Permian metamorphic event in the Alps

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ABSTRACT

In addition to the well-known Variscan and Alpine orogenic cycles, a Permian thermal event occurred in the European Alps. The geodynamic background of this event is not well understood. Here we suggest that the event is a reflection of lithospheric thinning accompanied by magmatic underplating causing partial melting of the lower crust and low-pressure–high-temperature metamorphism. The event was terminated by Early Triassic opening of the Meliata ocean and was followed by sag-stage subsidence during slow lithospheric cooling. This last stage of the evolution allowed the onset of the Mesozoic marine evolution with the orogen-wide formation of Triassic carbonate platforms well known from the Dolomites and the Northern Calcareous Alps. The combined evidence for magmatism, metamorphism, and late subsidence identifies the Permian event of the Alps as an excellent example of underplating events suggested as a cause for low-pressure–high-temperature terrains worldwide.

Keywords: Permian event, Alps, underplating, low-pressure–high-temperature metamorphism.

INTRODUCTION

For decades, rocks in the European Alps were thought to have only undergone Phanerozoic metamorphic events during the Variscan and Alpine tectonic cycles. Geochronological data outside the two identified periods for these orogenies were not interpreted in terms of an independent tectonic event. Ages between 290 and 140 Ma were usually thought to be mixed ages, were considered to be "very late" or "very early" reflections of the Variscan and Alpine tectonic cycles, or were simply ignored. Over the past decade an increasing body of data has emerged that testifies to the existence of a widespread independent high-temperature (T), low-pressure (P) Permian metamorphic event (Thöni and Miller, 2000; Schuster et al., 2001, 2004; Rebay and Spalla, 2001) that accompanies the already well-known Permian magmatic ages (Table 1).

The concurrence of Permian metamorphism and magmatism and the fact that the Permian thermal imprint immediately precedes the massive Triassic marine sedimentation (forming the carbonate platforms of the Dolomites and Northern Calcareous Alps) invite us to combine magmatism, metamorphism, and sedimentological evidence into a single tectonic model. Nevertheless, few studies have attempted to interpret the significance of the Permian event (e.g., Bertotti et al., 1999; Schuster et al., 2001). In this paper we summarize data that testify to this event and present the first orogen-scale map of the Permian–Triassic imprint (Fig. 1). We suggest magmatic underplating as a heat source for Permian metamorphism and use a thermal model to test this idea.

TABLE 1. SELECTED REPRESENTATIVE REFERENCES FOR GEOCHRONOLOGICAL AGES AND METAMORPHIC CONDITIONS DOCUMENTING THE PERMIAN EVENT IN THE ALPINE REALM

Igneous Rocks	Age (Ma)	References
gabbros and/or diorites	245–290	Rebay and Spalla (2001, Table 1): SA, AA, EM
		Thöni (1999, 2002): AA
		Miller and Thöni (1997): AA (Koralm)
		Mayer et al. (2000): SA, Ivrea Zone
pegmatites	250–290	Thöni (1999, 2002, Fig. 2, Table 2): AA
		Schuster et al. (2001): AA
		Thöni and Miller (2000): AA (Koralpe)
granites	265–285	Borsi et al. (1972): SA
		Pinarelli et al. (1988): SA, Stronna-Ceneri Zone
volcanics	265–290	Klötzli et al. (2003): SA, Bozen Quartz porphyries
		Barth et al. (1994): SA, Collio Graben
		Lelkes-Felvàri and Klötzli (2004): AA, Transdanubian range
Metamorphic Rocks		
formation ages	250–285	Thöni (2002): AA
		Schuster et al. (2001): AA
cooling ages		Bürgi and Klötzli (1990): SA, Ivrea Zone
		Bertotti et al. (1999): SA, Dervia Oligasca Zone
		Sanders et al. (1996): SA, Dervia Oligasca Zone
		Schuster et al. (2001, 2004): AA

Note: Intrusion and formation ages are U-Pb or Sm-Nd ages, except some older Rb-Sr whole rock isochrons. Cooling ages are Ar-Ar and Rb-Sr ages on muscovite and biotite.
SA—South Alpine Unit; AA—Austroalpine Nappes; PN—Penninic Nappes; EM—distal European margin.

