergent South Alpine thrust front to the west. There are conspicuous parallels in the style of deformation along the Karawanken Mountains with that found along other seismogenic convergent strike-slip faults, such as those of southern California, New Zealand and Anatolia.

INTRODUCTION

DEFORMATION of sedimentary and basement rocks at high crustal levels within major strike-slip fault systems results in complex structural patterns, because the effects of convergence (transpression) and divergence (transtension) tend to alternate both along strike and in time (Wilcox *et al.* 1973, Reading 1980, Sanderson & Marchini 1984, Aydin & Nur 1985, Christie-Blick & Biddle 1985, Woodcock & Fischer 1985, Sylvester 1988). This is especially the case where regional strike-slip displacement is modified by strong convergent components of motion, causing offset and rotation of pre-existing strike-slip fault segments (Sylvester & Smith 1976, Hancock & Atiya 1979, Aydin & Page 1984, Harding 1985, Namson & Davis 1988, Ron *et al.* 1990).

The Insubric (or Periadriatic) Line discussed here is a major fault zone within the northern Adriatic plate (inset Fig. 1). Sense, magnitude and timing of the strike-slip displacements of the Insubric Line and its relationship to other major structures within the growing Alpine edifice of south-central Europe are still poorly understood although some progress has been made in recent years (Laubscher 1970, 1983, 1988, Bögel 1975, Schmid *et al.* 1989, von Gosen 1989). The Insubric Line is relatively well defined along the axis of the Karawanken Mountains of southeastern Austria because pre-Mesozoic basement and the Austroalpine and South Alpine Mesozoic facies are juxtaposed along the fault zone, but show a distinct mismatch (Fig. 2). Polyphase structural patterns imprinted on both Mesozoic cover rocks and the Paleozoic low-grade basement result in a generally complex map pattern (Bauer 1982, 1985). Remapping of this area and analysis of relevant kinematic data (Polinski 1991) permitted spacial and temporal correlation of major structures along and away from the fault zone. Thus intraplate Alpine evolution of the easternmost Insubric Line segment can be related to the possible kinematics of convergent strike-slip faulting between late Mesozoic and Recent times.

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REGIONAL SETTING AND STRATIGRAPHY

The Karawanken Mountains, about 140 km long, and 15–25 km wide, with local relief in excess of 1500 m, are located in the southeastern Alps (Fig. 1). The morphologically dominant Austroalpine and South Alpine Permo-Mesozoic platform strata which rest on deformed and/or metamorphosed Paleozoic Variscan basement units display a distinct misfit of their respective sedimentary facies along the Insubric Line. Reconstruction of Mesozoic facies belts along the fault zone west of the Karawanken Mountains (inset Fig. 2) suggests some 100–150 km of dextral separation between Austroalpine and South Alpine cover rocks (Brandner 1972, Bögel 1975, Niedermayr 1975, Tollmann 1977, Laubscher 1988). There, the Insubric Line also appears to be offset along the sinistral Giudicarie Line (Doglioni & Bosellini 1987). Yet farther to the west, late Alpine SE- to S-directed thrust emplacement of the cooling Penninic infrastructure of the west-central Alps over the cold South Alpine crustal lid was also centred along the Insubric Line. This uplift led to erosion of the overlying Austroalpine crustal unit over large areas (Heitzmann 1987, Schmid *et al.* 1987, 1989, Hur-

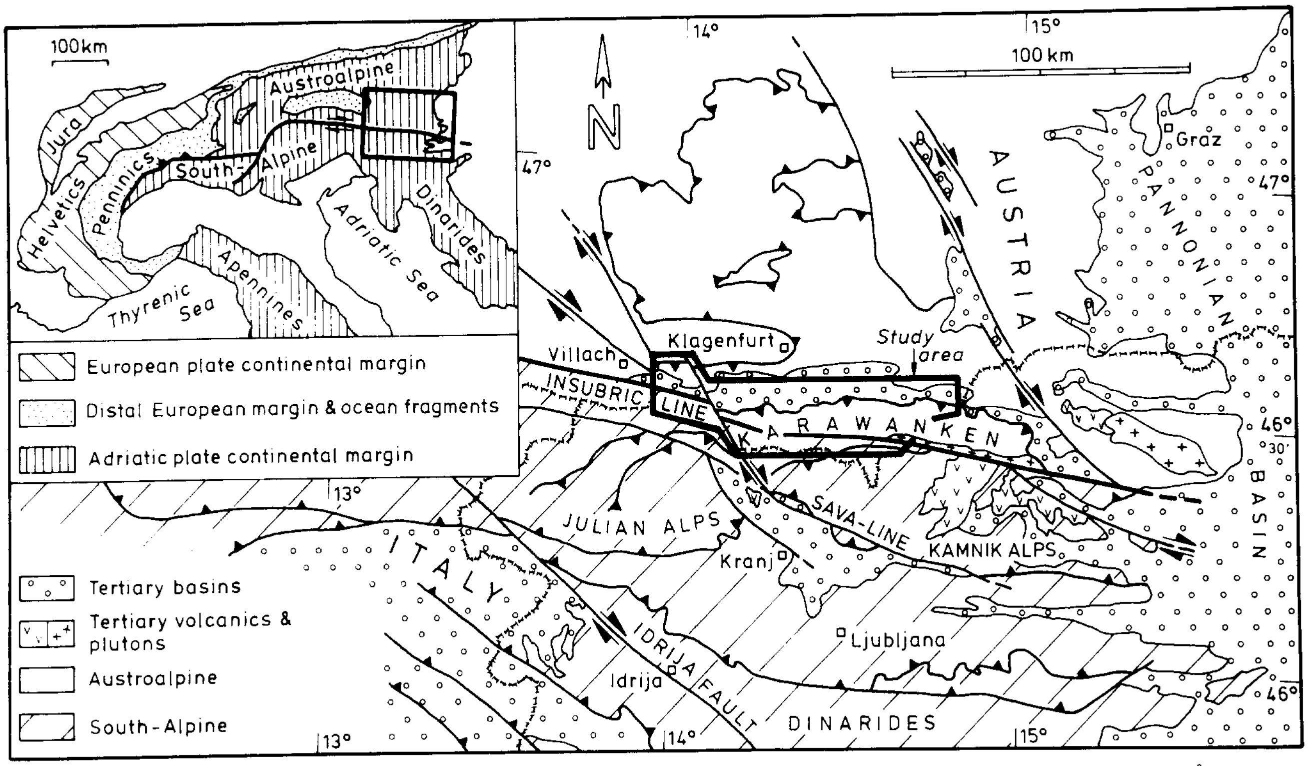

Fig. 1. Regional tectonic framework of the Neogene Karawanken Mountains which straddle the easternmost segment of the Insubric Line, a major intraplate fault zone within the northern Adriatic plate (see inset).

ford *et al.* 1989). Towards the east the Insubric Line disappears beneath Neogene–Pleistocene fill of the extensional western Pannonian Basin.

Mesozoic Austroalpine and South Alpine sedimentary strata were deposited on a wide and internally structured platform along the northern margin of the Adriatic plate. Within the Karawanken Mountains, regional variations in stratigraphy reflect differential subsidence patterns along this margin (Fig. 2). The Austroalpine cover is an 3.4 km thick Upper Permian to Lower Cretaceous succession (Bauer *et al.* 1983), that rests on Variscan metamorphic basement intruded by the Oligocene (29 ± 6 Ma, 28 ± 4 Ma, Scharbert 1975) tonalitic Karawanken pluton during late Alpine structural evolution. Austroalpine basement includes low-grade Ordovician metavolcanoclastics, micaschists, phyllites and Permian granite which are overlain by non-marine Permian redbeds (on average about 200 m thick). Mesozoic strata consist of the competent dolostone and limestone units of the Middle Triassic Wetterstein Formation (up to 1200 m thick) and Upper Triassic Hauptdolomit Formation (up to 700 m thick). Incompetent detachment horizons are basinal shale facies of the Middle Triassic Partnach Formation below or coeval with the Wetterstein Formation and shale members of the Raibl Formation below the Hauptdolomit Formation. Minor detachment also occurred in shales of the uppermost Triassic Kössen Formation and in overlying thinly bedded basinal Jura-Cretaceous limestones and marls (Fig. 2). The Neogene syntectonic coarse clastics of the adjacent Klagenfurt Basin overlying the Austroalpine strata locally attain a thickness of up to 900 m.

