Exhumation of high- and ultrahigh-pressure metamorphic rocks by slab extraction

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ABSTRACT

Exhumation of high- and ultrahigh-pressure metamorphic rocks in collisional orogens may be explained by upward extrusion of these rocks, erosion of their overburden, or extensional thinning of the overburden. Some high-pressure terranes, such as the Adula nappe in the Central Alps, fit none of these scenarios. We propose an additional way in which part of the overburden may be removed: it may sink off into the deeper mantle (slab extraction). Structural and metamorphic relationships in and around the Adula nappe indicate that the emplacement of this Alpine high- to ultrahigh-pressure nappe (to 3.2 GPa) in a pile of lower-pressure nappes resulted from the interaction of two subduction zones that accommodated the closure of two ocean basins, ultimately leading to the extraction of the intervening slab. In terms of mechanics, the cause of the exhumation is, in this case, not the buoyancy of the high-pressure rocks, but the negative buoyancy of the extracted slab.

Keywords: tectonics, Alps, Adula nappe, eclogite, ultrahigh-pressure metamorphism, exhumation.

INTRODUCTION

The ascent to Earth's surface of high- and ultrahigh-pressure metamorphic rocks that have been subducted to 100 km depth and more is an important and much debated phenomenon (Platt, 1993; Ring et al., 1999) with broad implications in the fields of plate tectonics, structural geology, metamorphic petrology, and geophysics. Such rocks are often emplaced in collisional orogens, in the form of thin high-pressure sheets underlain and overlain by rocks that were subjected to much lower pressures. Erosion of the overburden (Fig. 1A) alone is not a sufficient explanation because it does not explain the sandwiching between lower-pressure rocks. Extensional thinning (Fig. 1B), although it may contribute, is unlikely to be the main mechanism because exhumation in many cases occurred during plate convergence (e.g., Schmid et al., 1996), which hardly allows the extreme thinning required. Therefore, several authors have suggested exhumation by extrusion of a high-pressure sheet or wedge from a subduction channel (Michard et al., 1993; Fig. 1C), driven by buoyancy or externally applied stress. Herein we show that structural and metamorphic relations of high- to ultrahigh-pressure rocks in the Adula nappe (eastern Central Alps) fit none of these models, but suggest a new and fundamentally different scenario: the downward removal or extraction of overlying mantle rocks, driven by their negative buoyancy (Fig. 1D).

REGIONAL SETTING OF THE ADULA HIGH-PRESSURE ROCKS

The Adula nappe (Figs. 2 and 3) is a sheet of pre-Mesozoic, European, upper-crustal basement rocks interlayered with thin slices of Mesozoic European cover rocks. Because of the eastward tilt of the Alpine nappe pile in this area, a complete cross section of the 5–8-km-thick and, in the north-south direction, 45-km-long nappe is exposed at the surface. The upper part of the Adula nappe includes locally abundant eclogite and peridotite boudins embedded in orthogneiss and

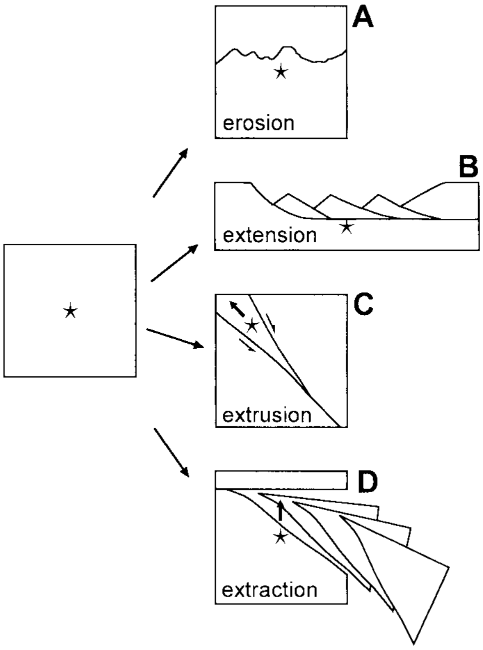

Figure 1. Possible kinematic modes of exhumation of high-pressure metamorphic rocks. A and B: Material overlying high-pressure rocks (star) may be (A) eroded or (B) thinned by extension. C: Alternatively, high-pressure rocks may extrude as wedge bounded by thrust below and normal fault above. D: Slab extraction as proposed here is shown schematically; wedge-shaped overburden is removed by sinking away into deeper mantle.

