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Geology 2009;37;603-606
doi: 10.1130/G30003A.1

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Magmatic plumbing of a large Permian caldera exposed to a depth of 25 km

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ABSTRACT

We report evidence for a ≥13-km-diameter Permian caldera associated with a renowned section through the continental crust comprising the Ivrea-Verbano Zone and Serie dei Laghi of northwest Italy. Correlation of ages of volcanic and middle to deep crustal plutonic rocks suggests that they constitute an unprecedented exposure of a subcaldera magmatic plumbing system to a depth of 25 km, and points to a cause and effect link between intrusion of mantle-derived basalt in the deep crust, and large-scale, silicic volcanism.

INTRODUCTION

Large caldera-forming eruptions rank among the most violent geologic events. Geophysical studies (e.g., Weiland et al., 1995) and petrochemical studies of eruptive products and shallow intrusions (e.g., Hildreth, 2004) indicate that magmatic systems of these eruptions are driven by intrusion of mantle-derived magma in the deep crust, a process commonly referred to as magmatic underplating. However, our understanding of the processes involved has been limited by the lack of a crustal section exposing rocks deeper than ~5 km beneath a caldera. In this paper we report evidence for a ≥13-km-diameter Permian caldera in northwest Italy situated atop a crustal section comprising the Ivrea-Verbano Zone and Serie dei Laghi (Fig. 1; Fountain, 1976). New data indicate that volcanism correlates closely in time with intrusion of mantle-derived basalt and crustal anatexis at depths ≥15 km. Removal of Alpine deformation results in a model crustal section for interpreting geophysical profiles and magmatic processes beneath active calderas.

GEOLOGIC SETTING

The Ivrea-Verbano Zone and Serie dei Laghi (Fig. 1) are the deep crustal and the middle to upper crustal components, respectively, of a section through the pre-Alpine crust of northwest Italy (Fountain, 1976; Handy and Zingg, 1991; Henk et al., 1997; Rutter et al., 1999; for a dissenting view see Boriani and Giobbi, 2004). Within the Ivrea-Verbano Zone, paragneiss of the Kinzigite Formation was intruded by gabbro and diorite of the Mafic Complex while in the lower crust (Rivalenti et al., 1980; Quick et al., 1994). Geobarometry (Demarchi et al., 1998) indicates that the roof of the intrusion, which corresponds to its eastern contact with the Kinzigite Formation, equilibrated at a depth of 15–20 km, and that equilibration pressures increase monotonically toward the Insubric Line, where rocks equilibrated at depths of ~25 km. Heat from the Mafic Complex induced partial melting in the Kinzigite Formation (Barboza and Bergantz, 2000), producing melts that crystallized as granitic rocks. East of the Ivrea-Verbano Zone, the Serie dei Laghi comprises orthogneiss, paragneiss, and two-mica schist intruded by Permian granitic plutons grouped as the Graniti dei Laghi (Boriani et al., 1988).

The Ivrea-Verbano Zone and Serie dei Laghi are juxtaposed by the CMB (Cossato-Mergozzo-Brissago) Line north of Figure 1, a ductile shear zone along which motion had ceased by 285–275 Ma (Mulch et al., 2002; Rutter et al., 2007). In Figure 1, the eastern limit of the Ivrea-Verbano Zone corresponds to Alpine faults and a contact along which granite intrudes the Kinzigite Formation (Quick et al., 2003). Subvertical strike-slip faults of the Cremosina Line have total right-lateral displacement of ~12 km (Boriani and Sacchi, 1973), splitting a large granitic pluton into two bodies, mapped as the Roccapietra and Valle Mosso Granites, and placing volcanic rocks in close proximity to the Ivrea-Verbano Zone (Fig. 1).

Volcanic rocks in the Sesia Valley are mostly rhyolite, although minor basalt, andesite, and dacite are present. These rocks comprise lava flows, massive porphyry, ignimbrites, and fragment-rich tuff intermixed with a spectacular megabreccia containing gigantic inclusions of schist and volcanic rock in a matrix of welded tuff (Fig. 2). Distribution of megabreccia, its intimate involvement in the volcanic stratigraphy (Govi, 1977), and the pyroclastic nature of its matrix preclude formation as fault breccia unrelated to volcanism. Similar megabreccias have been shown to be diagnostic of caldera-forming eruptions, forming as the subsiding caldera fills with volcanic ash mixed with landslide debris derived from the caldera walls (Lipman, 1997). East of the Sesia Valley, the contact between volcanic rocks and basement two-mica schist appears to be a relic of such a caldera wall based on an increase in abundance of schist inclusions in the tuff as the contact is approached. We project the caldera boundary west of the Sesia Valley based on the presence of megabreccia and welded tuff with inclusions of schist, the distribution of which indicates a minimum northeast-southwest caldera dimension of ~13 km.