The South Alpine succession is 3.2 km thick and consists of Ordovician to Lower Carboniferous metasediments overlain by Upper Carboniferous to Lower Jurassic sedimentary strata (Schönlaub 1979, Bauer *et al.* 1983). The Lower Paleozoic metasediments comprise pre-Alpine sheared clastic and calcareous rocks of unknown thickness. Within the Upper Carboniferous to Permian marine clastics and carbonates (1300–1500 m) the most competent unit is the dolostone of the Upper Permian Bellerophon Formation (about 100 m thick). The overlying Mesozoic succession contains the competent Middle Triassic 'Anisian' dolostone unit (about 340 m thick), the massive carbonates of the Middle Triassic Schlern Formation (up to 700 m thick) and the thick bedded limestone of the Upper Triassic Dachsteinkalk Formation (up to 1000 m thick). Potential detachment horizons are evaporites within the lower Bellerophon Formation, shales in the Lower Triassic Werfen Formation and the Middle Triassic recessive Wengen Formation (Fig. 2).

In general, the deformation of Mesozoic cover strata has produced polyphase fold–fault structures which originated at relatively shallow crustal levels. Superposition of folds with different trends has resulted in refolded hinges within incompetent units which were preserved within fault-bounded blocks of competent units. In other areas early formed folds were destroyed by a progressively pervasive cataclasis along splays of cross-cutting fault zones. The well defined thrust-related northern border of the Karawanken Mountains and other thrust- or strike-slip-bounded fault blocks to the south such as those of the Kamnik and Julian Alps are mainly of Neogene age, as are the related clastic Klagenfurt and Kranj basins.

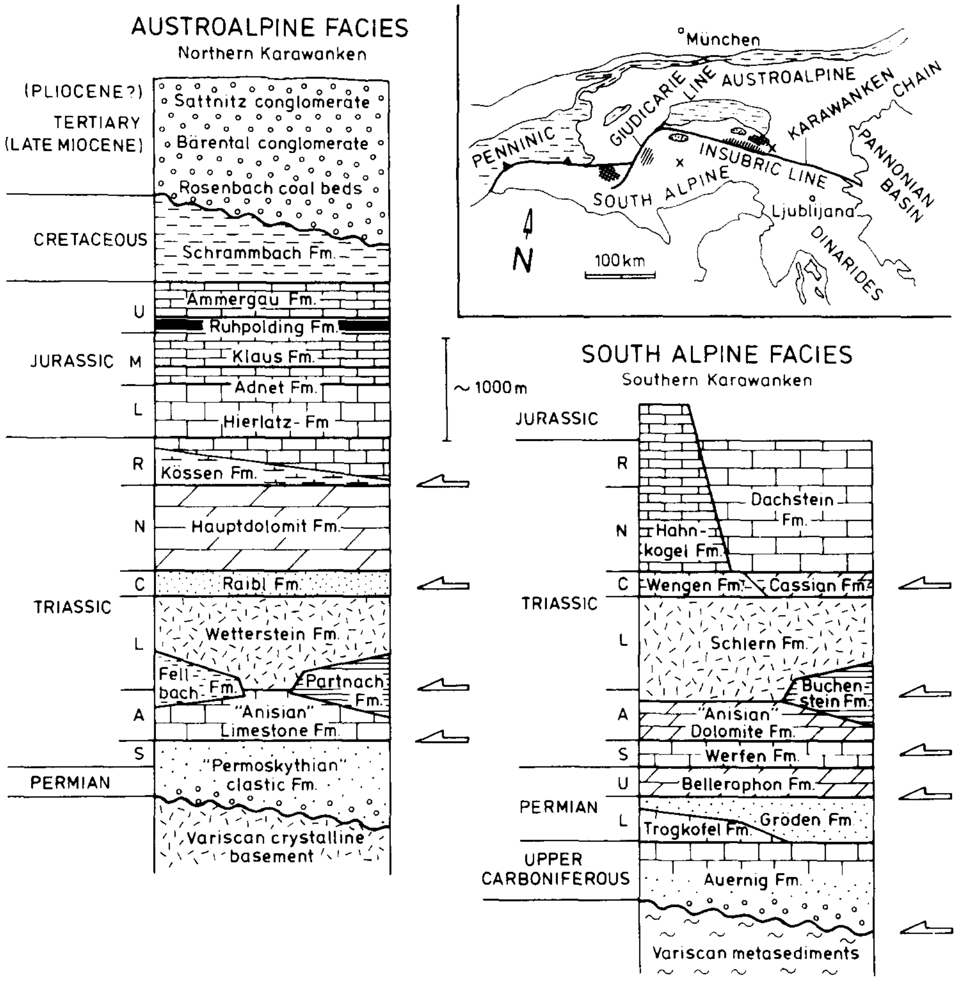

Fig. 2. Stratigraphic units of the Austroalpine and South Alpine facies domains juxtaposed along the Insubric Line and showing the distinct mismatch of sedimentary facies (modified from Bauer *et al.* 1983). Triassic stages are abbreviated with letters. Potential detachment horizons within the Mesozoic cover succession are indicated by open arrows. Inset in upper right corner shows possible facies correlations across the central Insubric Line (crosses, dots, vertical and crossed ruling; for site-specific references see Brandner 1972, Bögel 1975, Niedermayr 1975, Tollmann 1977).

GEOMETRY OF SUPERIMPOSED FOLD–FAULT STRUCTURES

Early NW-trending folds

Within the northwesternmost Karawanken Mountains the Austroalpine Permo-Mesozoic cover rocks display two superimposed structural trends (Fig. 3). The older structures are regional NW-trending and slightly NE-verging folds in Triassic carbonates (Matschach Syncline, Rabenberg Anticline, Singerberg Syncline, and the Ferlach Anticline–Syncline pair of Fig. 3); associated with and truncating these folds are NE-striking high-angle cross faults. In the upper Feistritz Valley, dipping beds within these structures are overlain unconformably by remnants of coarse clastic deposits which have been correlated with Upper Miocene basal clastic deposits of the Klagenfurt Basin (Kahler 1953, van Husen 1976, von Gosen 1989). Towards the east, remnants of several NW-trending folds are recognized locally above the Karawanken frontal thrust. Towards the south and southeast, NW-trending folds either did not develop or were later structurally overprinted beyond recognition. Their general absence in South Alpine strata of the Karawanken Mountains could mean, however, that the present juxtaposition of Austroalpine and South Alpine strata along the Insubric Line occurred after the NW-trending folds had already developed. It is also possible that the crustal substratum south of the Insubric Line at this time was more rigid. All NW-trending folds and NE-striking sinistral (?) cross faults were overprinted by sets of NE-trending folds and contraction faults including the composite frontal Karawanken thrust. The superimposed NW-striking dextral cross faults, which also offset the Karawanken Thrust possibly nucleated at least partly in the cores of early NW-trending folds. In the Karawanken Mountains the age of these early NW-trending folds cannot be inferred more precisely than pre-late Miocene.