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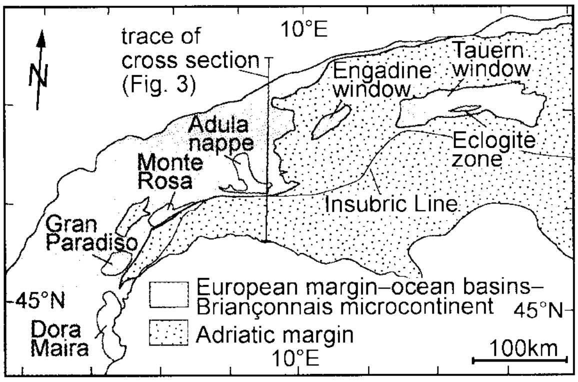

Figure 2. Tectonic sketch map of Alps.

paragneiss overprinted by amphibolite facies metamorphism in the south to greenschist facies metamorphism in the north. Both the Barrovian and high-pressure metamorphism are of Tertiary age (Becker, 1993; Gebauer, 1996). The peak pressures and temperatures determined from the eclogites and, in the southern part of the nappe, garnet peridotites gradually increase from north to south, from 1.2 GPa and 500 °C at the northern end of the nappe (Heinrich, 1986) to 3.2 GPa and 840 °C at Alpe Arami in the south (Fig. 3) (Nimis and Trommsdorff, 2001). The southward increase of the metamorphic conditions is compatible with south-directed subduction of the Adula nappe, which is also supported by the overall geometry of the nappe stack (Schmid et al., 1996). High-pressure rocks are missing in the lower part of the Adula nappe and in the underlying nappes. The eclogite-bearing upper Adula nappe must have been shortened in the north-south direction during its exhumation, because the present north-south length of the nappe (45 km) is less than the barometrically derived depth difference between north and south (~68 km assuming a density of 3000 kg/m^3).

The paleogeographic origin of the Adula nappe was in the southern, distal part of the European continental margin bordering the Valais Ocean (Schmid et al., 1996). The Adula nappe is directly overlain by the suture along which the Valais Ocean closed (the Misox zone), comprising calc-schists and metabasic rocks. The Misox zone is overlain by the Tambo and Suretta nappes. These comprise basement rocks of the upper crust of the former Briançonnais microcontinent, a northeastward extension of the Iberian continent into the Alpine realm. The Briançonnais microcontinent separated the Valais oceanic basin from the Piemont-Ligurian oceanic basin located farther southeast. Ophiolites from the latter basin occur above the Suretta nappe. The overlying Austroalpine nappes are derived from the margin of the Adriatic microcontinent southeast of the Piemont-Ligurian basin. Toward the south, the Briançonnais units (Tambo, Suretta) wedge out and are replaced by the Oligocene Bergell intrusion (Fig. 3), made up of tonalite (31 Ma) and granodiorite (30 Ma; von Blanckenburg, 1992).

The Tambo and Suretta nappes and the Misox zone were subjected to lower pressures than the Adula nappe. For the southern Tambo nappe, Alpine peak pressure was ~1.2 GPa at 550 °C (Marquer et al., 1994), and for the northern end of the Suretta nappe, 0.9–1.2 GPa at 450 °C (Challandes, 2001). The top of the Adula nappe is thus a major metamorphic discontinuity along which high-pressure rocks in the foot-