EVIDENCE FOR THE PERMIAN EVENT

The Permian event in the Alps followed in the wake of the Variscan tectonic evolution in Europe. The last stages of this orogen are documented by S-type granites in the Bohemian massif ca. 310 Ma and even younger cooling ages until 290 Ma (Thöni, 1999). From 290 Ma onward, Permian terrigenous sedimentation occurred across the Alps. The sediments discordantly overlie Variscan basement and indicate a transition from fluvial to shallow-marine conditions (Bellerophon Formation of the Southern Alps), indicating smoothening and lowering of the topography and a decrease of surface elevation.

The onset of the Permian event may be considered as when crustal thickness decreased below normal, and thus cannot be related to gravitational collapse of the Variscan orogen. Evidence for active thinning along the southern margin of the Variscan orogen is given by the formation of Permian grabens ca. 290 Ma (e.g., Collio Graben, grabens beneath the Molasse Basin), extensional fabrics in metamorphic rocks, and the first marine sediments ca. 265 Ma (Bosellini, 1991).

Lithospheric thinning was accompanied by widespread Permian metamorphism at sillimanite and andalusite grade (Fig. 2), now evidenced by a growing body of Permian mineral formation ages (Table 1). High-grade conditions are known particularly well from the Silveretta and Koralpe regions and the Ivrea Zone (the only region in the Alps with Permian kinzingites), but exemplary evidence is given south of the

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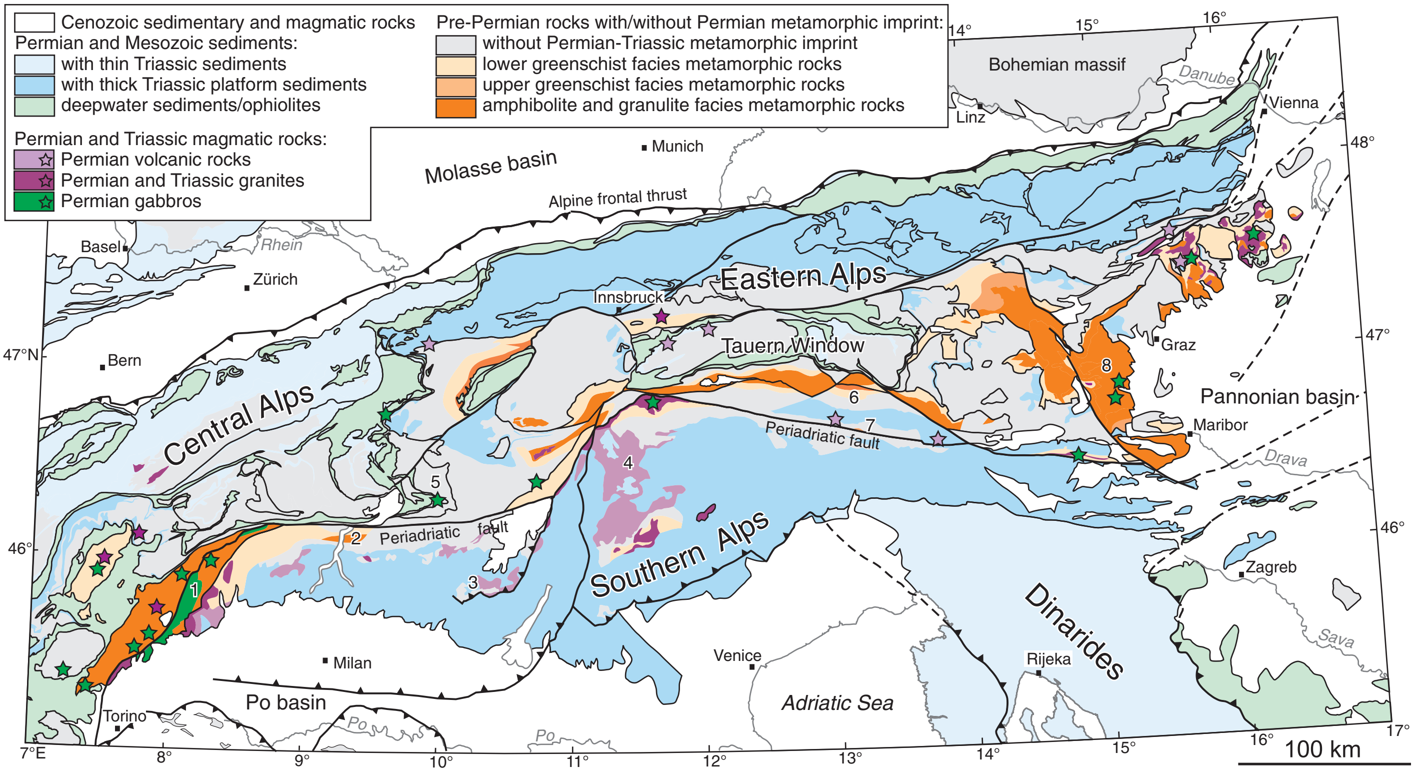

