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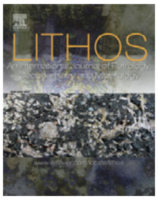

Anatomy of the Cretaceous Hobenzan pluton, SW Japan: Internal structure of a small zoned pluton, and its genesis

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ABSTRACT

Field, petrographic, geochemical, and K–Ar and U–Pb age data were used to elucidate the internal structure of the Cretaceous Hobenzan pluton, SW Japan, and the processes which generated that structure. The pluton is elongated E–W with dimensions of about 6.5 × 2.0 km (13 km^2), and was emplaced at ~95 Ma as a pluton in accretionary complexes. The pluton contains an early tonalite, but most of the body consists of later granitoids that show a continuous differentiation series from biotite–hornblende granodiorite (GD) to hornblende–biotite granite (HBG) and biotite granite (BG). The contacts between the GD and HBG are gradational. The pluton provides an exceptional cross-sectional view of a simple cooling magma body. The GD shows no vertical variations in modal and chemical compositions, whereas the HBG displays differentiation from the lowermost exposure to the top of the pluton. Initial Sr isotope ratios (SrI) in the HBG increase from the lower part to the top of the pluton. The granitoids show continuous compositional variations from 65 to 79 wt.% SiO$_2$ (anhydrous basis), and magmatic differentiation was dominantly controlled by crystal fractionation of hornblende and plagioclase. Field, elemental and Sr–Nd isotope data are consistent with limited operation of assimilation with pelitic rocks and fractional crystallization (AFC), in which assimilation increased with higher degrees of differentiation.

The Hobenzan pluton retains a history of granitoid magma evolution in a subvolcanic magma reservoir. The GD formed as a rigid sponge, and melt fraction increases inwards from the walls, forming the HBG mush by fractional crystallization, coupled with small degrees of assimilation of adjacent schists. A more evolved and enriched low-density melt segregated from the mushy cumulate of the HBG by incomplete crystal–melt separation, and moved upwards with the assistance of gas-driven filter pressing, as indicated by the presence of miarolitic cavities, thus forming the BG at the roof of the pluton.

1. Introduction

The processes by which plutons are constructed and the timescales over which these processes operate have fundamental implications for the link between volcanism and plutonism (e.g., Lipman, 2007; Macdonald et al., 2014), and ultimately for our understanding of the growth and evolution of the Earth's crust (e.g., Annen, 2011; Bachl et al., 2001; Menand et al., 2011). The building of plutons involves the generation, segregation, ascent, and emplacement of melts in the crust (Petford et al., 2000). These processes are accompanied by fractional crystallization, assimilation of wall rocks, crystal–melt separation, and magma mixing, as well as recharge and drainage of magmas by volcanic eruptions. Plutons are now recognized as growing incrementally, by the accretion of successive and relatively small magma pulses, over variable periods of time, from hundreds to millions of years, depending on geodynamic setting and source fertility (e.g., Annen, 2011; Davis et al., 2012; de Saint-Blanquat et al., 2001, 2006, 2011; Glazner et al., 2004; Horsman et al., 2010; Imaoka et al., 2012; Mahan et al., 2003; Matzel et al., 2006; McNulty et al., 1996, 2000; Menand et al., 2011; Miller and Paterson, 2001; Miller et al., 2007, 2011; Tappa et al., 2011; Walker et al., 2007; Wiebe and Collins, 1998).

Compositional zoning of plutons is common, but our understanding of the origin of such structure is incomplete. Zoning can be recognized

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as systematic changes in mode, whole-rock major and trace element chemistry, and often in isotopic ratios. In most documented cases, the most differentiated magma is inferred to occur at the top of the system, forming as a gravitationally stable low-density layer, or at the center of the system (e.g., De Silva and Wolff, 1995; Wolff et al., 1990). Zoning is most common in intermediate to silicic magma systems. A wide spectrum of zonation styles exists, but smaller-volume systems appear to show more extreme zoning than larger-volume systems (e.g., De Silva and Wolff, 1995; Hildreth, 1981). Numerous studies have examined zoned plutons, but most have been limited to two-dimensional horizontal views of internal structures. Many of the processes thought to be important in pluton construction should yield clearer records in the vertical plane rather than in the horizontal. Gravitational processes and consolidation strongly influence the internal evolution of plutons, and vertical sections would thus be most informative (e.g., Bachl et al., 2001; Barnes et al., 1986; Dilles, 1987; Duebendorfer et al., 1998; Haeussler and Paterson, 1993; John, 1988; Kamiyama et al., 2007; Metcalf et al., 1995; Miller and Miller, 2002; Rosenberg et al., 1995; Takahashi, 1986; Verplanck et al., 1999; Wiebe, 1994), although the exposure expressing detailed vertical structure is limited. Pluton zonation may arise through in situ magmatic processes by cooling from a single magma reservoir (see De Silva and Wolff, 1995), or by successive emplacement of magma batches of contrasting genesis reflecting deep, source-related processes before emplacement (e.g., Barbey et al., 2001; Bindeman and Valley, 2003; Clemens et al., 2009a, 2009b; Tappa et al., 2011) by the vertical stacking or lateral juxtaposition of individual magma pulses.

U–Pb geochronologic data for the 1200 km^2 Tuolumne Intrusive Suite, one of several large-volume zoned intrusive suite emplaced in the Sierra Nevada (Bateman, 1992), indicate that the Suite was assembled over a period of at least 10 m.y. between 95 and 85 Ma (Coleman et al., 2004; Glazner et al., 2004). Although identification of single magmatic pulses may be difficult (Horsman et al., 2010), the question of whether plutons cooled from a single batch of magma or accumulated incrementally is important for evaluating plutonic–volcanic connections, and petrologic evolution including models for intrusion. Therefore, zoned plutons should be reconsidered (Coleman et al., 2004; Glazner et al., 2004), and it is critical to identify single plutonic units (Leuthold et al., 2014).

