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ABSTRACT

Extension in the eastern Alps encompasses the following: (1) Extension accompanying simple shear crustal stacking. Subhorizontal stretching occurs along flat-lying foliations and regionally consistent stretching lineations with associated high strains. On a local scale, stretching results from extrusion of ductile sediments squeezed between rigid basement blocks during thrust-sheet imbrication. The overall geometric effect is crustal thickening. (2) Classical extensional tectonics. Extension first occurs as a consequence of accretion and underthrusting of continental and oceanic material and represents gravitational adjustment of an unstable orogenic wedge. Extension then occurs as a consequence of terminal continental collision and is accommodated by lateral extrusion of crustal blocks. The overall geometric effect is crustal thinning. Extension is generally oriented subparallel to the strike of the orogen.

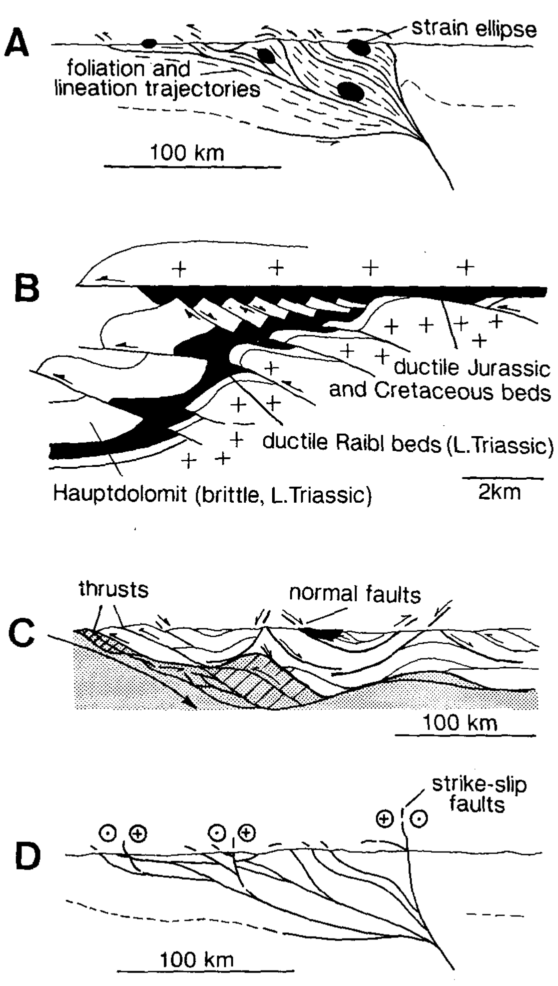

Figure 1. A: Extension accompanying simple shear crustal stacking. Subhorizontal stretching occurs along flat-lying foliations and regionally consistent stretching lineations. B: Extension during thrust imbrication by extrusion of rigid strata squeezed between ductile rocks. C: Extension in orogenic wedge; underplating triggers gravitational instability and backward crustal thinning. Black = basins formed by extension in basement; ruled = continental terranes; stippled = lower plate rocks. D: Continental escape along strike-slip faults during terminal continent-continent collision.

INTRODUCTION

Large-scale extension parallel to ductile stretching lineations is well known from many orogenic belts. High simple shear strains characterize crustal-scale shear zones with flat-lying foliations and stretching lineations subparallel to the dip-slip displacement vector. However, the overall effect is crustal thickening (Fig. 1A).

Additional stretching and thinning parallel to the displacement vector results from extrusion of sedimentary units squeezed between rigid basement blocks (e.g., Schmid and Haas, 1989; Fig. 1B).

An orogenic wedge (Platt, 1986) shows compression (crustal thickening) and extension (crustal thinning) alternating over a long period of convergence. Classical extensional tectonics, implying crustal thinning, occurs as backward crustal stretching due to underplating, in many cases involving buoyant continental terranes. Structural characteristics of the extending wedge are reactivation of thrusts as normal faults, metamorphic domes, deformation at peak metamorphic temperatures with condensed isograds, and basin formation (Fig. 1C).

