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A bigger tent for CAMP

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ABSTRACT

We present new high-precision geochemical and isotopic data showing that magmas related to the Central Atlantic Magmatic Province (CAMP) were emplaced at the base of the continental crust in the Ivrea Zone of northwest Italy. These results significantly extend the known footprint of one of the largest examples of a large igneous province (LIP) on the planet. The La Balma–Monte Capio (LBMC) intrusion ranges from dunitic at the base to plagioclase-bearing pyroxenitic at the top. Zircons were extracted from two samples at different levels, and dated using the chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) U-Pb method. The two weighted-mean $^{206}Pb/^{238}U$ ages at 200.5 ± 0.3 Ma and 200.1 ± 0.5 Ma indicate a short-lived magmatic system that fractionated in place. The timing of emplacement is different from that of all other mafic-ultramafic intrusions in the Ivrea Zone and is consistent with magmatism associated with the CAMP. We suggest that exposure in the Ivrea Zone provides a unique glimpse into the presently unknown character of LIP magmas at the base of the continental crust, where the emplacement of this intrusion was facilitated by its location at a lithospheric suture.

INTRODUCTION

The Ivrea Zone, a well-known section of exhumed lower continental crust in the southern Alps of Italy, was deformed and metamorphosed during the ca. 420–300 Ma Variscan orogeny, the result of collision between Laurussia and Gondwana during formation of Pangaea. Following the peak of regional metamorphism, emplacement of voluminous mafic magmas formed the 287 Ma Mafic Complex underplate (e.g., Fiorentini et al., 2018). A series of alkaline pipes intruded both the Mafic Complex and the metasedimentary host rocks from 287 Ma to 249 Ma (cf. Fiorentini et al., 2018). Reworking during the Alpine orogeny from ca. 100 Ma onward was relatively minor and mainly resulted in tilting of the entire section and subsequent exhumation along a major lithospheric boundary marked by the Insubric Line (Fig. 1A; e.g., Wolff et al., 2012).

Extending north from the Mafic Complex are mafic and ultramafic bodies that have historically been considered as attenuated intrusions emplaced in the lower to middle crust. The largest ultramafic body among these is the La Balma–Monte Capio (LBMC) intrusion (Figs. 1B and 1C). Ferrario et al. (1983) suggested that it formed by *in situ* differentiation of a high-magnesium magma emplaced coevally with the Mafic Complex (i.e., at 287 Ma). New isotopic and geochronological data presented here reveal that the LBMC intrusion represents a distinct—and until now largely unrecognized—magmatic event in the Ivrea Zone, with major implications for our understanding of the emplacement of one of the largest large igneous provinces (LIPs) in the geological record, and for the development of a significant mineralization event.

Architecture of the LBMC Intrusion

The LBMC intrusion is a tabular, steeply dipping body, ≥400 m thick and ≥3 km long, with basal dunites grading to plagioclase pyroxenites at the top (cf. Ferrario et al., 1983). Magmatic Ni-Cu-PGE (platinum group element) mineralization occurs as disseminated, blebby, and locally net-textured sulfides in horizons throughout the intrusion, in places reaching 10% in volume. The roof of the body displays meter-scale intrusive relationships with the overlying high-grade metasedimentary rocks, locally known as the Kinzigite Formation (Garuti et al., 1980). The base of the intrusion is strongly modified by southeast-vergent thrust faults in the footwall of the Insubric Line (Fig. 1C). Across this faulted footwall contact, migmatites of the Kinzigite Formation are interlayered with a belt of garnet-bearing gabbros of Permian–Carboniferous age, previously referred to as the Monte Capio sill (Klötzli et al., 2014). The original lateral extent of the LBMC intrusion is unconstrained because of faulting and younger cover.