Miocene NE-trending fold–fault structures, NW-striking cross faults, and the Klagenfurt clastic basin

The structure of the Karawanken Mountains is dominated by both NW- and SE-directed thrust faults and arrays of related ENE- to NE-trending folds, truncated by NW- to WNW-striking high-angle cross faults spaced at intervals of about 2–4 km. The cross faults commonly

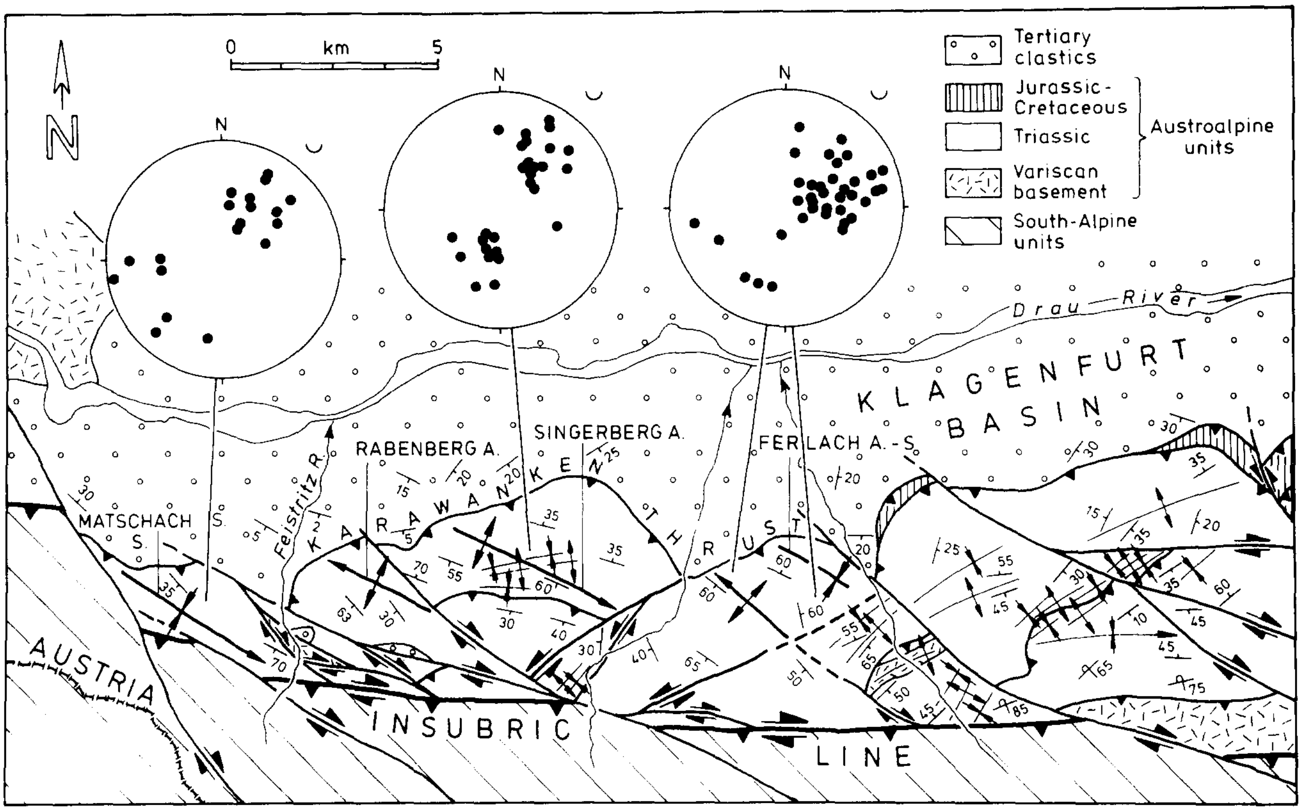

Fig. 3. Structural sketch map of the Austroalpine cover rocks of the northwestern Karawanken Mountains where older NW-trending fold–thrust structures (heavy lines) and related sinistral (?) cross faults were overprinted by NE-trending contraction structures and related dextral cross faults. Equal-area, lower-hemisphere stereoplots show poles to bedding in major NW-trending fold structures.

show dextral offsets of fold axial surfaces, thrust faults or steeply dipping marker units by amounts ranging from a few hundreds of metres to a few kilometres. This structural pattern is observed in both Austroalpine and South Alpine units, and cross faults merge with or offset the Insubric Line dextrally. Generally, however, they do not extend beyond the frontal Karawanken thrust. Along the Insubric Line in the east-central Karawanken Mountains, the Austroalpine basement of the Eisenkappel zone contains a Permian granite and the Oligocene tonalitic Karawanken pluton (Fig. 4). The zone is laced by E-striking and steeply S-dipping ductile-to-brittle fault zones and the Insubric Line is subparallel to transposed bedding and foliation fabrics in the low-grade metasedimentary units. Asymmetry of shear bands, together with locally observed semi-penetrative stretching lineations, indicate post-intrusive distributed dextral shear, which elongated the enclosed Permian granite (46 km long, 2 km wide) and possibly the Karawanken pluton (41 km long, 2.2 km wide) as well. Post-emplacement uplift of the Karawanken pluton and its low-grade metamorphic country rocks was probably of the order of 5–10 km. Apatite fission track ages of about 16 Ma for samples of the Permian granite and the Karawanken pluton (L. Ratschbacher personal communication 1991) point to a cooling below 100°C near the Insubric Line at that time. South of the Insubric Line, South Alpine pre-Permian units are also intensely sheared and towards the west, dextral distributed displacement on WNW-striking cross faults transferred South Alpine units towards the frontal Karawanken thrust (Fig. 4). This displacement transfer produced an apparent dextral separation of steeply dipping pre-Permian units of the order of 20 km and offsets fold axial surfaces and steeply dipping beds along similarly oriented cross faults of the order of 10–15 km. We estimate that in this manner about 30–40 km of distributed dextral shear occurred along WNW-striking cross faults (Polinski 1991). This suggests that the overall orientation of the Insubric Line also could have changed from a more east-northeasterly strike to the present easterly strike by distributed internal shortening and by frontal thrusting of the Karawanken Mountains over its foreland to the north. On account of small-scale tilting, cataclasis and rotation around vertical axes the behaviour of individual blocks is difficult to quantify.

Frontal thrusting is clearly reflected in the history of clastic sedimentation in the Klagenfurt Basin, which began with the fine-grained coal-bearing late Miocene clastics (Rosenbach Beds). Progradation of latest Miocene to (?) Pliocene coarse fluvial deposits with a basal South Alpine provenance (Bärental Conglomerate) indicate uplift in the vicinity of the Insubric Line. Carbonate slide blocks are locally interbedded with coarse proximal deposits of alluvial fans and braided alluvial plain deposits (Sattnitz Conglomerate) and suggest high-gradient erosion and deposition near the Karawanken thrust front (van Husen 1976, 1984). A gravity survey across the mountain front (Steinhauser *et al.*