The volcanic rocks were described by Zezza et al. (1984) as intruded by the Valle Mosso (also known as Biellese) Granite based on fine-grained granophyre at the contact and microgranite and pegmatitic dikes in the volcanic rocks. Zezza et al. (1984) identified an epizonal facies with heterogeneous granophyric to medium-grained texture and miarolitic cavities, and a mesozonal facies consisting of more uniform, medium- to coarse-grained rocks. In Figure 1, the epizonal and mesozonal facies are shown as upper and lower Valle Mosso Granite, respectively.

GEOCHRONOLOGY

New sensitive high-resolution ion microprobe (SHRIMP) zircon ages for volcanic and granitic rocks are reported in Figures 1 and 3. Errors are reported as 2σ standard deviations unless otherwise stated.

Age determinations were attempted for five volcanic samples following exclusion of a few inherited cores. Sample R6, an andesitic-basalt flow interlayered with rhyolite at deep levels of the exposed volcanic section, yielded a concordia age of 288 ± 2 Ma (Fig. 3A). R16, collected from a megabreccia block of dense rhyolite porphyry devoid of inclusions, yielded another concordia age of 285 ± 2 Ma (Fig. 3B). The remaining volcanic samples, R4, R9, and IVR2, were problematic. Following exclusion of grains based on Pb loss, or high common Pb, the remaining zircons in each of these rocks were dispersed along the concordia from ca. 295 to ca. 275 Ma, a range too great to allow calculation of a single concordia age (see the GSA Data Repository[1]).

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[1]GSA Data Repository item 2009141, analytical techniques, tables, diagrams, and detailed analysis of geochronologic data, and an explanation of the construction of the model crustal section and synthetic seismic profiles, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Geology, July 2009; v. 37; no. 7; p. 603–606; doi: 10.1130/G30003A.1; 4 figures; Data Repository item 2009141.