Figure 1. Map showing the Permian–Triassic imprint in the Alps (based on tectonic map of Schmid et al., 2004). Rocks outside area shown have no Permian imprint. Localities referred to in text: 1—Ivrea Zone; 2—Dervio-Oligasca Zone; 3—Collio Graben; 4—Bozen quartz porphyries; 5—Malenco; 6—Strieden Complex; 7—Jenig Complex; 8—Koralpe.

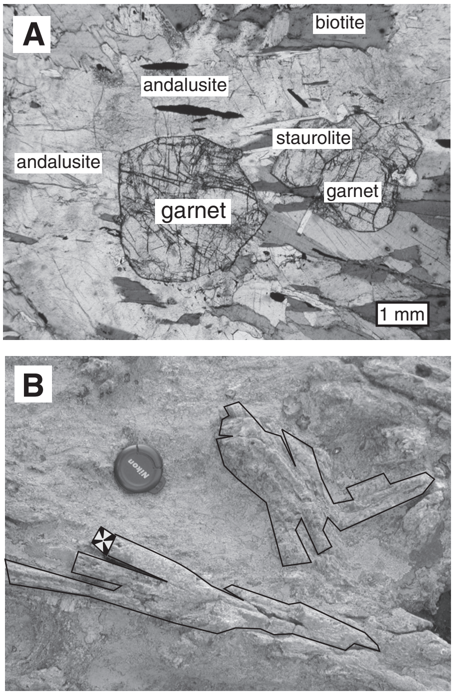

Figure 2. Exemplary evidence for Permian metamorphic event in the field and in thin section. A: Permian assemblage from Jenig complex dated as 253 Ma. B: Meter-scale paramorphism of Eoalpine kyanite after Permian chiastolite (head section emphasized below lens cap) in the Koralpe. Lens cap is 4 cm in diameter.

Tauern Window. There an oblique crustal section is exposed that covers Permian metamorphism from sillimanite to andalusite grade at the base and extends to the surface (Strieden and Jenig complexes; Schuster et al., 2001; Figs. 1 and 2). Permian *P-T* paths terminate with isobaric cooling (Schuster et al., 2001), leaving rocks at middle and deep crustal levels at the end of the Permian evolution. Exhumation of the Permian assemblages followed much later during the Eoalpine orogeny, when some units were buried and overprinted, often causing a close spatial correlation between Eoalpine and Permian metamorphism (Fig. 1).