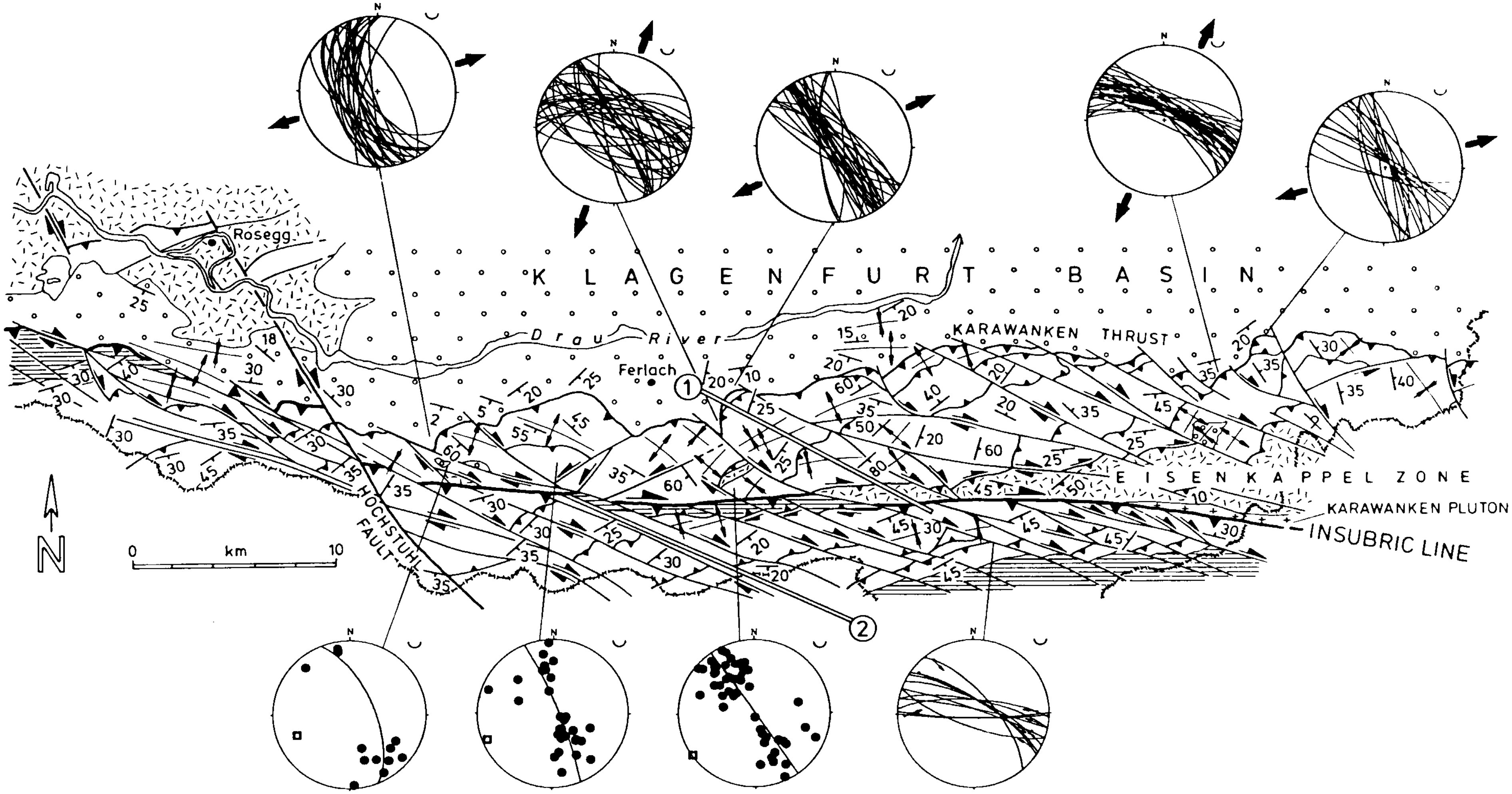

Fig. 4. Sketch map of the Karawanken Mountains. Austroalpine metamorphic basement of the Eisenkappel zone (random dashes), South Alpine pre-Permian metasediments (ruling), Mesozoic cover rocks (blank) and Neogene clastics of the Klagenfurt Basin (circles) are shown. Location of cross-sections 1 and 2 as shown in Fig. 5. Equal-area, lower-hemisphere stereoplots in the upper part of the diagram display local orientation of extension fractures in rounded conglomerate clasts of the Neogene basin fill near the frontal Karawanken thrust, stereoplots below the map show poles to bedding for major NE-trending fold structures on the left and striations on high-angle faults subparallel to a major WNW-striking cross fault on the right.

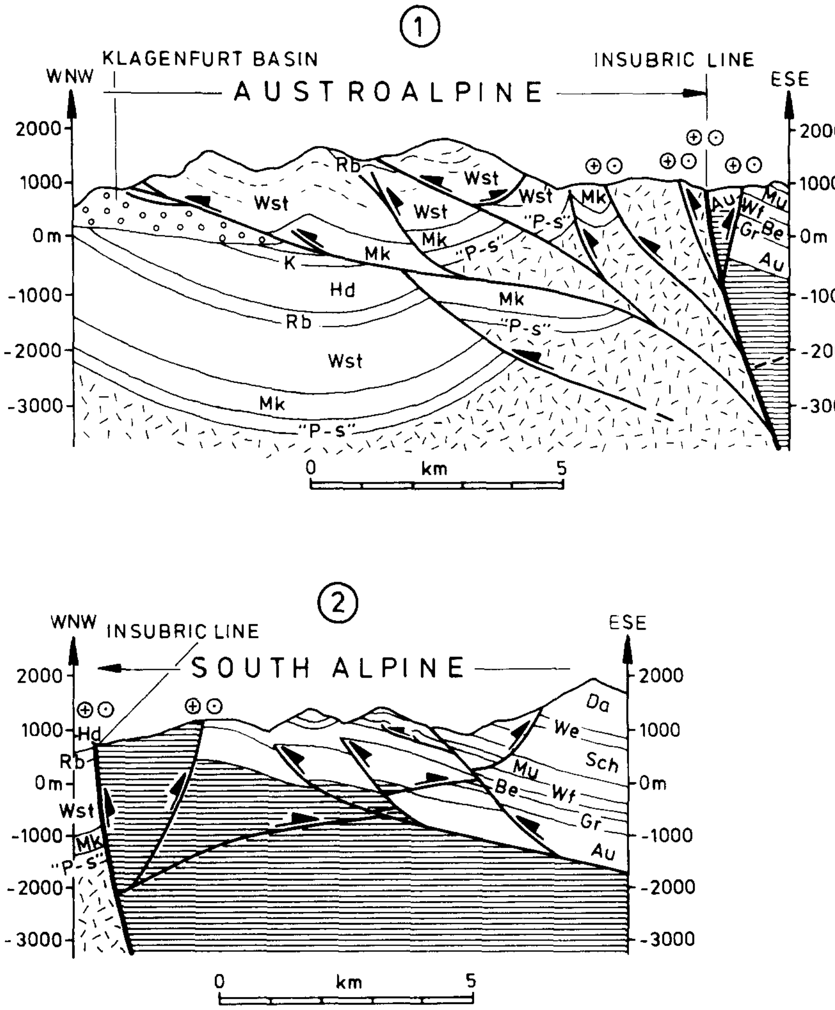

Fig. 5. Two semi-balanced cross-sections oriented parallel to the inferred local direction of contraction in the Austroalpine (northern Karawanken Mountains, section 1 of Fig. 4) and South Alpine (southern Karawanken Mountains, section 2 of Fig. 4) facies domains.

1980) corroborates a geologically reasonable value of 4–5 km of thrust displacement of Karawanken carbonates over proximal clastic deposits of the Klagenfurt Basin. The basin therefore constitutes a short-lived foreland in which clastic sedimentation of the order of 700–900 m occurred at or near the mountain front. Rounded clasts in the Tertiary conglomeratic facies of the footwall near the frontal thrust show systematic extension fractures, similar to stress-induced fractures described previously by Eisbacher (1969). Their orientation (Fig. 4) is compatible with a general NW–SE-oriented regional contraction and concomitant NE–SW extension during dextral shear on a E–W-oriented plane of movement. Contraction also created a few open folds in the Klagenfurt clastic units. Towards the west the basin was disrupted by the younger Hochstuhl Fault (see below).

In order to obtain a quantitative estimate for the amount of internal shortening of the Karawanken Mountains perpendicular to the frontal thrust and parallel to the dominant dextral cross faults, several semi-balanced sections were constructed. Two of these are shown in Fig. 5. Together with the map pattern, the cross-sections indicate that pre-Permian units near the Insubric Line were uplifted along upward fanning longitudinal fault strands that were truncated and offset dextrally by high-angle cross faults. These cross faults either merge with or displace the longitudinal faults and merge with the Insubric Line at depth. Interference between longitudinal fault zones, thrust and cross faults suggest that deep-seated distributed strike slip faulting is expressed near the surface by closely spaced synthetic en échelon cross faults linking folds and thrust faults, a pattern also reported for coseismic surface deformation along convergent strike-slip faults (e.g. Philip & Meghraoui 1983). The almost ubiquitous and intense cataclastic deformation of carbonate rocks near fault surfaces supports the notion of both internal disruption and rotation of relatively small blocks between discrete cross faults.