Extension is also initiated during terminal continental collision and is partly accommodated by lateral extrusion of crustal blocks (Fig. 1D). The strain hardening for frontal imbrication caused by crustal thickening and ongoing convergence initiates lateral flow of material in front of the continuously indenting upper plate.

In this paper we discuss extension in the ambit of the compressional orogenic history of the eastern Alps and relate it to the evolution of the Alpine orogenic wedge. Deformations implying crustal thickening and crustal thinning occur simultaneously, and related structures interact on all scales.

EXTENSION IN THE EASTERN ALPS

Extension Connected With Thrusting During Simple Shear Crustal Stacking

The Austroalpine units, which represent the northern margin of the Adriatic plate, overrode the generally oceanic Penninic units (Fig. 2). Stacking commenced in the upper and easternmost units and progressed downward and westward (e.g., Ring et al., 1988). Compression structures are thrust imbricates and ductile mylonites with prominent stretching lineations parallel to the direction of thrusting (Fig. 2). Finite strain is plane and reveals strong extension along subhorizontal mineral lineations. The sense of motion is indicated by numerous shear criteria (e.g., Ratschbacher, 1987; Schmid and Haas, 1989). Thus, early compression in the eastern Alps had the following characteristics: building of a crustal-

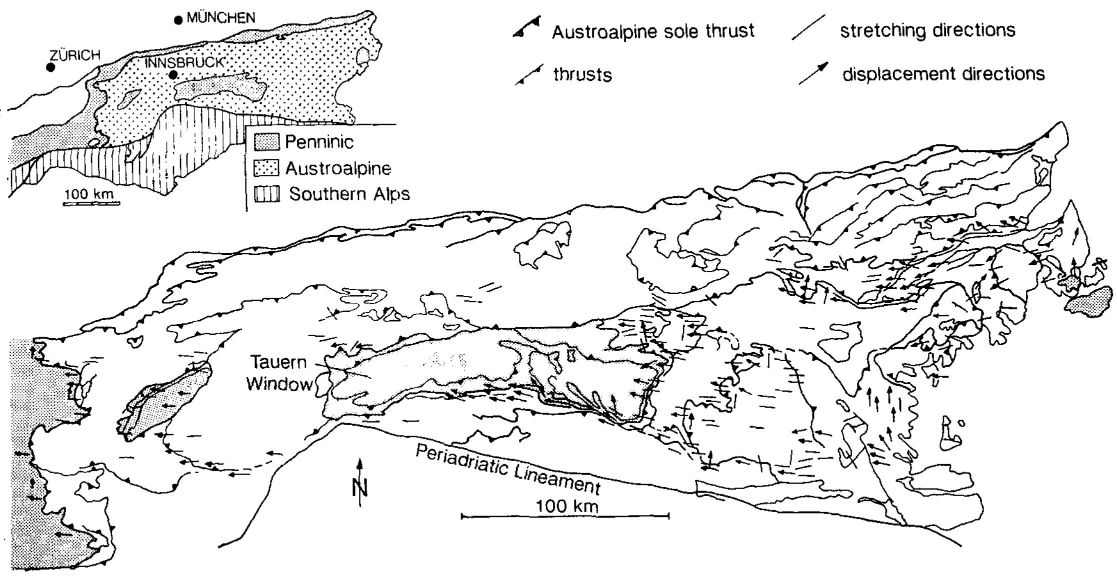

Figure 2. Stretching and displacement (assuming simple shear deformation) during Cretaceous-early Tertiary stacking in eastern Alps. Inset: Alpine structural zonation in eastern Alps.