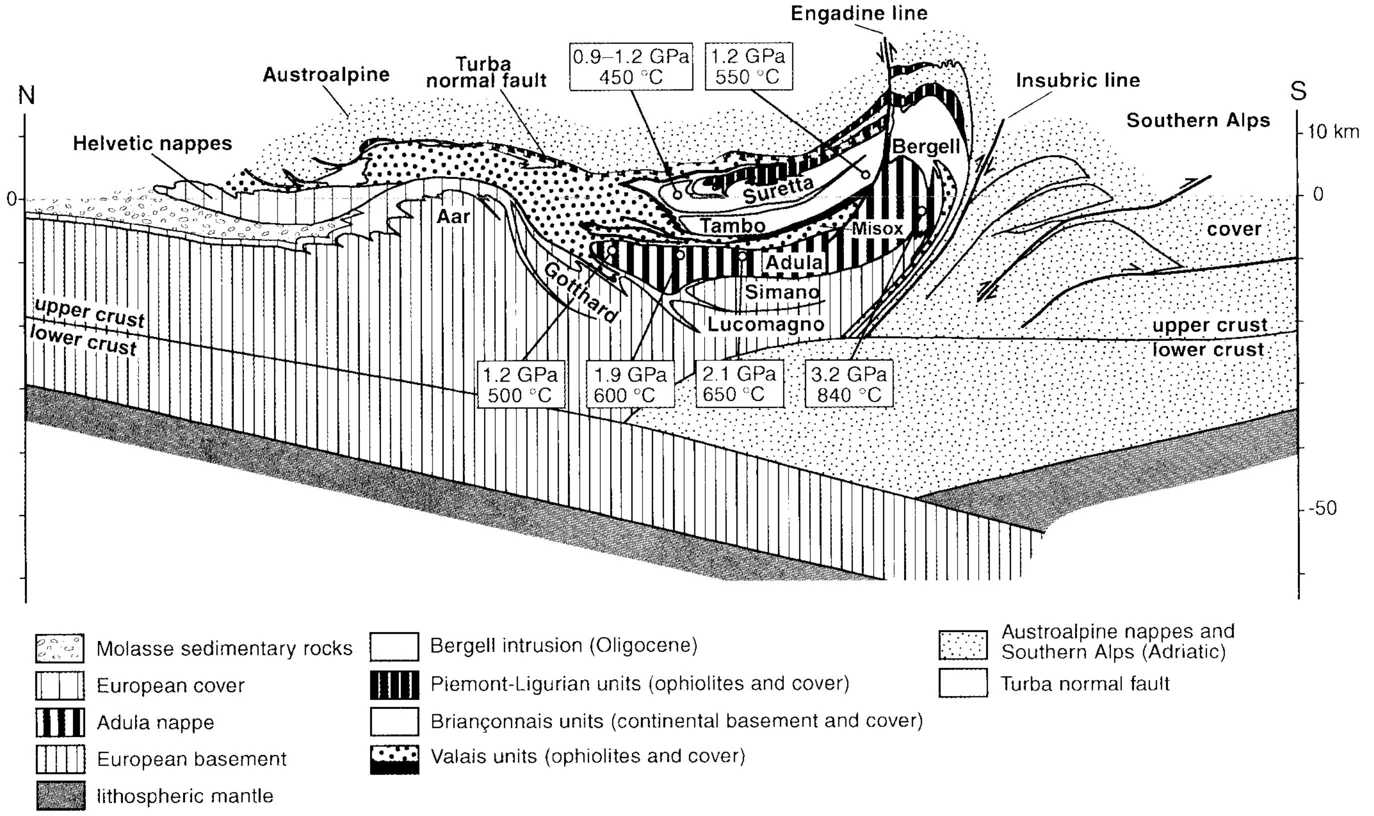

Figure 3. North-south cross section of eastern Central Alps, modified after Schmid et al. (1996). Eclogite- and ultrahigh-pressure-rock–bearing Adula nappe is sandwiched between lower-pressure nappes below (Simano, Lucomagno) and above (Tambo, Suretta). Pressure and temperature estimates are from Heinrich (1986), Marquer et al. (1994), Challandes (2001), and Nimis and Trommsdorff (2001). Important, southward-increasing pressure gap coincides with Misox zone between Adula and Tambo nappes, i.e., suture along which Valais Ocean closed. Tambo and Suretta nappes represent detached upper-crustal basement of Briançonnais microcontinent. Briançonnais lower crust and mantle of microcontinent are not present in profile, having disappeared into deeper mantle. At depth, Neogene northward indentation of Adriatic lower crust (stippled) along lower crust–upper crust interface of European plate (vertical ruling) is shown.

wall are juxtaposed to lower-pressure rocks in the hanging wall. The missing pressure range (i.e., the pressure gap) increases from north to south. In the north it is negligible, but in the south it amounts to ~1.8 GPa, equivalent to a missing thickness of ~60 km (assuming a mean density of the missing rocks of 3000 kg/m^3).