The Permian metamorphic imprint is associated with a series of magmatic events (Table 1): gabbros intruded into both the middle and lower crust between 290 Ma and 245 Ma. Permian gabbros are known in the Alps wherever the Moho is exposed (Ivrea, Malenco; Fig. 1), suggesting that they formed underplates (Voshage et al., 1990; Müntener et al., 2000). Intrusion of Permian gabbros was accompanied by granite and pegmatite intrusions at mid-crustal levels, formation of quartz-andalusite veins, and Permian volcanics. For example, the extensive volcanics of the Bozen quartz porphyry extruded at 285–275 Ma (Klötzli et al., 2003). Less intense magmatism continued in Triassic time (e.g., Bosellini, 1991; Thöni, 2002).

From 240 Ma onward a facies distribution typical for an ocean-continent transition developed in the Alpine realm, with carbonate platforms on the continent and slope and deep-water sediments toward the basin (Bosellini, 1991; Mandl, 2000). Schmid et al. (2004) interpreted this as the result of the opening of the Meliata ocean, which is the westernmost part of the Neotethys ocean. The marine evolution was contemporaneous with cooling of the Permian metamorphics from their peak to a normal geothermal gradient (Table 1).

TECTONIC MODEL

The data summarized above are consistent with a simple model for an extensional tectonic cycle (Fig. 3): we suggest that lithospheric thinning in the Permian occurred by north-south extension in response to westward propagation of the Neotethys ocean. Crust and mantle parts of the lithosphere are less and more dense than the underlying mantle, respectively. We suggest that the two parts of the lithosphere extended in a ratio that caused negligible surface subsidence between 290 and 240 Ma (e.g., thinning of crust to 80% and lithosphere to 60% of its original thickness; Fig. 3). This caused decompression melting in the mantle part of the lithosphere, resulting in mafic underplating at the Moho (Voshage et al., 1990), and ultimately in secondary crustal melting

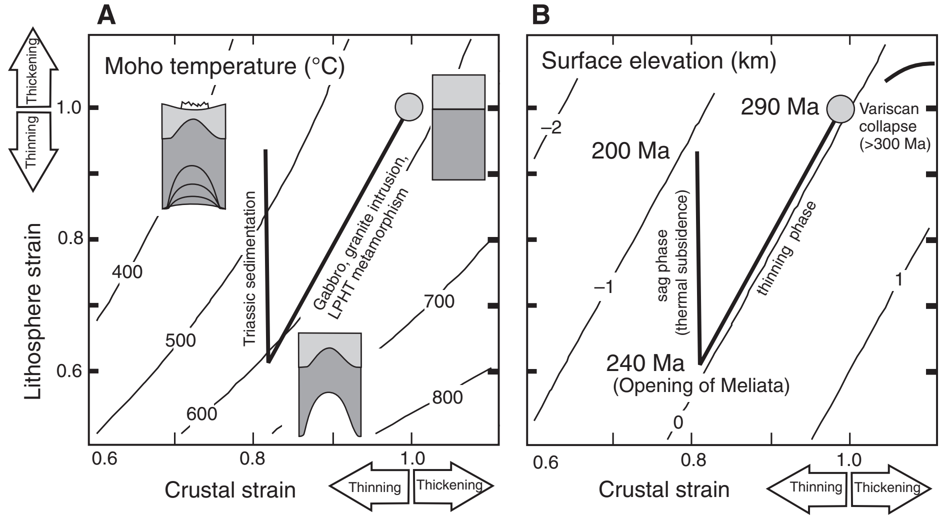

Figure 3. Conceptual tectonic model for Permian–Triassic evolution of the Alps showing evolution of lithosphere strain (vertical axis) versus crustal strain (horizontal axis). Thick black arrow shows suggested evolution involving mechanical thinning of both crust and mantle lithosphere (at ratio causing only negligible surface subsidence) until 240 Ma and subsequent thermal thickening of mantle part of the lithosphere thereafter. Arrow is labeled at left for observed and at right for inferred events. Insets in A show cartoons of lithospheric column. Underlying contours for Moho temperature and surface elevation are for approximate reference only (calculated with equations 3.76 and 4.35 from Stüwe [2007] using 35 km and 120 km for crust and lithosphere thickness). LPHT—low pressure–high temperature.

that caused granite and pegmatite intrusions at mid-crustal levels. Underplates and secondary melts caused widespread low-*P*–high-*T* metamorphism (Habler and Thöni, 2001), for example, as indicated by a strong correlation between the occurrence of Permian pegmatites and sillimanite- and andalusite-bearing Permian metamorphic assemblages.