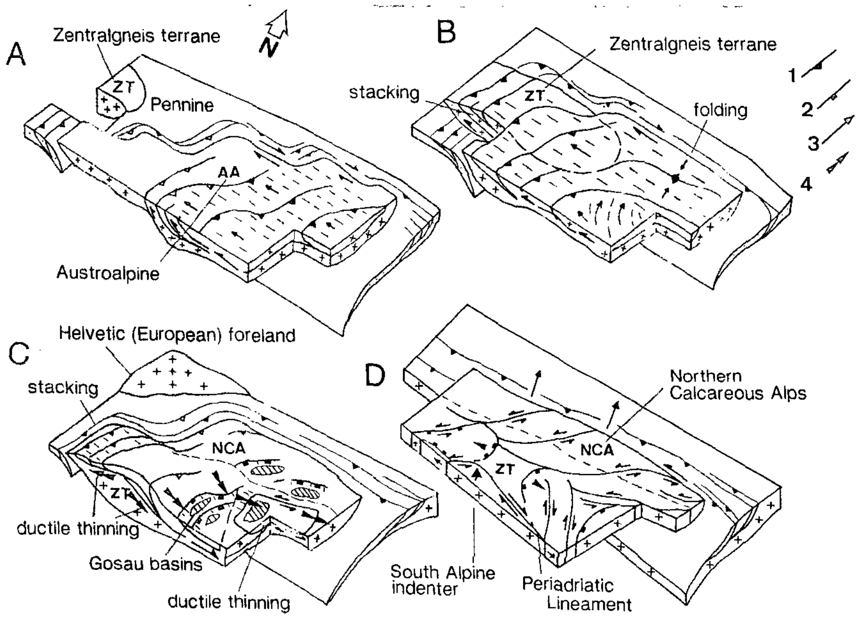

Figure 3. Orogenic wedge evolution in eastern Alps. A: Stacking and orogen-parallel extension during simple shear crustal imbrication. B: Underplating of Zentralgneis terrane. C: Unroofing extension and formation of Gosau basins. D: Continental escape. 1—Thrusts and shear zones. 2—Normal faults and extensional shear zones. 3—Thrust and shear directions during compression. 4—Motion directions during crustal thinning.

stacking orogenic wedge by thrusting, and westward migration of deformation and thickening with time. Extension occurred in a direction that is subparallel to the present strike of the main tectonic units (Fig. 3A).

Local Extension During Thrust-Sheet Imbrication

Imbrications of Austroalpine units west of the Tauern Window are evidence for strata-parallel extension associated with thrusting during orogenic wedge formation (Schmid and Haas, 1989). Figure 1B shows a cross section parallel to the direction of thrusting; the roof thrust carries a sheet of rigid basement over deformed sediments originally deposited on a lower rigid basement sheet. A thick, brittle, stratigraphic horizon squeezed between ductile horizons consists mainly of Hauptdolomit: this horizon has spectacular domino structures. Schmid and Haas (1989) interpreted this extension to be associated with extrusion of the sediments in a westerly direction between the basement sheets.

Unroofing of the Alpine Orogenic Wedge by Subhorizontal Extension

In the course of orogenic-wedge thickening, stacking affected the Penninic units, and foreland progression of deformation led to accretion and underplating of the Penninic Zentralgneis terrane (mainly granitic basement) of the Tauern Window beneath the Austroalpine stack (Fig. 3B). Underplating is indicated by metamorphic pressures of $\geqslant 10$ kbar (Selverstone, 1985).

Subhorizontal extension of rocks in the Tauern Window is related to initial uplift after cessation of thrusting and affected rocks above the buoyant gneisses. East-directed subhorizontal extension in the Penninic units along the western edge of the eastern Alps (Fig. 4) is interpreted as resulting from buoyant uprise of the Penninic basement nappes to the west (Ticino gneiss dome). Extension is again subparallel to strike of the main tectonic units.