STRUCTURAL EVOLUTION

The internal structures of the Adula nappe record a polyphase Alpine deformation. The oldest structures (Sorreda phase; Löw, 1987) are early thrusts of basement over Mesozoic sedimentary rocks that led to the present interlayering of these units. This thrusting occurred during burial of the Adula nappe. Under eclogite facies conditions, at the pressure peak and during the earliest stages of exhumation, the eclogites were ductilely deformed to varying degrees, leading to a foliation and well-developed stretching lineation of the eclogite (Trescolmen phase; Meyre and Puschnig, 1993; Pleuger et al., 2003). The stretching lineation is mostly oriented east-west, but it is not clear whether this is the original orientation or results from a systematic rotation of the eclogite boudins during later shearing as assumed by Partzsch (1998).

The main deformation phase in the Adula nappe is the Zapport phase of mylonitic shearing. The Zapport foliation dips shallowly east, parallel to the nappe boundaries, and the stretching lineation is north-south to northwest-southeast. Ubiquitous shear-sense criteria consistently indicate top-to-the-north shearing, not only in the Adula nappe, but also in the overlying Misox zone (Partzsch, 1998; Nagel et al., 2002; Pleuger et al., 2003). The Zapport shearing occurred under greenschist facies conditions in the northern part of the nappe and amphibolite facies conditions in the southern part of the nappe. The Zapport structures (foliation, lineation) are continuous from the Adula nappe into the Misox zone and Tambo nappe. Hence, the emplacement of these nappes on the Adula nappe was completed by the end of the Zapport phase.

The Zapport mylonites are locally overprinted by top-to-the-east to southeast shearing (Nagel et al., 2002; Pleuger et al., 2003). This deformation is associated with the formation of the Turba normal fault (Fig. 3), a top-to-the-east to southeast low-angle normal fault of late Eocene to early Oligocene age (35–31 Ma, Nievergelt et al., 1996), cutting Earth's surface east of the Adula nappe. Still later folding led to the relative uplift of the southern part of the Adula nappe and to the southward overturning of the root of the nappe (Fig. 3).

DISCUSSION

There are two key constraints for the exhumation process of the Adula nappe. (1) A wedge-shaped volume of rock, to 60 km thick in the south, must have separated the Adula nappe from the overlying Tambo and Suretta nappes at peak-pressure time. (2) During and after the main stage of exhumation, the Adula nappe and the overlying units were overprinted by pervasive top-to-the-north shearing. A simple extrusion model (Fig. 1C) does not meet these constraints. Instead, we suggest that the missing rock volume comprised lithosphere, oceanic crust, and lower continental crust of the Briançonnais (Iberian) plate and that it disappeared by sinking into the deeper mantle. In Figure 4, we show a hypothetical reconstruction of the regional tectonic evolution. The timing constraints of this evolution were discussed in Schmid et al. (1996) and Pleuger et al. (2003). We modified the reconstruction of Schmid et al. (1996) in one important respect: in our new reconstruction, subduction of the northern Valais Ocean and European margin begins while the southern Valais Ocean and transition to the Briançonnais continent are still open (Fig. 4B). This is necessary because Bagnoud et al. (1998) found biostratigraphic evidence for marine sedimentation in the southernmost Valais basin until 40 Ma or even later. At that time, the Adula nappe was already being subducted.