Cretaceous to Paleogene granitoids are extensively distributed in the Inner Zone of SW Japan (Fig. 1a). One of these, the Cretaceous Hobenzan pluton is a small (i.e., tens of cubic kilometers) zoned pluton, and provides excellent three-dimensional exposure. A ca. 500 m section below the roof exposes a shallow pluton with distinct petrographic and geochemical 3-D zoning. Hobenzan thus provides an excellent opportunity to investigate the internal anatomy of plutons, and hence assesses the history of emplacement, filling, and solidification, as well as the processes responsible for the zoning, including fractional crystallization, assimilation, and crystal–melt separation. This paper addresses the 3-D geometry and construction of the Hobenzan pluton based on field, petrographic, geochemical, and K–Ar, Rb–Sr and U–Pb age data.

In this paper, the term "magma chamber" is used to define a discrete region beneath the Earth's surface in which mobile (and eruptible) magma (crystal fraction <50%) is stored. We also refer to a "magma reservoir", meaning a reservoir encompassing the entire liquid-bearing region within a magmatic system, including crystal mush (rigid or semi-rigid magma composed of a framework of touching crystals and interstitial liquid) which acts mostly as a "rigid sponge" (rheologically solid, melt-poor, cf. Hildreth, 2004), following earlier definitions by Miller and Wark (2008) and Bachmann and Berzantz (2008a).

2. Geological setting

2.1. Basement rocks

The basement in the study area comprises the Lower Carboniferous–Upper Permian Ota Group, Suo metamorphic rocks, Cretaceous volcanic rocks, and some dikes (Fig. 1b). The Ota Group, distributed around the northwestern part of the pluton, is an accretionary complex consisting

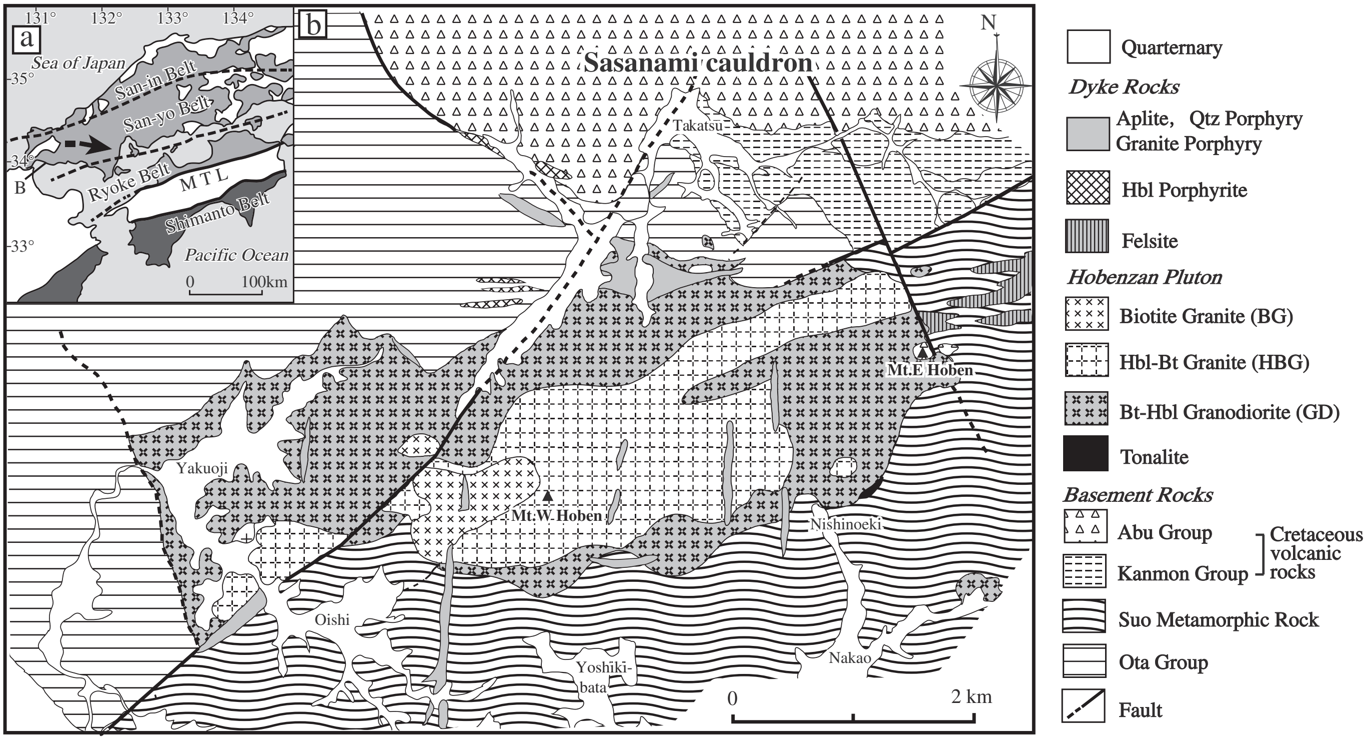

Fig. 1. (a) Map showing distribution of Cretaceous and Paleogene igneous rocks in the Inner Zone and the Shimanto Belt of the Outer Zone of Southwest Japan, and the location of the Hobenzan pluton; modified after the 1:1,000,000 geologic map of Japan, 3rd ed. (Geological Survey of Japan, 1992). MTL = Median Tectonic Line. (b) Geological map of the Cretaceous Hobenzan pluton, Yamaguchi Prefecture, SW Japan (partly modified after Nakashima et al., 1984).