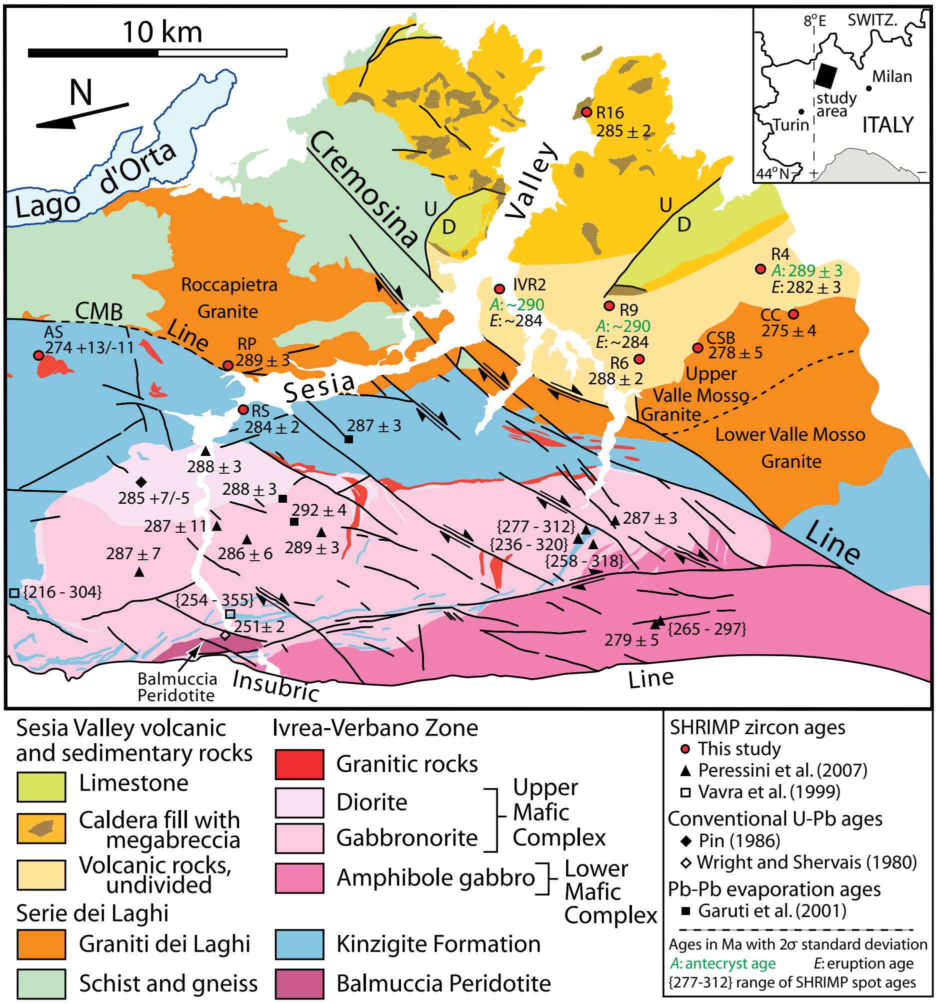

Figure 1. Compiled geology (Zingg, 1983; Govi, 1977; Boriani et al., 1988; Quick et al., 2003) oriented to place roof of Mafic Complex in its original subhorizontal position. CMB—Cossato-Mergozzo-Brissago Line. Deposits of megabreccia are based on Govi (1977) and a month of field work in 2007. Arrows indicate motion on predominantly strike-slip faults; U/D—up and down motion on predominantly dip-slip faults; SHRIMP—sensitive high-resolution ion microprobe; CC, CSB, RP, RS, AS, R4, R9, R16, and IVR2 are sample names.

Figure 2. Sesia Valley Megabreccia. Student points to contact between inclusion of maroon rhyolite and light-gray matrix of welded tuff.

Insight into the origin of these dispersed ages is provided by R4, a rhyolite with inclusions of glomerophyric feldspar ≤2 mm. The sample yielded magmatically zoned, stubby, and elongate zircon populations, having distinct age peaks on a cumulative probability plot with weighted ^{206}Pb/^{238}U average ages of 289 ± 3 and 282 ± 3 Ma (Fig. 3C), and distinct Th/U <0.55 and >0.55 (see the Data Repository). Age spreads up to 10 Ma in single samples from silicic volcanic provinces have been attributed to the presence of zircon antecrysts produced in early phases of related magmatism (e.g., Charlier et al., 2004; Bryan et al., 2008), and we conclude that the eruption age of R4 is best approximated by the ca. 282 Ma age, and that the ca. 289 Ma age dates an older, deeper magmatic component entrained in the R4 magma during its ascent. Based on similar age distributions in cumulative probability plots for IVR2 and R9 (Fig. 3D), we conclude that the ages in these samples are also explained by eruption between 285 and 280 Ma of a magma entraining older, ca. 290 Ma, zircon antecrysts.

Granitic rocks were collected at progressively deeper crustal levels, with CC and CSB sampled near the intrusive contact with the volcanic rocks, RP sampled near the base of the Roccapietra Granite, and RS and AS sampled from granitic bodies within the Kinzigite Formation. CC and CSB yielded concordia ages of 275 ± 4 and 278 ± 5 Ma (Fig. 3E), respectively, similar within error to the younger ages inferred for volcanic samples R4, R9, and R16 and a conventional zircon intercept age of 281.8 ± 1.5 Ma measured by Schaltegger and Brack (2007) on the Montorfano Granite, 12 km north of the area of Figure 1. RP yielded a concordia age of 289 ± 3 Ma (Fig. 3F). Zircon analyses in RS are dominated by Pb loss, defining a regression line with an upper intercept anchored by three concordant analyses at 284 ± 2 Ma (Fig. 3G), which we interpret to be the crystallization age. Ages for RP and RS agree within errors with the age of andesitic basalt R6 and are similar to the older age components indentified in the rhyolites. Sample AS returned a poorly constrained upper intercept age of 274 +13/–11 Ma, which has errors too large to relate uniquely to the other data.

DISCUSSION

The geochronology of deep crustal rocks of the southern Ivrea-Verbano Zone was reviewed in detail by Peressini et al. (2007). The most significant magmatic event, a major pulse of mantle-derived melt into the deep crust, is dated by SHRIMP, conventional, and Pb-Pb evaporation zircon ages of mafic to intermediate plutonic rocks in the Upper Mafic Complex, most of which range from 289 ± 3 to 286 ± 6 Ma (Fig. 1). Individual SHRIMP spot ages at deeper levels of the Mafic Complex range from older than 310 to younger than 250 Ma (Fig. 1), reflecting continuous recrystallization of zircons during a prolonged period of slow cooling and deformation in the deep crust punctuated by repeated intrusive events.