Large-scale subhorizontal extension also affected the Austroalpine units east of the Tauern Window (Fig. 3C). Figure 4 shows regions in which this event has been recognized. West-directed thrust geometries and mylonitic fabrics formed during initial stacking were overprinted by distinct extensional crenulation-cleavage sets, which reveal downdip movement. Less penetrative but similar mylonitic fabrics are widespread in the basement of the central and southeastern eastern Alps. Klippen of Mesozoic cover show east-directed normal faults, and thrusts were reactivated as normal faults (Ratschbacher and Neubauer, 1989). The formation of the Gosau basins in the Turonian and their rapid subsidence in the Campanian indicate extension at high crustal levels (Fig. 4; Krohe, 1987).

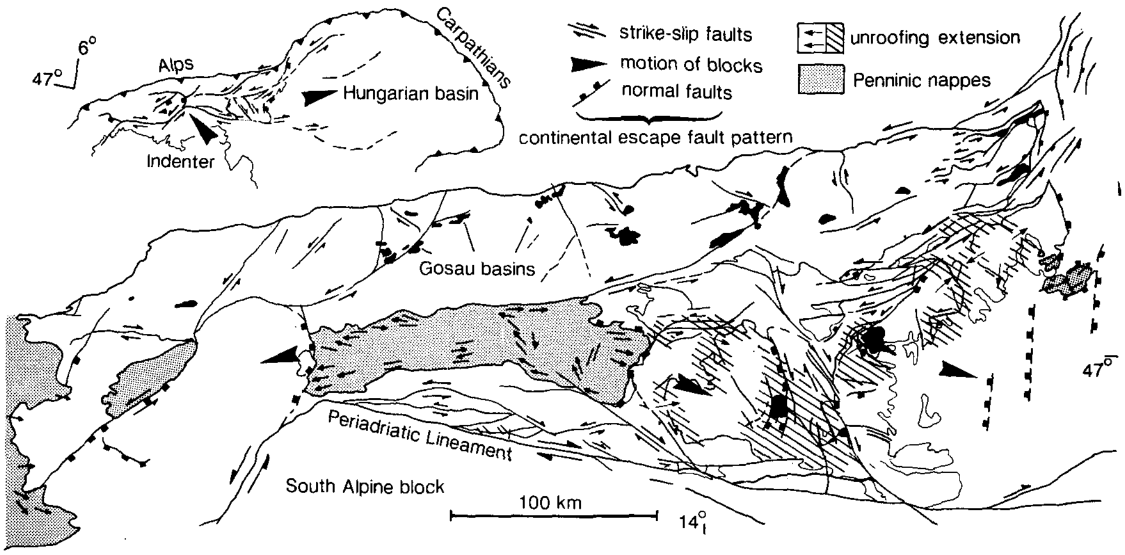

Figure 4. Late Cretaceous–Oligocene unroofing extension, Gosau basins (black), and Oligocene-Miocene transpression and continental escape strike-slip fault pattern and extensional structures in eastern Alps and their relation to Carpathian loop. Stretching lineations and rotation directions with extensional geometry in Penninic windows and areas of penetrative unroofing extension (shaded) in Austroalpine east of Tauern Window.

Dominantly coaxial stretching occurred in the basement units of deep tectonic position and in regions with medium-grade Alpine metamorphism in eastern Austria.

Condensed isograds of Alpine metamorphism are further evidence for extension. Spacing of isograds in cover and basement rocks of the east-central eastern Alps indicates apparent thermal gradients of 60 °C/km. Gradients of 120 °C/km and, locally, up to 250 °C/km were reported in the basement of the southeastern eastern Alps (Neugebauer, 1970). Stacking was active during prograde metamorphism. Penetrative deformation, however, occurred during or after the thermal peak in the Austroalpine units with large-scale thinning. Pressure-temperature paths indicate rapid decompression.

A phase of compression following unroofing extension is proved by out-of-sequence thrusting, which affected most Gosau basins.