Post-Miocene structures

Post-Miocene (i.e. post-Klagenfurt Basin) to Recent structures occur mainly in the western Karawanken Mountains. Here, the Insubric Line is offset by about

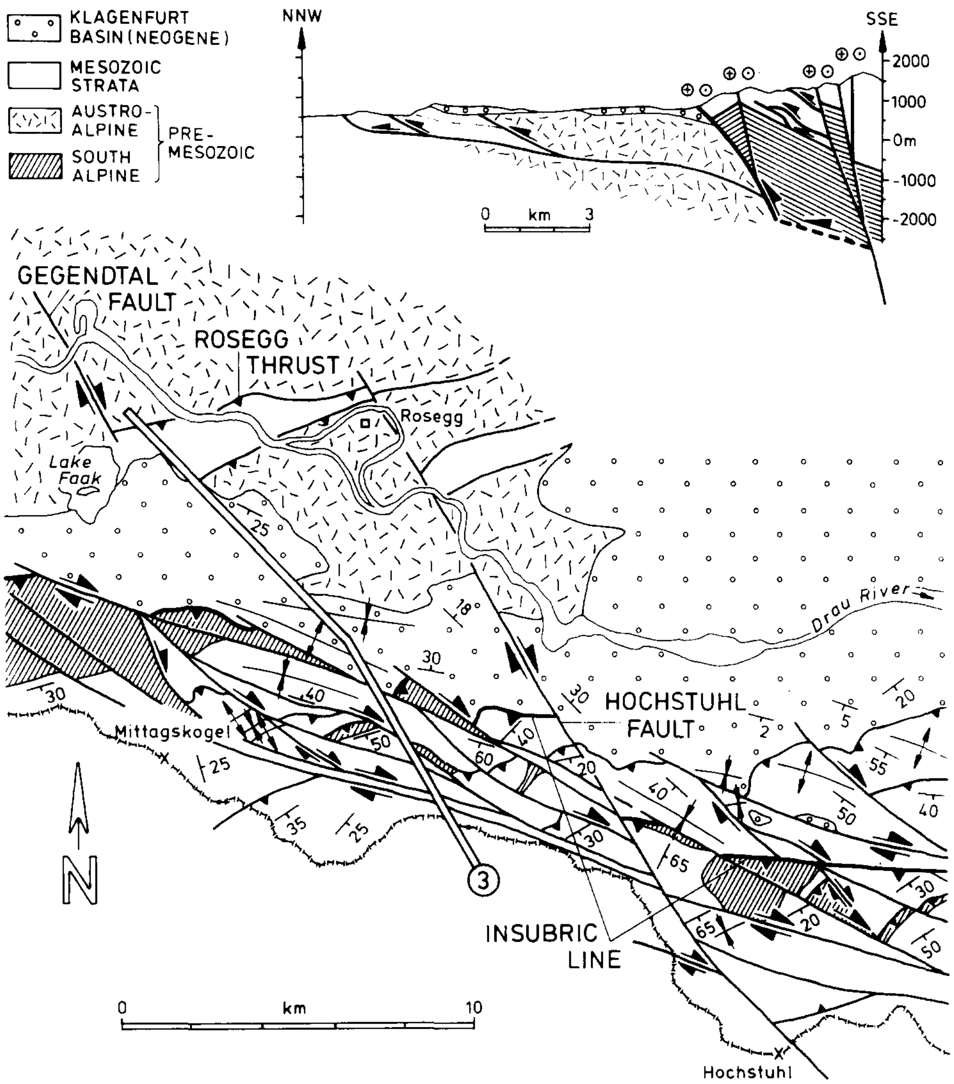

Fig. 6. Sketch map and cross-section along line 3 for the Hochstuhl–Rosegg–Gegendtal system of displacement transfer which is probably characterized by Recent seismic activity.

3.5 km along the NNW-striking dextral Hochstuhl Fault. Towards the SSE displacement along the fault probably increases because there lithologies and structures cannot be matched across its trace. The Hochstuhl Fault eventually merges with the major and presumably still active dextral Sava fault zone to the south. Towards the north-northwest, the Hochstuhl Fault terminates near the town of Rosegg in Austroalpine basement units (Fig. 6). However, displacement is probably transferred via the Rosegg Thrust on to the NNW-striking Gegendtal Fault. Inferred forward motion and internal shortening of the westernmost Karawanken Mountains relative to the east-central Karawanken Mountains along the Hochstuhl Fault is also expressed by a narrowing of the westernmost Klagenfurt Basin, suggesting syndepositional deformation. West of the Hochstuhl Fault, the basinal fill is made up of about 150 m of gently folded Tertiary strata and a few tens of metres of Quaternary deposits, while east of the fault more than 600 m of flat-lying Tertiary clastics are overlain by up to 150 m of Quaternary deposits. A conspicuous bend of the Drau River in the Lake Faak–Rosegg area (Fig. 6) could also be a post-Pleistocene geomorphic response of the river channel to ongoing uplift above the Rosegg basement thrust. A distinct cluster of historical seismic events, including the strong Villach earthquake of 1348 (Drimmel 1980, Degasperi *et al.* 1991), is possibly related to active fault propagation in the vicinity of the transfer fault system between the Hochstuhl and Gegendtal fault zones. NNW- to N-oriented extension fractures in semi-consolidated Quaternary deposits and embedded clasts in several localities along the Karawanken front (Polinski 1991) suggest ongoing contraction throughout this area.

CRUSTAL SCALE KINEMATICS OF THE KARAWANKEN MOUNTAINS

The oldest regional structures recognized in Mesozoic cover rocks of the Karawanken region are NW-trending folds, related thrusts, and sinistral (?) NE-striking cross faults in Austroalpine strata north of the Insubric Line. In South Alpine strata, NW-trending fold trains occur in the Julian–Kamnik Alps of western Slovenia (see Fig. 1 for location) and in the Dolomite Mountains of northern