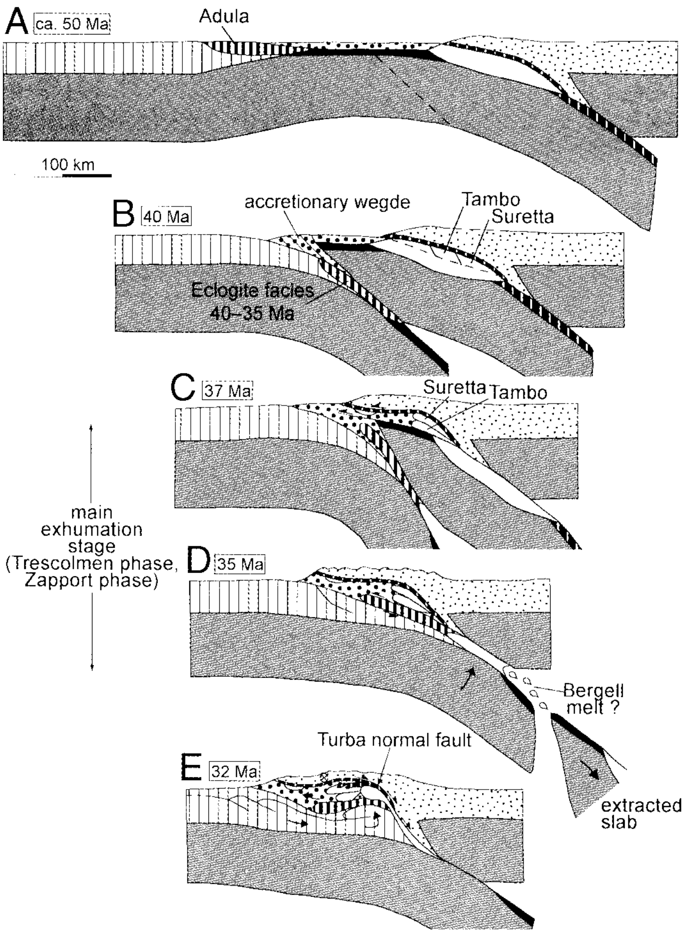

Figure 4. Reconstruction of tectonic evolution of eastern Central Alps. Patterns as in Figure 3. A: Adria-Briançonnais collision by closure of Piemont-Ligurian oceanic basin. B: Europe-Briançonnais collision by closure of Valais Ocean and subduction of European lithosphere and distal European margin (Adula nappe). C: Beginning extraction of Briançonnais slab and exhumation of Adula nappe. D: Extraction of slab completed; unflexing of European plate and partial melting of sinking slab to form Bergell melts. E: Top-to-southeast to top-to-east movement along Turba normal fault and corner flow of underlying Penninic nappes, accommodating rise of Bergell intrusion and further exhumation of Adula nappe.

The Piemont-Ligurian oceanic lithosphere was subducted toward the south under the Adriatic margin during the Late Cretaceous to early Eocene. This subduction zone was locked (Fig. 4A) when the Briançonnais microcontinent collided with the Adriatic margin ca. 50 Ma ("transient blockage" as modeled by Pfiffner et al., 2000). To accommodate further plate convergence, a new subduction zone formed inside the Valais basin. In this subduction zone, the northern part of the Valais basin and the distal European margin including what would become the Adula nappe were subducted toward the south under the Briançonnais plate (Fig. 4B). The sediment fill of the northern Valais basin (calc-schists) was sheared off and formed an accretionary wedge. When the Adula rocks reached their maximum depth ca. 40 Ma (Becker, 1993; Gebauer, 1996), the rocks of what would become the Tambo and Suretta nappes were still attached to the top of the Briançonnais plate (Fig. 4B). They were separated from the Adula nappe rocks by the wedge-shaped northern tip of the Briançonnais plate, made up of lower continental crust, mantle lithosphere, and some oceanic crust. The northern subduction zone also became locked when the normal-thickness crust of the European continent entered it. Further shortening became possible when the light upper crust of the Briançonnais continent (Tambo, Suretta) was detached from the lower crust (Fig. 4C; cf. Fig. 12 of Pfiffner et al., 2000). The European plate together with the Briançonnais slab moved southward under the Adriatic margin. The Briançonnais slab, devoid of its light upper continental crust, became gravitationally unstable and started to sink into the deeper mantle between ca. 37 and 35 Ma, the stages shown in Figures 4C and 4D. The void resulting from the extraction of the slab was filled by the rising Adula rocks and by the unflexing of the European plate. Thus, the Adula nappe came into direct contact with the Tambo nappe across the Misox zone. Southward subduction of the European plate continued during this process, so that the exhumed Adula rocks together with the Misox and Tambo rocks were emplaced on lower-pressure nappes and were overprinted by pervasive top-to-the-north shearing (Zapport phase) that completely erased older fabrics, except in the eclogite boudins. Partial melts from the crust and mantle lithosphere of the sinking Briançonnais slab may have formed the Bergell granitoid melt (Fig. 4D). Such an origin of the Bergell melt is compatible with geochemical results indicating a mixture of lithosphere- and continental-crust–derived melts (von Blanckenburg, 1992). The garnet peridotite bodies found in the upper Adula nappe (e.g., at Alpe Arami) may represent relict fragments of the mantle wedge. After this main stage of exhumation, the Adula nappe was further exhumed by corner flow of the Penninic nappes in the footwall of the Turba normal fault (Fig. 4E; Nagel et al., 2002).