Lateral Continental Escape

Sets of sinistral, northeast-trending, ductile to brittle shear zones contrast with dextral displacements along southeast-trending shear zones, mainly the Periadriatic and related lineaments in the eastern Alps (Fig. 4; e.g., Neubauer, 1988). A gradation from ductile to brittle behavior attests to the long history of some of these faults. Fault steps cause pull-apart basins. We interpret the sets of fault zones as conjugate pairs of shear zones leading to lateral extrusion of crustal blocks in front of the South Alpine rigid indentor and into the "open" space (Hungarian basin) provided by the evolving Carpathian loop (Neubauer, 1988; Figs. 3D and 4). Detachment zones with east-west extension bound the extruding blocks at the eastern and western ends of the updoming Tauern Window, which reflects the uplift of underplated continental material (e.g., Selverstone, 1988).

AGES OF MOVEMENTS

Data used to constrain ages of deformations are given in Table 1. Stacking of the Austroalpine cover has been interpreted as being related to the peak of pretectonic to syntectonic metamorphism (140–100 Ma). The age of imbrication in the Austroalpine basement and in the Penninic units is poorly constrained; ages between 95 and 70 Ma in the basement reflect regional cooling after stacking and during ductile thinning. The basement west of the Tauern Window underwent thermal climax around 90 Ma; stacking was premetamorphic to synmetamorphic. Accretion of the Penninic units in the Tauern Window started in the Late Cretaceous; Penninic accretion is Paleocene and older along the western edge of the eastern Alps. The ages appear to be younger from east to west and from upper to lower thrust sheets. Because of the irregular northern margin of the Adriatic plate in the eastern Alps and its oblique approach to the foreland, accretion of Penninc units of similar paleogeographic position occurred at different times along the margin.

TABLE 1. TIME CONSTRAINTS ON DEFORMATION EVENTS IN THE EASTERN ALPS

	Stacking (Ma)	Method of dating*	Unroofing* (Ma)	Escape* (Ma)
Austroalpine cover	143-92 139,122	Rb/Sr, K/Ar (1,2) U/Pb (3)		
Gosau basins			90-60, flysch sediments: ≤80	
Austroalpine basement				≤25 (5,6, 7)
east of TW⁺	>90	Rb/Sr (1)	95-70 (1)	
west of TW⁺	≈90	Rb/Sr, K/Ar (4)	80-75 (4)	
Penninic units, TW⁺	90-65		60-35 (5)	

* Numbers in parentheses are references. 1: Frank et al. (1987), 2: Kralik et al. (1987); 3: Neubauer et al. (1987); 4: Thöni (1983); 5: Selverstone (1988); 6: Neubauer (1988); 7: Schmid et al. (1989).
⁺ TW = Tauern Window.

Age of sedimentation in the Gosau basins constrains age of unroofing extension in the Austroalpine east of the Tauern Window to about 90–60 Ma. Rapid deepening of all basins, indicated by the abrupt beginning of flysch sedimentation in the Campanian (about 80 Ma), marks maximal extension. K/Ar cooling ages of biotite in extensional shear zones cluster around 80 Ma. Together with low-temperature plasticity of quartz in extensional mylonites, this indicates cooling of basement units affected by unroofing extension to about 300 °C at about 80 Ma. Selverstone (1988) placed the onset of ductile thinning at the western end of the Tauern Window in the early Eocene; it is post-Paleocene along the western edge of the eastern Alps.

Sedimentation in pull-apart basins associated with faults of continental escape began around 20 Ma. Normal faulting along the western margin of the Tauern Window is constrained by cooling ages of biotite in the Tauern Window to 20 Ma or later. Major strike-slip offset along the Periadriatic lineament occurred during late Oligocene and Miocene time. However, earlier initiation of faulting is indicated by ductile fabrics, paleomagnetic work (Balla, 1988), and magmatism around 30 Ma.