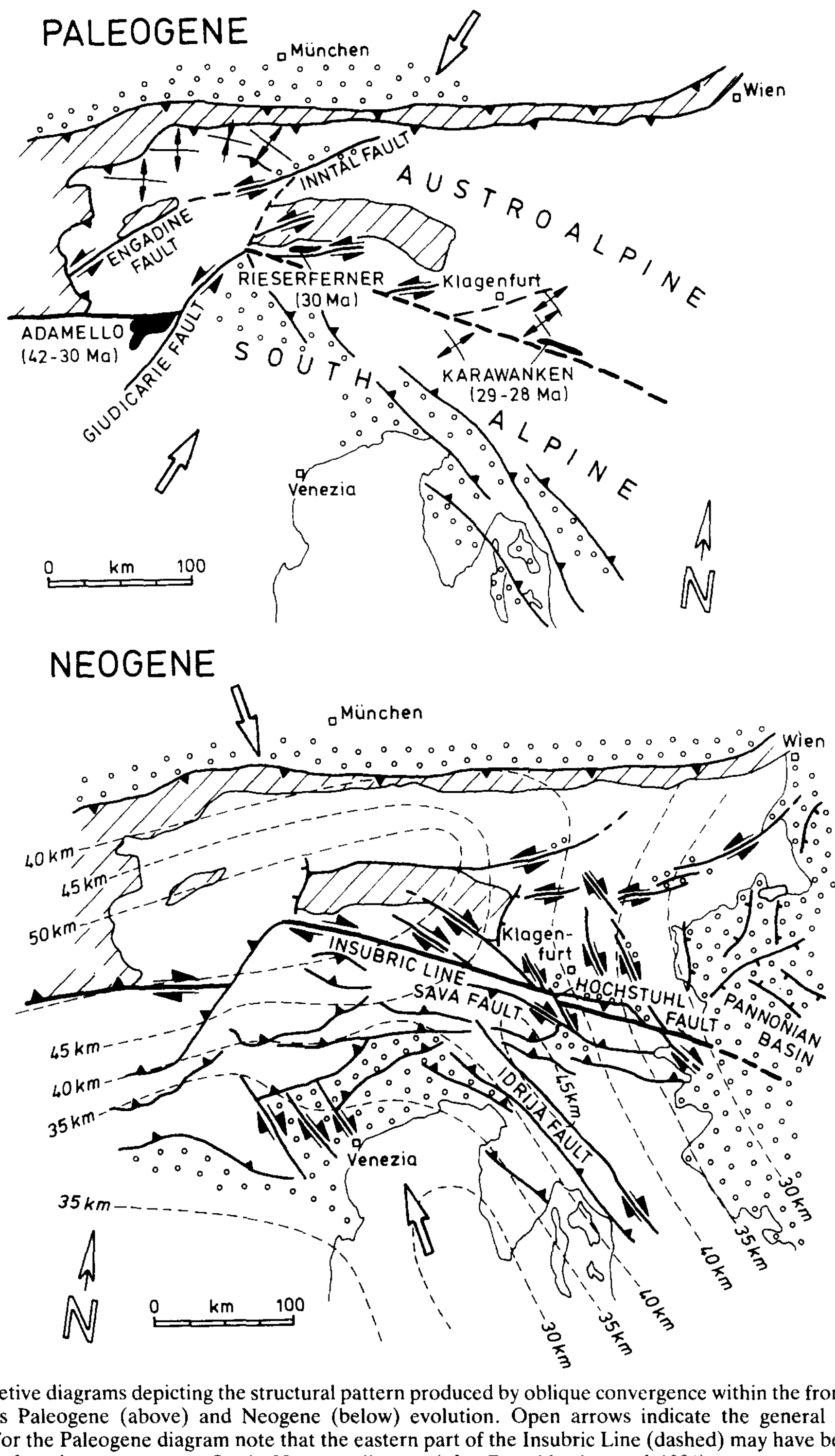

Fig. 7. Interpretive diagrams depicting the structural pattern produced by oblique convergence within the frontal Adriatic plate during its Paleogene (above) and Neogene (below) evolution. Open arrows indicate the general direction of convergence. For the Paleogene diagram note that the eastern part of the Insubric Line (dashed) may have been oriented quite differently from its present trace. On the Neogene diagram (after Ratschbacher *et al.* 1991) present crustal thickness is indicated by thin broken lines; note that the strongly curved 40 km isopach roughly parallels the transition from the predominantly divergent strike-slip to predominantly convergent strike-slip structures.

Italy, where they originated mainly during Paleogene NE–SW-oriented regional contraction (Doglioni 1987, Doglioni & Bosellini 1987, Carulli *et al.* 1990, Buser personal communication 1990). We therefore consider the NW-trending folds and related NE-striking cross faults of the northern Karawanken to be part of a relatively broad fold belt that extended northwesterly from the Dinaride Chain across the Southern Alps to the east-central Alps (Behrmann & Frisch 1990) and possibly as far as the northwestern Calcareous Alps (Burchfiel 1980). There, WNW- to NW-trending fold–thrust structures and related NE-striking sinistral cross faults overprinted Late Cretaceous NE- to ENE-trending structures of the frontal Austroalpine accretionary wedge (Tollmann 1977, Eisbacher *et al.* 1990, Eisbacher & Brandner in preparation). To the south, minor (?) sinistral displacement along the Insubric Line probably was concurrent with NE–SW shortening (Kleinschrodt 1987). How much of the 100–150 km of dextral displacement along the Insubric Line was achieved prior to this

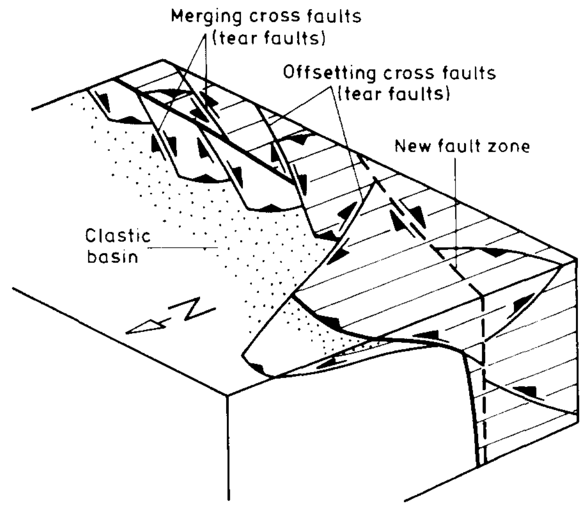

Fig. 8. Schematic block diagram of the Karawanken frontal zone illustrating the presumed relationships between the thrust faults and cross faults which both merge with or offset the Insubric Line. At present they are in the process of being replaced by new throughgoing strike-slip faults which propagate west-northwesterly across the previously deformed South Alpine (ruled) and Austroalpine (blank) basement and cover strata, and the clastic Klagenfurt Basin.

Paleogene contraction is uncertain. However, the occurrence of Upper Cretaceous synorogenic clastics in the western parts of the South Alpine carbonate platform (Bernoulli & Winkler 1990) and major westward-directed thrust emplacement of Austroalpine and South Alpine basement rocks (Schmid *et al.* 1987, Ratschbacher *et al.* 1989, Schmid & Haas 1989) suggests that some of the dextral displacement along the Insubric Line could have occurred during early intraplate convergence within the Adriatic domain. This opens the possibility that subsequent sinistral offset of the Insubric Line along a Giudicarie–Inntal transfer fault system occurred contemporaneous with latest Cretaceous (?)–Paleogene tectonic emplacement of the frontal Adriatic plate over Penninic cover and basement (Ring *et al.* 1988).

After an early Oligocene interval of intrusive activity, which possibly could have coincided with local sinistral (?) divergence along the Insubric Line, contraction of the Karawanken area set in again at about middle (?) to late Miocene time. A pattern of NW- and SE-directed thrust faults and NW-striking dextral cross faults in both Austroalpine and South Alpine rock complexes also initiated subsidence of the Klagenfurt Basin north of the frontal Karawanken Thrust (Fig. 7). The Karawanken Mountains thus became part of a WNW-trending Miocene to Recent zone of dextral convergence along which numerous WNW-striking dextral faults transferred displacement between the South Alpine–Dinaric fold–thrust belt on the southwest (Massari *et al.* 1986, Doglioni & Bosellini 1987, Roeder 1989) to the extending crust of the easternmost eastern Alps and the Pannonian Basin in the northeast (Royden *et al.* 1983, Horvath 1984, Ratschbacher *et al.* 1991). How much total dextral motion accompanied this Neogene convergence is not clear. However, the offsets within the Karawanken Mountains discussed above suggest at least 30–40 km of distributed dextral shear on the WNW-striking cross faults which merge with or displace the Insubric Line and link up with major WNW- to NW-striking fault zones south of the Karawanken Mountains (Fig. 8). The pattern of deformation partitioning onto shallow crustal thrusts and strike-slip faults and a progressive shift in the location of major throughgoing strike-slip faults is reminiscent of other obliquely convergent strike-slip fault zones, such as the San Andreas fault zone in the Transverse Ranges of California (Meisling & Weldon 1989), the Alpine Fault system of New Zealand (Norris *et al.* 1990), and the North and South Anatolian fault systems of Turkey (Şengör *et al.* 1985, Karig & Kozlu 1990). The most recent displacements in the convergent transfer zone of the western Karawanken mountains disrupt all pre-existing structures and appear to be concentrated along the dextral NNW-striking Hochstuhl system. This fault system is possibly linked to the seismically active and NW-striking dextral Sava–Idrija fault system which merges westward with the seismically active and SSE-directed South Alpine thrust front (Müller 1977, Ribaric 1979, Zanferrari *et al.* 1982, Carulli *et al.* 1990, Degasperi *et al.* 1991). The entire structural transition zone is also characterized by strong lateral gradients in crustal thickness.