Once the Neotethys embayment entered the Alpine realm from the east ca. 240–230 Ma, all extensional strain was concentrated into the oceanic domain in the eastern part, whereas it continued to the west of the embayment (units of the Southern Alps; Bertotti et al., 1993). We suggest that this time marks the onset of a prolonged sag phase that lasted until ca. 190 Ma, in which cooling of the thinned mantle part of the lithosphere reequilibrated the 1200 °C isotherm to its original depth prior to 290 Ma. This phase caused cooling of the crust, thermal subsidence at the surface, and mechanical strengthening of the Alpine lithosphere. The proposed sag-phase stage (Figs. 3A, 3B) is consistent with the thickness of Triassic carbonate platforms (3–4 km of mostly intertidal sediments over large areas: Bertotti et al., 1993; Rantitsch, 2001) and with the observed cooling ages of the metamorphic rocks, as shown below.

DISCUSSION WITH A THERMAL MODEL

We test the idea suggested above using a one-dimensional thermal model. For this, we assume a continental geotherm that is vertically shortened to describe lithospheric extension, then thermally perturbed at the Moho to describe underplating, and ultimately left to passive thermal reequilibration to its original depth extent. The initial geotherm is described with equation 3.96 of Stüwe (2007), using standard thermal parameters described therein. Thickness for crust and lithosphere were assumed to be 35 km and 120 km, respectively.

For 50 m.y. after model start (i.e., 290–240 Ma), we assume homogeneous lithospheric thinning, which allows only minor subsidence consistent with the absence of geological evidence for subsidence during this time (for the parameter ranges chosen here, an initial thickness ratio of crust to mantle lithosphere of 1:5 would cause no surface subsidence). The extensional strain is not very well documented, but estimates based on the *P-T* paths of Schuster et al. (2001) suggest a crustal stretch of ~1.4 (homogeneous thinning of lithosphere to 71% of its original thickness), which is used here. As homogeneous thinning will cause only small