DISCUSSION AND CONCLUSIONS

Upper Plate (Austroalpine Nappes)

The oldest Alpine structures reflect west-directed crustal stacking during plate convergence. Motions in the eastern Alps were largely oblique to the Austroalpine plate boundary, which had an overall east-northeast trend. In this context, compression structures and associated strains reflect a maximum of stretching in a simple shear regime oriented subparallel to the present-day strike of the orogen.

Successive accretion of Austroalpine and Penninic units to the orogenic hanging wall is reflected by the foreland migration of deformation. Crustal thinning structures developed as the hanging wall emerged through isostatic adjustments of the orogenic wedge to attain a stable geometry (Platt, 1986). We suggest that the primary reason for uplift was the underplating of the buoyant Zentralgneis terrane of the Tauern Window beneath the Austroalpine stack. Extension in the Austroalpine, mainly limited to the area east of the Tauern Window, developed simultaneously with, and as a direct consequence of, underplating and uplift along the eastern flank of the ramp structure of the Zentralgneis terrane to compensate for gravitational disequilibrium. Thus, emplacement of the Zentralgneis terrane was accommodated by tectonic denudation and thinning of the overlying rocks. Compressional structures formed at deep structural levels within the deforming wedge at the same time that brittle-ductile extensional structures formed at shallow levels.

Another mechanism may have contributed to the initiation of crustal thinning: motion of the Adriatic plate changed to predominantly northerly during the Tertiary (Dercourt et al., 1986), marking a decrease in the rate of convergence. This caused a decrease in shear stress at the base of the orogenic wedge and may have triggered extension (Platt, 1986).

Lower Plate (Penninic Nappes)

Correlation of early ductile thinning in the Tauern Window with unroofing in the Austroalpine nappes is straightforward. (1) As newly underplated material was added to the wedge, the level of extensional deformation moved toward the tip and down. (2) The thermal budget to activate ductile deformation was reached later in the Penninic units (Tertiary metamorphism).

Large-scale ductile extension occurred during adiabatic heating but prior to attaining the maximum temperature. It is clearly linked to the unroofing history after the maximum amount of overburden was acquired. Buoyancy of continental material in the Tauern Window triggered instability of the orogenic wedge immediately after underplating. This buoyant material governed the structural shape of the eastern Alps from that time on.

Continental Escape

Eocene and post-Eocene collisional tectonics of the eastern Alps was mainly south over north and is reflected by a suture that is parallel to the European plate margin. In contrast to the western and central Alps, backthrusting along the Periadriatic line and in the rear of the orogenic wedge was not important in the eastern Alps (Schmid et al., 1989). Instead, crustal thickening, convergence, and shortening were compensated by extension parallel to the orogen.

The eastern Alps were split into blocks during continental escape. The detachment faults at the margins of the Tauern Window bound the rising, underplated continental material. No structural evidence has been found for the reappearance of these detachments, in accordance with the extrusion model. Similar detachment faults center around the Lepontine Dome in the central Alps (Merle and Le Gal, 1988). Extrusion of blocks to the east in the eastern part of the Alps may have been facilitated by the formation of the Carpathian loop, where the foreland buttress is farther to the north than in the eastern Alps. Oblique convergent plate motions during the early Oligocene–early Miocene may have initiated the formation of this pattern and the fracturing of the rigid Austroalpine crust into blocks within a wide zone of dextral transpression.

Extension in the eastern Alps is oriented subparallel to the strike of the orogen regardless of its mode of formation. Early extension during stacking reflects the direction of convergence between Austroalpine and Penninic units which was highly oblique to the trend of great parts of the continental margins. East-west extension during unroofing reflects the stacking geometry of the Alpine orogenic wedge. Extension combined with continental escape was forced to be approximately parallel to the European margin against which the orogen was compressed; its east-west trend is incidental.

REFERENCES CITED

Balla, Z., 1988, Clockwise paleomagnetic rotations in the Alps in the light of structural pattern of the Transdanubian Range (Hungary): Tectonophysics, v. 145, p. 277–292.