CONCLUSIONS

The Karawanken Mountains of the southeastern Alps developed along the Insubric Line between the Austroalpine and South Alpine facies domains of the Adriatic plate. A previously observed mismatch of Mesozoic sedimentary facies suggesting bulk separation of the order of 100–150 km along this intraplate fault zone was probably achieved by dextral strike-slip faulting first in late Cretaceous and then again in Miocene to Recent times. The bulk of mappable structures in the Mesozoic platform strata developed by deformation partitioning during polyphase Tertiary convergence. It can be demonstrated that early Paleogene NW-trending fold–thrust structures and related NE-striking sinistral (?) strike-slip faults were overprinted by Neogene NE-trending fold–thrust structures and related NW- to WNW-striking dextral cross faults. The cross faults merge with and offset the Insubric Line which suggest a shift in the position of the main crustal shear zone with respect to the position of the Insubric Line within the Karawanken Mountains. Thrust loading and downflexing could have caused subsidence and the development of the clastic Klagenfurt Basin on top of the fault-weakened crust. In the east the southern fringe of the basin also was overridden by the frontal thrust mass of the Karawanken Mountains while towards the west the basinal fill was uplifted above emerging and blind (?) basement thrusts below the Tertiary clastics. The two domains are separated by an active NNW-striking cross fault. In general the broadly WNW-striking zone of dextral displacement transfer of the Karawanken area intervenes between the thickening crustal domains of the convergent South Alpine thrust front in the west with thinner crust of the divergent Pannonian Basin in the east. Deformation partitioning into discrete upper crustal thrusts, folds and strike-slip faults above obliquely convergent crustal blocks resembles the structural patterns in other areas characterized by strong deformation gradients and lateral heterogeneities within the lithosphere, such as the Transverse Ranges of southern California, the Alpine Fault system of New Zealand and the Anatolian fault system of Turkey.

Acknowledgements—This work was partly financed by a DFG—SFB 108 (Universität Karlsruhe) grant. We like to express our appreciation to Dr F. Bauer (Vienna), Dr S. Buser (Ljubljana) and R. Brandner (Innsbruck) for discussions of regional geology, and to N. Mancktelow (Zürich) and Jan Behrmann (Giessen) for reviewing the manuscript.

REFERENCES

Aydin, A. & Page, B. M. 1984. Diverse Pliocene–Quaternary tectonics in a transform environment, San Francisco Bay region, California. *Bull. geol. Soc. Am.* **95**, 1303–1317.

Aydin, A. & Nur, A. 1985. The types and role of stepovers in strike-slip tectonics. In: *Strike-slip Deformation, Basin Formation, and Sedimentation* (edited by Biddle, K. T. & Christie-Blick, N.). *Spec. Publ. Soc. econ. Paleont. Miner.* **37**, 35–44.

Bauer, F. K. 1982. *Geologische Karte der Karawanken*, 1:25,000, *Ostteil*. Geol. Bundesanstalt, Wien.

Bauer, F. K. 1985. *Geologische Karte der Karawanken*, 1:25,000, *Westteil*. Geol. Bundesanstalt, Wien.

Bauer, F. K., Cerny, I., Exner, C., Holzer, H.-L., v. Husen, D., Loeschke, J., Suette, G. & Tessensohn, F. 1983. *Erläuterungen zur geologischen Karte der Karawanken* 1:25,000, *Ostteil*. Geol. Bundesanstalt, Wien.

Behrmann, J. & Frisch, W. 1990. Sinistral ductile shearing associated with metamorphic decompression in the Tauern window, Eastern Alps. *Jb. geol. Bundesanstalt* **133**, 135–146.

Bernoulli, D. & Winkler, W. 1990. Heavy mineral assemblages from Upper Cretaceous South- and Austroalpine flysch sequences (Northern Italy and Southern Switzerland): source terranes and palaeotectonic implications. *Eclog. geol. Helv*. **83**, 287–310.

Bögel, H. 1975. Zur Literatur über die "Periadriatische Naht". *Verh. geol. Bundesanstalt* **1975**, 163–199.

Brandner, R. 1972. "Südalpines" Anis in den Lienzer Dolomiten (Drauzug). (Ein Beitrag zur alpin-dinarischen Grenze). *Mitt. geol. Ges. Bergbaustud. Österr.* **21**, 143–162.

Burchfiel, B. C. 1980. Eastern European Alpine system and the Carpathian orocline as an example of collision tectonics. *Tectonophysics* **63**, 31–61.

Carulli, G. B., Nicolich, R., Rebez, A. & Sleijko, D. 1990. Seismotectonics of the Northwest External Dinarides. *Tectonophysics* **179**, 11–25.

Christie-Blick, N. & Biddle, K. T. 1985. Deformation and basin formation along strike-slip faults. In: *Strike-slip Deformation, Basin Formation, and Sedimentation* (edited by Biddle, K. T. & Christie-Blick, N.). *Spec. Publ. Soc. econ. Paleont. Miner.* **37**, 1–34.

Degasperi, C., Slejko, D., Rebez, A. & Cergol, M. 1991. Earthquakes felt in Trieste from the Middle Ages to the 18th century. *Tectonophysics* **193**, 53–63.

Doglioni, C. 1987. Tectonics of the Dolomites (Southern Alps, Northern Italy). *J. Struct. Geol.* **9**, 181–193.

Doglioni, C. & Bosellini, A. 1987. Eoalpine and mesoalpine tectonics in the Southern Alps. *Geol. Rdsch.* **76**, 735–754.

Drimmel, J. 1980. Rezente Seismizität und Seismotektonik des Ostalpenraums. In: *Der Geologische Aufbau Österreichs* (edited by Oberhauser, R.). Springer, Wien, 507–527.

Eisbacher, G. H. 1969. Displacement and stress field along part of the Cobequid Fault, Nova Scotia. *Can. J. Earth Sci.* **6**, 1095–1104.

Eisbacher, G. H., Linzer, H.-G., Meier, L., Polinski, R. 1990. A depth-extrapolated structural transect across the Northern Calcareous Alps of western Tirol. *Eclog geol. Helv.* **83**, 711–725.

Gosen, W., von 1989. Fabric development and the evolution of the Periadriatic Lineament in southeast Austria. *Geol. Mag.* **126**, 55–71.

Hancock, P. L. & Atiya, M. S. 1979. Tectonic significance of mesofracture systems associated with the Lebanese segment of the Dead Sea transform fault. *J. Struct. Geol.* **1**, 143–154.

Harding, T. P. 1985. Seismic characteristics and identification of negative flower structures, positive flower structures and positive structural inversion. *Bull. Am. Ass. Petrol. Geol.* **69**, 582–600.

Heitzmann, P. 1987. Evidence of late Oligocene/early Miocene backthrusting in the central alpine "root zone". *Geodinamica Acta* **1**, 183—192.

Horvath, F. 1984. Neotectonics of the Pannonian Basin and the surrounding mountain belts: Alps, Carpathians and Dinarides. *Ann. Geophys.* **2**, 147–154.

Hurford, A. J., Flisch, M. & Jäger, E. 1989. Unravelling the thermotectonic evolution of the Alps: a contribution from fission track analysis and mica dating. In: *Alpine Tectonics* (edited by Coward, M. P., Dietrich, D. & Park, R. G.). *Spec. Pap. geol. Soc. Am.* **45**, 369–398.