Our data indicate that volcanism and formation of granitic plutons occurred within a 5–10 Ma interval similar to Early Permian volcanic activity elsewhere in the Alps (Schaltegger and Brack, 2007; Marocchi et al., 2008), and within the time frame for volcanic activity in large silicic complexes (e.g., Bryan et al., 2008) and growth of zoned granitic plutons (Coleman et al., 2004). Ages for volcanic and granitic rocks in the range of 289 ± 2 to 284 ± 2 Ma correlate well with ages for the Upper Mafic Complex, indicating that volcanism and granitic plutonism were coincident with and probably triggered by intrusion of mantle-derived mafic melt in the deep crust. Post-284 Ma volcanism and granitic pluto-

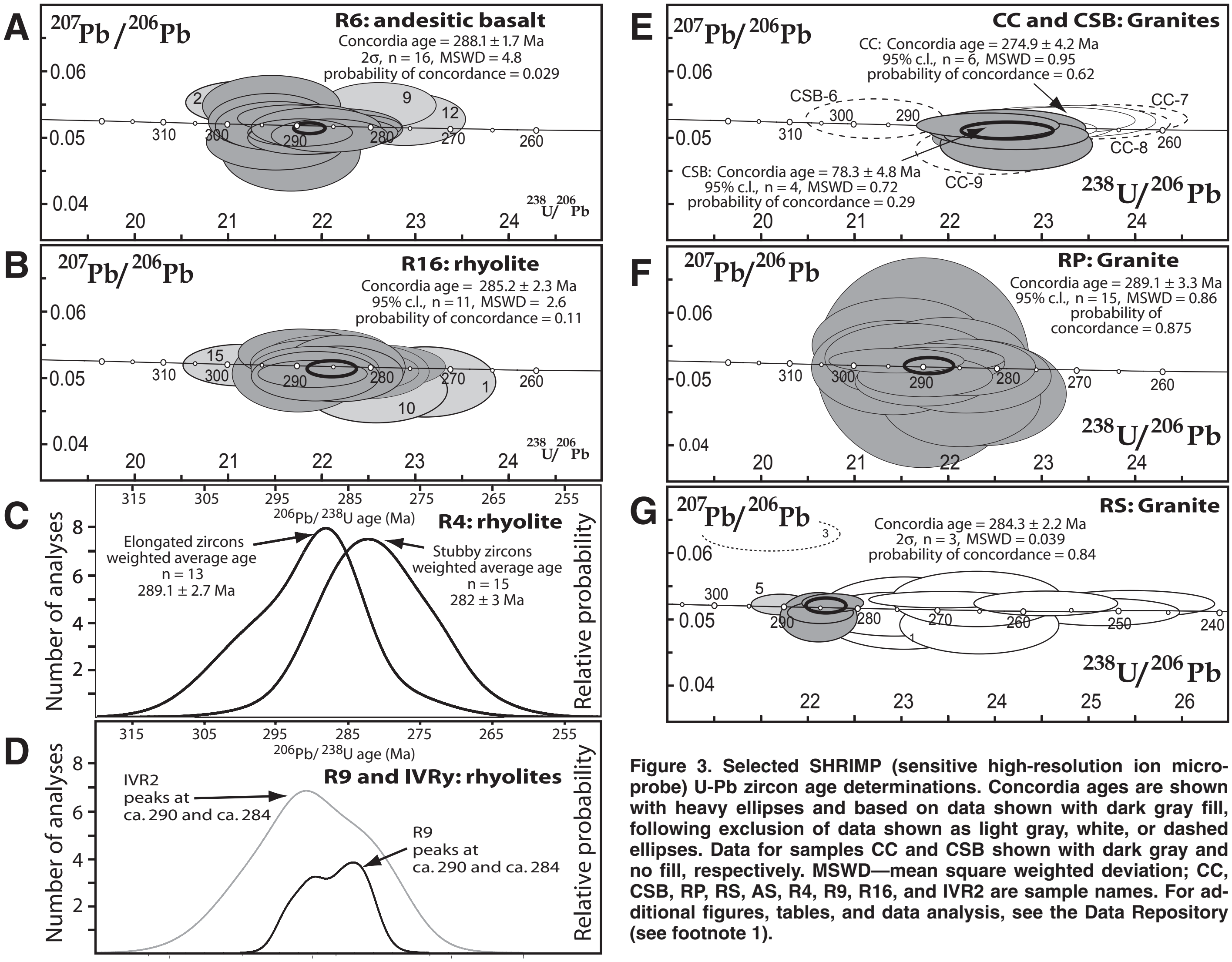

Figure 3. Selected SHRIMP (sensitive high-resolution ion microprobe) U-Pb zircon age determinations. Concordia ages are shown with heavy ellipses and based on data shown with dark gray fill, following exclusion of data shown as light gray, white, or dashed ellipses. Data for samples CC and CSB shown with dark gray and no fill, respectively. MSWD—mean square weighted deviation; CC, CSB, RP, RS, AS, R4, R9, R16, and IVR2 are sample names. For additional figures, tables, and data analysis, see the Data Repository (see footnote 1).