Dercourt, J., Zonenshain, L.P., Ricou, L.-E., and 19 others, 1986, Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias: Tectonophysics, v. 123, p. 241–315.

Frank, W., Kralik, M., Scharbert, S., and Thöni, M., 1987, Geochronological data from the Eastern Alps, *in* Flügel, H.W., and Faupl, P., eds., Geodynamics of the Eastern Alps: Vienna, Deuticke, p. 272–281.

Kralik, M., Krumm, H., and Schramm, J.M., 1987, Low grade and very low grade metamorphism in the Northern Calcareous Alps and in the Greywacke Zone: Illite-crystallinity data and isotopic ages, *in* Flügel, H.W., and Faupl, P., eds., Geodynamics of the Eastern Alps: Vienna, Deuticke, p. 164–178.

Krohe, A., 1987, Kinematics of Cretaceous nappe tectonics in the Austroalpine basement of the Koralpe region (eastern Austria): Tectonophysics, v. 136, p. 171–196.

Merle, O., and Le Gal, P., 1988, Post-amphibolitic westward thrusting and fold vergence in the Ticino domain: Eclogae Geologicae Helvetiae, v. 81, p. 215–226.

Neubauer, F., 1988, Bau und Entwicklungsgeschichte des Rennfeld-Mugel und des Gleinalmkristallins (Ostalpen): Abhandlungen der Geologischen Bundesanstalt Wien, v. 42, p. 1–37.

Neubauer, F., Frisch, W., and Hansen, H.T., 1987, Time relations between eoalpine metamorphism and thrusting, *in* Flügel, H.W., and Faupl, P., eds., Geodynamics of the Eastern Alps: Vienna, Deuticke, p. 263–271.

Neugebauer, J., 1970, Altpaläozoische Schichtfolge, Deckenbau und Metamorphose-Ablauf im Saualpen-Kristallin (Ostalpen): Geotektonische Forschungen, v. 35, p. 23–93.

Platt, J.P., 1986, Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks: Geological Society of America Bulletin, v. 97, p. 1037–1053.

Ratschbacher, L., 1987, Strain, rotation, and translation of Austroalpine cover nappes, *in* Flügel, H.W., and Faupl, P., eds., Geodynamics of the Eastern Alps: Vienna, Deuticke, p. 237–243.

Ratschbacher, L., and Neubauer, F., 1989, West-directed décollement of Austroalpine cover nappes in the Eastern Alps: Geometrical and rheological considerations: Geological Society of London Special Publication (in press).

Ring, U., Ratschbacher, L., and Frisch, W., 1988, Plate-boundary kinematics in the Alps: Motion in the Arosa suture zone: Geology, v. 16, p. 696–698.

Schmid, S.M., and Haas, R., 1989, The transition from near surface thrusting to intra-basement décollement during west-directed movement of the Ötztal basement along the Schlining thrust (Austroalpine west of the Tauern window): Tectonics (in press).

Schmid, S.M., Aebli, H.R., and Zingg, A., 1989, The role of the Periadriatic line in the tectonic evolution of the Alps: Geological Society of London Special Publication (in press).

Selverstone, J., 1985, Petrologic constraints on imbrication, metamorphism and uplift in the SW Tauern Window, Eastern Alps: Tectonics, v. 4, p. 687–704.

—— 1988, Evidence for east-west crustal extension in the Eastern Alps: Implications for the unroofing history of the Tauern Window: Tectonics, v. 7, p. 87–105.

Thöni, M., 1983, The thermal climax of the Early Alpine metamorphism in the Austroalpine thrust sheet: Istituti di Geologia dell'Università di Padova, Memorie, v. 36, p. 211–238.

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Reviewer's comment

This paper represents the considered opinion of a significant group of geologists who have been working in the eastern Alps for a long time and who have recently been engaged in an intense debate in the German-language literature about the reality of this phenomenon. It therefore brings to the English-language literature something of the flavour of the debate.

J. P. Platt