RESULTS

Guided by the mapping and detailed studies of Ferrario et al. (1983) and Garuti et al. (1986), we systematically sampled the intrusion from its dunitic base through to the overlying pyroxenitic units (Fig. 1). Geochemical patterns are broadly consistent with the findings of Ferrario et al. (1983) and will be reported elsewhere with the details of the petrology of this sample set. Here we focus on the precise whole-rock Sr-Nd-Hf-Pb isotope signature of one dunite sample (PDR-5) and two chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) zircon U-Pb ages: those of a dunite near the base of the intrusion (sample AD-15) and of a pyroxenite near the contact with the Kinzigite Formation at the roof of the intrusion (sample PDR-12). The two analyzed dunite samples are located at the same stratigraphic level (Figs. 1B and 1C). All results, including whole-rock geochemical compositions, and analytical methods are available in the GSA Data Repository[1].

Whole-Rock Geochemical and Isotopic Data

Whole-rock MgO contents in the LBMC intrusion range from 38–43 wt% in the dunites to 17–24 wt% in the overlying, more differentiated plagioclase pyroxenites. Rare earth element (REE) patterns in dunites and pyroxenites are flat to enriched in light REEs (LREEs) (La/Sm_N ~1.4; Fig. 2A). The Sr-Nd-Hf-Pb isotope signature of the LBMC intrusion inferred from the analyzed dunite sample ($^{87}Sr/^{86}Sr$ = 0.7062, ε_{Nd} = +0.2, ε_{Hf} = +4.9, $^{206}Pb/^{204}Pb$ = 18.2; Fig. 2B) is within the isotopic range of the Mafic Complex and mineralized ultramafic pipes (Fiorentini et al., 2018).

U-Pb Geochronology

CA-ID-TIMS zircon U-Pb ages were obtained for two samples from the LBMC intrusion. While two of the six analyzed zircon grains from the pyroxenite (sample PDR-12) have Proterozoic dates and are xenocrystic, the remaining four grains yield a coherent age cluster with a weighted-mean $^{206}Pb/^{238}U$ age of 200.5 ± 0.3 Ma (N = 4, MSWD = 2.2; Fig. 2C; Table DR1 in the Data Repository). Uranium concentrations are relatively low, ~100 ppm, and correspondingly the $^{206}Pb/^{204}Pb$ ratios for every analysis are between 26 and 80; Th/U ratios are typical for

[1]GSA Data Repository item 2018306, geochemical and geochronological data and methods, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

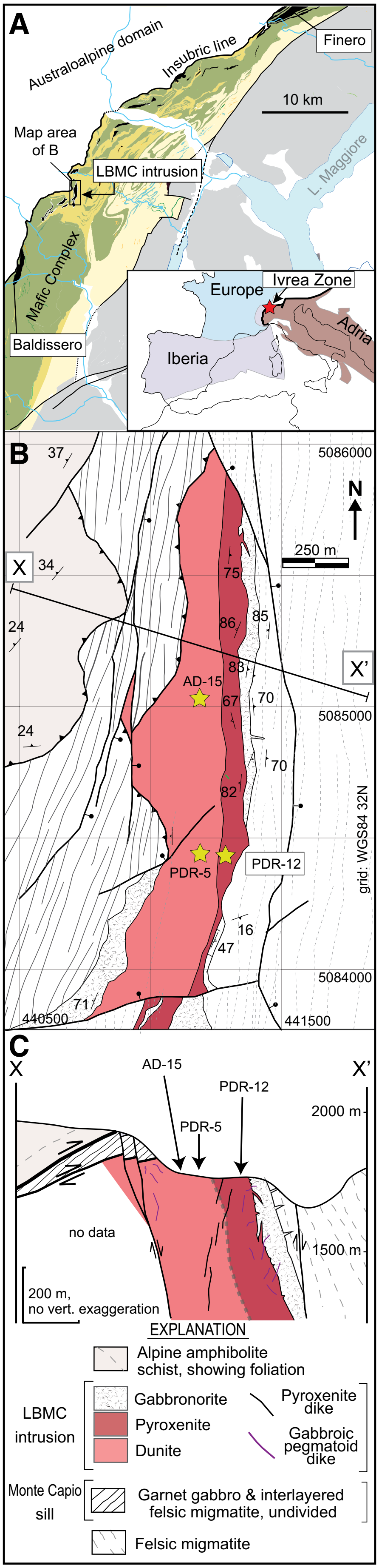

Figure 1. A: Regional geological map showing location of La Balma–Monte Capio (LBMC) intrusion, southern Alps, Italy. See text for discussion of Finero and Baldissero mantle tectonites. B: Local geological map of LBMC intrusion, with locations of dated samples (stars). Coordinates given in UTM system, zone 32N. C: Cross section through LBMC intrusion.

magmatic zircon, at ~0.4. We interpret this age as the crystallization age of the rock.