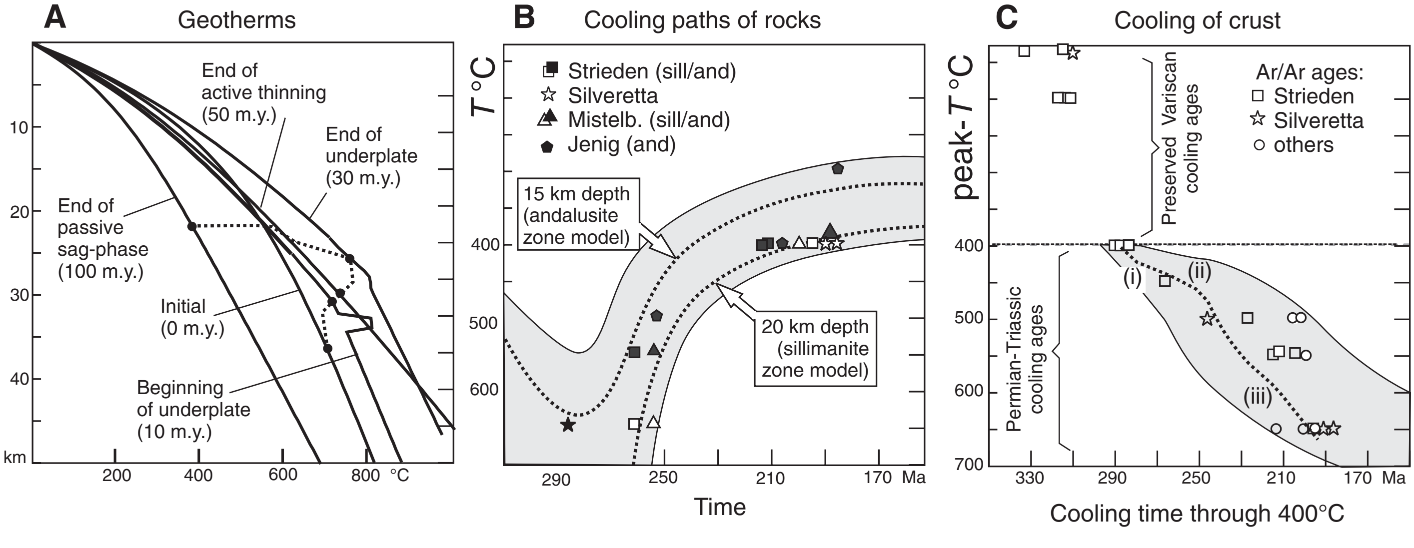

Figure 4. Thermal model for the Permian event showing thermal evolution of crust as a consequence of lithospheric thinning accompanied by magmatic underplating and subsequent thermal relaxation of mantle part of the lithosphere. A: Geotherms (labeled in m.y.; modeled pressure-temperature path is dotted). B: Modeled (curves) and measured (symbols) temperature-time evolution for andalusite (and; dark symbols) and sillimanite (sill; white symbols) bearing parageneses. C: Metamorphic peak versus time of cooling through 400 °C isotherm.

changes in Moho temperature (Fig. 3A), an additional heat source needs to be invoked to cause metamorphism. Here we assume a 5-km-thick, 800 °C mafic underplate to be emplaced at the Moho from 10–30 m.y. after the model start (i.e., 280–260 Ma). Thermal evolution is tracked by solving the one-dimensional diffusion equation. After 50 m.y. of the model evolution, thinning is stopped and subsequent lithospheric thickening is modeled by passively reequilibrating the temperature profile to a lower boundary condition at 120 km depth (Fig. 4A).

From the model we extracted two sets of data that can be compared with geochronological evidence for the Permian event. First, we tracked the thermal evolution of rocks at two crustal levels (15 and 20 km depth) corresponding to those containing andalusite- and sillimanite-bearing rocks (Fig. 4B). The modeled cooling histories (dotted lines) correspond well to the observed data with cooling rate decreasing at low temperatures. Second, we tracked the time when various crustal levels of the model cooled through the 400 °C isotherm and plotted these times against peak temperature as a proxy for depth (Fig. 4C). This may be compared to Ar/Ar cooling ages (documenting the time of 400 °C cooling) of rocks from a series of known Permian metamorphic grades across the Alps. The modeled cooling has three components: (1) cooling due to mechanical thinning, (2) due to thermal relaxation of the underplate, and (3) sag-stage cooling of the mantle lithosphere after the termination of active thinning. Overall, the model conforms well with observations, in that lower-grade (upper crustal) rocks cool earlier than high-grade (lower crustal) rocks as the lithosphere reequilibrates in the Triassic. Results for realistic parameter ranges of all geometric and thermal parameters tested are all within the shaded bands shown in Figures 4B and 4C.

In summary, our model suggests a long-lasting extensional tectonic cycle for the Permian–Triassic evolution of the Alpine realm. The heat sources are mafic underplates generated by decompression melting from the subcontinental mantle during lithospheric thinning, enhanced by secondary formation of crustal melts at the Moho. As such, it conforms with thermal models for low-*P*–high-*T* metamorphism originally suggested by Huppert and Sparks (1988) and applied to many high-grade terrains worldwide. The event is terminated by sag-stage subsidence and lithospheric cooling. The thickness of the Triassic sediments is matched by the calculated tectonic subsidence during the sag stage (Fig. 3B). We have successfully tested the model by comparing it with geochronological data (Figs. 4B, 4C) and with an overall heat budget estimate.

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