The process of slab extraction as described here depends on particular circumstances, i.e., the interaction of two neighboring subduction zones dipping to the same side. This requirement is fulfilled in the Alps, because the Iberian (Briançonnais) microplate wedged out in the region of the Eastern Alps, whereby the plate boundaries on both sides of this microplate converged in the Western and Central Alps (Frisch, 1979). In addition to Adula, the model of slab extraction may apply to other Alpine high-pressure units derived from the distal European margin: the Monte Rosa, Gran Paradiso, and Dora Maira nappes, and the eclogite zone of the Tauern window (Fig. 2; Froitzheim, 2001).

We propose the following features to be diagnostic of slab extraction: (1) the occurrence of two stacked oceanic sutures with a continental unit in between; (2) the position of the high-pressure unit below the lower oceanic suture; and (3) an important pressure gap coincident with the lower oceanic suture.

CONCLUSION

When crustal rocks are subducted to depths of as much as 100 km and more, they are necessarily buried under mantle rocks, because the maximum thickness of the crust is only ~70 km. We suggest here that this overburden may be removed in a downward direction, by the overburden sinking into the deeper mantle. This descent is caused by the slightly higher density of lithospheric mantle as compared to asthenosphere, leading to a negative buoyancy, which is identical to the slab-pull force. When the overburden is removed in this way, the underlying high-pressure rocks are unloaded and isostatically uplifted, irrespective of their own density, in order to fill the void resulting from the overburden's extraction. In the case of the Adula nappe, this mechanism explains the exhumation of high- and ultrahigh-pressure rocks from great depths. It complements the existing models (Fig. 1A–1C), which have been shown to accommodate exhumation in other cases.

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REFERENCES CITED

Bagnoud, A., Wernli, M., and Sartori, M., 1998, Découverte de foraminifères planctoniques paléogènes dans la zone de Sion-Courmayeur à Sion (Valais, Suisse): Eclogae Geologicae Helvetiae, v. 91, p. 421–429.

Becker, H., 1993, Garnet peridotite and eclogite Sm-Nd mineral ages from the Lepontine Dome (Swiss Alps): New evidence for Eocene high-pressure metamorphism in the central Alps: Geology, v. 21, p. 599–602.

Challandes, N., 2001, Comportement des systèmes isotopiques ^{39}Ar-^{40}Ar et Rb-Sr dans les zones de cisaillement: Exemples du massif de l'Aar (Massifs cristallins externes) et de la nappe de Suretta (Alpes centrales suisses) [Ph.D. thesis]: Neuchâtel, Switzerland, Université de Neuchâtel, 268 p.

Frisch, W., 1979, Tectonic progradation and plate tectonic evolution of the Alps: Tectonophysics, v. 60, p. 121–139.

Froitzheim, N., 2001, Origin of the Monte Rosa nappe in the Pennine Alps—A new working hypothesis: Geological Society of America Bulletin, v. 113, p. 604–614.