nism suggest that crustal melting continued for several million years after the Mafic Complex had largely crystallized. The span of ages for major igneous events in the upper and lower crustal rocks of the Sesia Valley is so narrow as to be difficult to explain in terms of completely unrelated events given the spatial proximity of the rocks, and we conclude that this magmatic system is a "golden spike" that tied together the Serie dei Laghi and Ivrea-Verbano Zone as a single crustal section by the Early Permian.

Figure 4 presents a model crustal section constructed by palinspastic restoration of Alpine and Mesozoic deformation (see the Data Repository). Our result is similar to that of Rutter et al. (1999), differing primarily by addition of volcanic rocks in the upper crust and placement of a caldera above the Valle Mosso–Roccapietra Granite and Mafic Complex, a result consistent with their formation within a single magmatic system. Synthetic seismic profiles calculated using measured velocities for Ivrea-Verbano Zone and Serie dei Laghi rocks (Khazanehdari et al., 2000) indicate that, under subsolidus conditions, a weak P wave low-velocity zone corresponds to the granite, but no P wave low-velocity zones are present in the lower crust, and no significant S wave low-velocity zones are present at any crustal level. We estimate the effect of residual melt in the Roccapietra Granite and the Mafic Complex shortly after the caldera-forming event by assuming 7% residual interstitial melt and velocity reductions of 1 and 2% per % melt for P and S waves. Resulting low-velocity zones (Fig. 4) are similar in scale and depth to those detected beneath young calderas such as Campi Flegrei (Guidarelli et al., 2006), suggesting that rocks in the Sesia Valley may provide a geologic reference section for the crustal seismic structure beneath large, silicic calderas analogous to that provided by the ophiolite model for the seismic structure of the oceanic crust.

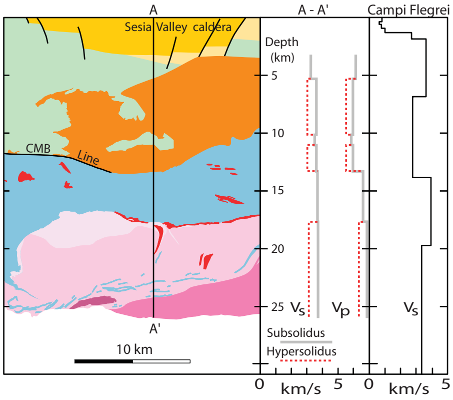

Figure 4. Palinspastic reconstruction of Early Permian Ivrea Verbano–Serie dei Laghi crust shortly after caldera formation. Faults in caldera floor are schematic. Units as in Figure 1. P wave and S wave velocities (Vp ,Vs) calculated along profile A-A′ for subsolidus and hypersolidus conditions are compared to S wave velocity profile beneath Campi Flegrei Caldera (Guidarelli et al., 2006). CMB—Cossato-Mergozzo-Brissago Line.

CONCLUSIONS

Intrusion of the upper Mafic Complex at depths ≥15 km induced anatexis in the continental crust, generating silicic melts that fed granites and erupted as rhyolites for ~10 Ma from ca. 289 to ca. 280 Ma ago. Collectively, these rocks constitute an unprecedented reference section for the geometry and processes within the magmatic plumbing systems of large silicic calderas, and validate the hypothesis that the large-scale silicic volcanism is driven by the intrusion of mantle-derived magma in the deep crust.

ACKNOWLEDGMENTS

Financial support was provided by MIUR (Ministero dell'Istruzione dell'Universita e della Ricerca) Project PRIN 2007 and University of Trieste Project GR-2005 to Peressini, and logistical support was provided by Graziella Gull. This manuscript was improved by reviews by E. Stein, U. Schaltegger, and D. Hill.

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Manuscript received 5 January 2009
Revised manuscript received 14 February 2009
Manuscript accepted 18 February 2009

Printed in USA