The U-Pb geochronological results for zircons from dunite AD-15 do not show evidence for any inheritance (Fig. 2C; Table DR1). While one analysis with a $^{206}Pb/^{238}U$ date of 191 Ma probably reflects Pb loss, the remaining five grains have a weighted-mean $^{206}Pb/^{238}U$ age of 200.1 ± 0.5 Ma (*N* = 5, MSWD = 0.04). Similarly to PDR-12, U concentrations in the zircons extracted from the dunite are low at ~100 ppm, Th/U ratios are ~0.3, and $^{206}Pb/^{204}Pb$ ratios are between 39 and 184. Taken together in the context of the established geological architecture of the area, these results indicate a robust 200 Ma age for the emplacement of the LBMC intrusion.

DISCUSSION

The LBMC intrusion differs from other mafic-ultramafic bodies in the Ivrea Zone in its geometry and mineralization style (Garuti et al., 1990). It is >400 m thick and mostly dunitic, compared to the <30-m-thick pyroxenitic sills in the lowermost Mafic Complex or the <300-m-wide alkaline peridotite pipes emplaced within the Mafic Complex and Kinzigite Formation. Likewise, the LBMC instrusion contains a larger amount of magmatic Ni-Cu-PGE sulfide mineralization distributed across multiple horizons (Garuti et al., 1986).

With its crystallization age of 200 Ma, the LBMC intrusion is much younger than the Mafic Complex (286.8 ± 0.4 Ma; Fiorentini et al., 2018) and alkaline pipes (as young as 249.1 ± 0.2 Ma; Locmelis et al., 2016). $^{40}Ar/^{39}Ar$ hornblende cooling ages near 200 Ma are known from the country rocks of the LBMC intrusion (Siegesmund et al., 2008), however most published $^{40}Ar/^{39}Ar$ ages are older. Diorite dikes associated with the Baldissero mantle tectonite located ~180 km southwest of the LBMC intrusion (Fig. 1A) record ca. 200 Ma Sm-Nd isochron ages (Mazzucchelli et al., 2010), and some zircons within chromitites of the Finero mantle tectonite (Fig. 1A) have yielded sensitive high-resolution ion microprobe (SHRIMP) U-Pb dates of ca. 200 Ma (Zanetti et al., 2016; Grieco et al., 2001). Syenitic pegmatites hosted within the Finero chromitites also contain ca. 200 Ma zircon megacrysts, although CA-ID-TIMS dating of megacryst fragments revealed a protracted crystallization history primarily related to mantle metasomatism (up to 20 Ma; Schaltegger et al., 2015). Therefore, the high-precision zircon U-Pb ages from the LBMC intrusion reported here represent the first unequivocal evidence for significant, short-lived 200 Ma mafic magmatism in the Ivrea Zone.

This 200 Ma age signal is distinct from the age of emplacement of the 287 Ma Mafic Complex and 287–249 Ma ultramafic pipes, as well