Gebauer, D., 1996, A *P-T-t* path for an (ultra?-) high-pressure ultramafic/mafic rock-association and its felsic country-rocks based on SHRIMP-dating of magmatic and metamorphic zircon domains. Example: Alpe Arami (Central Swiss Alps), *in* Basu, A., and Hart, S., eds., Earth processes: Reading the isotopic code: American Geophysical Union Geophysical Monograph 95, p. 307–329.

Heinrich, C.A., 1986, Eclogite facies regional metamorphism of hydrous mafic rocks in the Central Alpine Adula nappe: Journal of Petrology, v. 27, p. 123–154.

Löw, S., 1987, Die tektono-metamorphe Entwicklung der Nördlichen Adula-Decke: Beiträge zur Geologischen Karte der Schweiz (N.F.), v. 161, 84 p.

Marquer, D., Baudin, T., Peucat, J.-J., and Persoz, F., 1994, Rb-Sr mica ages in the Alpine shear zones of the Truzzo granite: Timing of the Tertiary alpine *P-T* deformations in the Tambo nappe (Central Alps, Switzerland): Eclogae Geologicae Helvetiae, v. 87, p. 225–239.

Meyre, C., and Puschnig, A.R., 1993, High-pressure metamorphism and deformation at Trescolmen, Adula nappe, Central Alps: Schweizerische Mineralogische und Petrographische Mitteilungen, v. 73, p. 277–283.

Michard, A., Chopin, C., and Henry, C., 1993, Compression versus extension in the exhumation of the Dora-Maira coesite-bearing unit, Western Alps, Italy: Tectonophysics, v. 221, p. 173–193.

Nagel, T., de Capitani, C., Frey, M., Froitzheim, N., Stünitz, H., and Schmid, S.M., 2002, Structural and metamorphic evolution during rapid exhumation in the Lepontine dome (southern Simano and Adula nappes, Central Alps, Switzerland): Eclogae Geologicae Helvetiae, v. 95, p. 301–321.

Nievergelt, P., Liniger, M., Froitzheim, N., and Ferreiro Mählmann, R., 1996, Early to mid Tertiary crustal extension in the Central Alps: The Turba mylonite zone (eastern Switzerland): Tectonics, v. 15, p. 329–340.

Nimis, P., and Trommsdorff, V., 2001, Revised thermobarometry of Alpe Arami and other garnet peridotites from the Central Alps: Journal of Petrology, v. 42, p. 103–115.

Partzsch, J.H., 1998, The tectono-metamorphic evolution of the middle Adula nappe, Central Alps, Switzerland [Ph.D. thesis]: Basel, Switzerland, Universität Basel, 142 p.

Pfiffner, O.A., Ellis, S., and Beaumont, C., 2000, Collision tectonics in the Swiss Alps: Insight from geodynamic modeling: Tectonics, v. 19, p. 1065–1094.

Platt, J.P., 1993, Exhumation of high-pressure rocks: A review of concepts and processes: Terra Nova, v. 5, p. 119–133.

Pleuger, J., Hundenborn, R., Kremer, K., Babinka, S., Kurz, W., Jansen, E., and Froitzheim, N., 2003, Structural evolution of Adula nappe, Misox zone, and Tambo nappe in the San Bernardino area: Constraints for the exhumation of the Adula eclogites: Mitteilungen der Österreichischen Geologischen Gesellschaft (in press).

Ring, U., Brandon, M.T., Willett, S.D., and Lister, G.S., 1999, Exhumation processes, *in* Ring, U., et al., eds., Exhumation processes: Normal faulting, ductile flow and erosion: Geological Society [London] Special Publication 154, p. 1–27.

Schmid, S.M., Pfiffner, O.A., Froitzheim, N., Schönborn, G., and Kissling, E., 1996, Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps: Tectonics, v. 15, p. 1036–1064.

von Blanckenburg, F., 1992, Combined high-precision chronometry and geochemical tracing using accessory minerals: Applied to the Central-Alpine Bergell intrusion (central Europe): Chemical Geology, v. 100, p. 19–40.

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