Husen, D., van 1976. Zur Schichtenfolge und Tektonik des Jungtertiärs zwischen Rechberg und Homarow-Berg und seine Beziehung zur Heraushebung der Karawanken. *Carinthia II* **86**, 113–126.

Husen, D., van 1984. Synsedimentäre Gleitschollen grossen Ausmasses im terrestrischen Jungtertiär der Karawanken. *Geol. Rdsch.* **73**, 433–445.

Kahler, F. 1953. Der Bau der Karawanken und des Klagenfurter Beckens. *Carinthia II Sdh.* **16**.

Karig, D. & Kozlu, H. 1990. Late Palaeogene–Neogene evolution of the triple junction region near Maras, south-central Turkey. *J. geol. Soc. Lond.* **147**, 1023–1034.

Kleinschrodt, R. 1987. Quarzkorngefüge im Altkristallin südlich des westlichen Tauernfensters (Südtirol, Italien). *Erlanger geol. Abh.* **114**, 1–82.

Laubscher, H. P. 1970. Das Alpen-Dinaridenproblem und die Palinspastik der südlichen Tethys. *Geol. Rdsch.* **60**, 813–833.

Laubscher, H. P. 1983. The late Alpine (Periadriatic) intrusions and the Insubric Line. *Mem. Soc. geol. Italia* **26**, 21–30.

Laubscher, H. P. 1988. Material balance in Alpine Orogeny. *Bull. geol. Soc. Am.* **100**, 1313–1328.

Massari, F., Grandesso, P., Stefani, C. & Jobstraibizer, P. G. 1986. A small polyhistory foreland basin evolution in a context of oblique convergence: the Venetian basin (Chattian to Recent, Southern Alps, Italy). In: *Foreland Basins* (edited by Allen, P. A. & Homewood, P.). *Spec. Publ. Int. Ass. Sedim.* **8**, 141–168.

Meisling, K. E. & Weldon, R. J. 1989. Late Cenozoic tectonics of the northwestern San Bernardino Mountains, southern California. *Bull. geol. Soc. Am.* **101**, 106–128.

Müller, G. 1977. Fault-plane solution of the earthquake in Northern Italy, 6 May 1976, and implications for the tectonics of the Eastern Alps. *J. Geophys.* **42**, 343–349.

Namson, J. S. & Davis, T. L. 1988. Seismically active fold and thrust belt in the San Joaquin Valley, central California. *Bull. geol. Soc. Am.* **100**, 257–273.

Niedermayr, G. 1975. Gedanken zur lithofaziellen Gliederung der postvariskischen Transgressionsserie der westlichen Gailtaler Alpen, Österreich. *Mitt. geol. Ges. Wien* **66/67**, 105–126.

Norris, R. J., Koons, P. O. & Cooper, A. F. 1990. The oblique-convergent plate boundary in the South Island of New Zealand: implications for ancient collision zones. *J. Struct. Geol.* **12**, 715–725.

Philip, H. & Meghraoui, H. 1983. Structural analysis and interpretation of the surface deformations of the El Asnam earthquake of October 10, 1980. *Tectonics* **2**, 17–49.

Polinski, R. K. 1991. Ein Modell der Tektonik der Karawanken. Unpublished Ph.D. thesis, University of Karlsruhe, Germany.

Ratschbacher, L., Frisch, W., Neubauer, F., Schmid, S. M. & Neugebauer, J. 1989. Extension in compressional orogenic belts: The eastern Alps. *Geology* **17**, 404–407.

Ratschbacher, L., Frisch, W., Linzer, H.-G. & Merle, O. 1991. Extrusion in the Eastern Alps, part 2: Structural analysis. *Tectonics* **10**, 257–271.

Reading, H. G. 1980. Characteristics and recognition of strike slip faults. In: *Sedimentation in Oblique-slip Mobile Zones* (edited by Ballance, P. F. & Reading, H. G.). *Spec. Publ. Int. Ass. Sedim.* **4**, 7–26.

Ribaric, V. 1979. The Idrija earthquake of March 26, 1511—a reconstruction of some seismological parameters. *Tectonophysics* **53**, 315–324.

Ring, U., Ratschbacher, L. & Frisch, W. 1988. Plate boundary Kinematics in the Alps: Motion in the Arosa Suture zone. *Geology* **16**, 696–698.

Roeder, D. 1989. South-Alpine thrusting and trans-Alpine convergence. In: *Alpine Tectonics* (edited by Coward, M. P., Dietrich, D. & Park, R. G.). *Spec. Pap. geol. Soc. Am.* **45**, 211–227.

Ron, H., Nur, A. & Hofstetter, A. 1990. Late Cenozoic and Recent strike-slip tectonics in Mt. Carmel Northern Israel. *Annales Tectonicae* **4**, 70–80.

Royden, I., Horvath, F. & Rumpler, J. 1983. Evolution of the Pannonian basin system. 1. Tectonics. *Tectonics* **2**, 63–90.

Sanderson, D. J. & Marchini, W. R. D. 1984. Transpression. *J. Struct. Geol.* **6**, 449–458.

Scharbert, S. 1975. Radiometrische Altersdaten von Intrusivgesteinen im Raum Eisenkappel (Karawanken, Kärnten). *Verh. geol. Bundesanstalt* **1975**, 301–304.

Schmid, S. M. & Haas, R. 1989. Transition from near-surface thrusting to intrabasement decollement, Schlinig Thrust, eastern Alps. *Tectonics* **8**, 697–718.

Schmid, S. M., Zingg, A. & Handy, M. 1987. The kinematics of movements along the Insubric Line and the emplacement of the Ivrea Zone. *Tectonophysics* **135**, 47–66.

Schmid, S. M., Aebli, H. R., Heller, F. & Zingg, A. 1989. The role of the Periadriatic Line in the tectonic evolution of the Alps. In: *Alpine Tectonics* (edited by Coward, M. P., Dietrich, D. & Park, R. G.). *Spec. Pap. geol. Soc. Am.* **45**, 153–171.

Schönlaub, H. P. 1979. Das Paläozoikum in Österreich. *Abh. geol. Bundesanstalt* **33**, 124S.

Şengör, A. M. C., Görür, N. & Saroglu, F. 1985. Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study. In: *Strike-slip Deformation, Basin Formation, and Sedimentation* (edited by Biddle, K. T. & Christie-Blick, N.). *Spec. Publ. Soc. econ. Paleont. Miner.* **37**, 227–264.

Steinhauser, P., Seiberl, W., Zych, D. & Ruess, D. 1980. Bestimmung des Bouguer-Schwerefeldes der Karawanken und der Sattnitz. *Mitt. geol. Ges. Österr.* **71/72**, 299–306.

Sylvester, A. G. 1988. Strike-slip faults. *Bull. geol. Soc. Am.* **100**, 1666–1703.

Sylvester, A. G. & Smith, R. R. 1976. Tectonic transpression and basement-controlled deformation in San Andreas fault zone, Salton Trough, California. *Bull. Am. Ass. Petrol. Geol.* **60**, 2081–2102.

Tollmann, A. 1977. *Geologie von Österreich, Volume* 1. Deutike, Wien.

Wilcox, R. E., Harding, T. P. & Seely, D. R. 1973. Basic wrench tectonics. *Bull. Am. Ass. Petrol. Geol.* **57**, 74–96.

Woodcock, N. H. & Fischer, M. 1986. Strike-slip duplexes. *J. Struct. Geol.* **8**, 725–735.

Zanferrari, A., Bolletinari, G., Carobene, L., Carton, A., Carulli, G. B., Castaldini, D., Cavallin, A., Panizza, M., Pellegrini, G. B., Pianetti, F. & Sauro, U. 1982. Evoluzione neotettonica dell'Italia nord-orientale. *Mem. Scien. Geol.* **35**, 355–376.