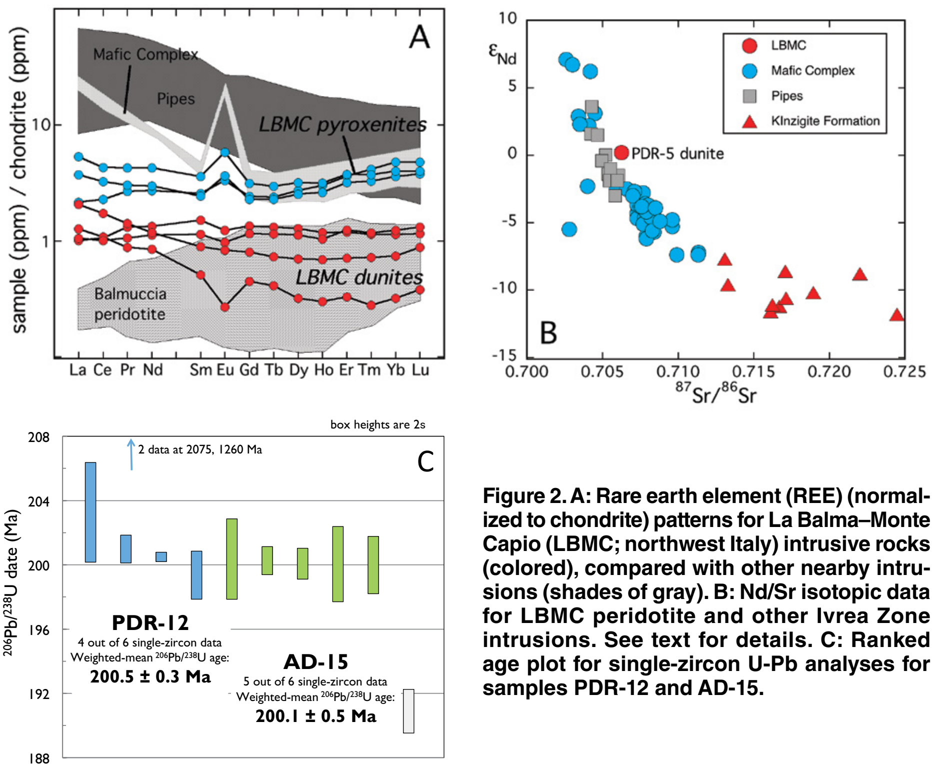

Figure 2. A: Rare earth element (REE) (normalized to chondrite) patterns for La Balma–Monte Capio (LBMC; northwest Italy) intrusive rocks (colored), compared with other nearby intrusions (shades of gray). B: Nd/Sr isotopic data for LBMC peridotite and other Ivrea Zone intrusions. See text for details. C: Ranked age plot for single-zircon U-Pb analyses for samples PDR-12 and AD-15.

as from that of the ca. 170–160 Ma emplacement of mafic intrusions in the western and central Alps associated with opening of the Tethyan Ocean (Li et al., 2013; Kaczmarek et al., 2008; Schaltegger et al., 2002). The LBMC intrusion was emplaced near the southern margin of the European plate during a period of protracted extension (ca. 245–165 Ma) that became progressively focused into discrete continental rift zones, resulting in the separation of the Adriatic microplate and opening of the Alpine Tethys (Schettino and Turco, 2011). As reviewed by Ewing et al. (2015) and Zanetti et al. (2013), mineral chronometers were reset or overprinted via recrystallization over a relatively broad age range, recording the effects of a multistage tectonic history. The magmatic ages presented here, however, record a discrete, short-lived and previously unknown period of mafic-ultramafic magmatism within a more protracted period of pre-Alpine Tethyan rifting.

We hypothesize that the 200 Ma mafic-ultramafic magmatism in the Ivrea Zone may represent a distal and deep expression of the Central Atlantic Magmatic Province (CAMP), which is related to the opening of the central Atlantic Ocean and thus the breakup of Pangaea (e.g., Ruiz-Martínez et al., 2012). The CAMP is one of the largest LIPs, with an areal extent of at least 10^7 km^2, and was formed rapidly from 202 to 198 Ma (e.g., Marzoli et al., 2018). Intense volcanic activity associated with the CAMP was coeval with—and likely caused—the catastrophic end-Triassic mass extinction (Schoene et al., 2010). The driver for CAMP magmatism may be a mantle plume (e.g., Wilson, 1997), though thermal anomalies inducing mantle melting in the absence of any deeper mantle source have also been proposed (e.g., McHone, 2000). The flat to LREE-enriched geochemical pattern, with the Sr-Nd-Hf-Pb isotopic signatures, indicate mixing between a mantle-derived source and a crustal component with the composition of the Kinzigite Formation (Fiorentini et al., 2018). The isotopic signature at this age would be dominated by the crustal component; the LBMC intrusion has values that are broadly similar to those of the other (older) mafic-ultramafic intrusions in the Ivrea Zone (Fiorentini et al., 2018).

The currently defined northeastern boundary of CAMP magmatism (Fig. 3; cf. Marzoli et al., 2018) extends to the Iberian Peninsula, France, and Sicily (Cirrincione et al., 2014). Inclusion of the LBMC intrusion with the CAMP event would increase its known areal extent by thousands of square kilometers. Given the unique lower crustal exposures in the Ivrea Zone, it represents a rare opportunity to examine the style of emplacement of LIP-related magmas at the base of the continental crust. Although LIPs are generally thought to be linked to their mantle source by a network of dikes and sills (e.g., Ernst and Bleeker, 2010), exposures of the feeder system of continental LIPs are usually limited to the upper few kilometers of their vertical extent. Therefore, the LBMC intrusion may preserve a record of deep crustal magma storage and fractionation that is widely inferred but rarely exposed.

At the time of emplacement of the LBMC intrusion, the physical and chemical structure of the crust in the Ivrea Zone had been strongly modified by emplacement of the Mafic Complex >80 Ma earlier. The process of magmatic underplating in the Ivrea Zone (e.g., Quick et al., 2009) has been compared to layering and densification of lower continental crust in other extensional terranes, such as the central Basin and Range province (western North America) (Rutter et al., 1993), yet the long-term effects of these physical changes on crustal evolution and the effects on later magmatic episodes are poorly known. The LBMC intrusion seems to have exploited the transition in the lower crust where the Permian underplate (i.e., the Mafic Complex) is in contact with metasedimentary host rocks (i.e., the Kinzigite Formation). Studies of the structural position of the LBMC intrusion with respect to such petrological and rheological boundaries may yield insight into mechanisms of magma ascent and arrest in the lower crust.

The proposed temporal and genetic link between 200 Ma magmatism in the Ivrea Zone and the CAMP is supported by the position of the Ivrea Zone near a major lithospheric suture, the Insubric Line, which separates the European and Adria plates. Emplacement of mantle-derived magmas is commonly localized along lithospheric boundaries (Gorczyk et al., 2017), as is the occurrence of magmatic Ni-Cu-PGE mineralization (Begg et al., 2010), preferentially in areas where previous sulfur and metal enrichment of the lower continental crust may enhance localized sulfide saturation in ascending mantle-derived magmas (Fiorentini et al., 2018). The crustal suture represented by the Insubric Line may have created pathways that promoted migration of CAMP-related magma with associated Ni-Cu-PGE ores into the crust along the lithospheric boundary (Insubric Line). Trans-lithospheric structures may be critical for magma ascent at the margins of LIP systems, where melt production and migration may be weaker than at their cores.

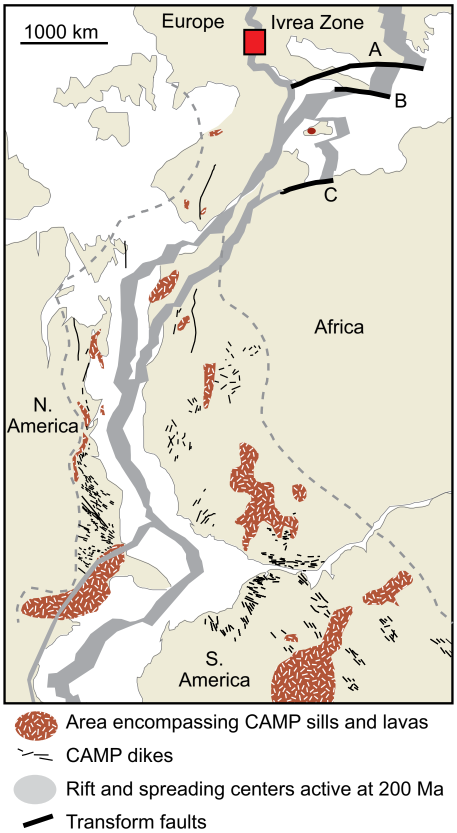

Figure 3. Reconstruction at ca. 200 Ma, with extent of intrusive and extrusive rocks of Central Atlantic Magmatic Province (CAMP) large igneous province (LIP). Star denotes location of La Balma–Monte Capio (LBMC) intrusion. A—Apulian-Iberian transcurrent structure; B—Malta escarpment; C—Gafsa fault.

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