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# Observations from the floor of a granitoid pluton: Inferences on the driving force of final emplacement

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## ABSTRACT

**An east-west profile across the tilted Bergell pluton exposes a 10-km-thick interval in terms of crustal depth. Consequently, the floor as well as the root and "side" of the main intrusive body of the pluton crop out at the surface and a tentative three-dimensional geometry is constructed. At the highest crustal level, the geometry and deformation features at the margin of the pluton indicate ballooning, whereas the folded floor of the main intrusive body indicates synmagmatic shortening related to regional deformation. These contrasting features are best explained by shortening of the base of the pluton which caused an expansion at a higher crustal level. Final emplacement of the pluton into higher crustal levels was, therefore, not driven primarily by buoyancy, but rather by regional deformation within deeper levels of the crust.**

## INTRODUCTION

Geologists have inferred the ascent mechanisms of granitic melts through the continental crust mainly from the observation and reconstruction of the present geometry of plutons. However, little is known about the three-dimensional shape of intrusions (Vigneresse, 1990; Pitcher, 1992). Furthermore, the present shape of a pluton may not reflect the shape of the magma body at the time it ascended through the crust. This has led many earth scientists to make a distinction between the ascent and final emplacement of silicic magmas (Leake, 1978; Bateman, 1984; Clemens and Mawer, 1992; Petford et al., 1993), and the shapes of many plutons, which were classically interpreted as diapirs, have been reinterpreted as resulting from ballooning during final emplacement (Petford et al., 1993).

Cruden's (1990) modeling work suggests that many of the strain features usually considered as diagnostic of ballooning can be produced by mere diapiric ascent without any radial expansion. Moreover, field-related studies have given rise to a reevaluation of the importance of ballooning as a final emplacement mechanism (Paterson and Fowler, 1993). The main concern of these works is the geometric evolution of plutons during final emplacement. The principal aim of this study is to constrain the force driving forceful intrusions during final emplacement. Most of the literature has taken for granted that buoyancy is the only driving force for ballooning (Martin, 1953; Akaad, 1956; Bateman, 1984; Courrioux, 1987; Ramsay, 1989). Some authors (Brun and Pons, 1981; Hutton, 1988; Guineberteau et al., 1987; Brun et al., 1990) have also considered the effect of regional deformation on ballooning, but only as an independent factor, interacting and overprinting the gravity-driven ballooning process. Only Castro (1987) suggested that regional deformation is a necessary condition for the development of ballooning.

Knowledge of the three-dimensional shape of a pluton helps to constrain modeling of the final emplacement mechanism in terms of its driving force. However, for the overwhelming majority of granitoid plutons, the map pattern unfortunately only reveals a subhorizontal section through the body at any particular depth in the Earth's crust. Furthermore, seismic and gravity methods can rarely give a precise reconstruction of the roots and/or the floors of plutons (Pitcher, 1992). The Bergell intrusion offers at least a 10-km-depth crustal profile along an east-west traverse (Trommsdorff and Nievergelt, 1983). This reconstruction provides a rare opportunity to observe the floor of a pluton and the three-dimensional geometry of the body as a whole. It shows that the upper parts of the pluton were affected by ballooning, whereas the floor was folded during regional deformation. In the following section we show that this apparent contradiction can provide an alternative emplacement model.

## GEOLOGIC SETTING

The Bergell pluton is a late Alpine intrusion located in the Central Alps (southern Switzerland and northern Italy; Fig. 1). Purely geometrically speaking, it is a nappe (Wenk, 1973), with a steep root zone in the south and a larger, flat-lying, compositionally zoned body in the north. The root zone is an east-west–striking, steeply north dipping tabular body of tonalite, parallel to the Insubric mylonitic belt (Figs. 1 and 2). Dextral transpression along this lineament caused back thrusting of the Pennine nappes over the Austroalpine and Southern Alpine nappes, associated with east-directed escape of the Central Alps (Schmid et al., 1989).

The main body of the pluton intruded rocks of different metamorphic grade. At the western contact, the country rocks were at upper amphibolite to granulite facies conditions at the time of intrusion. However, at the eastern margin, regional metamorphism at the time of intrusion was only at greenschist facies conditions, and it is overprinted by contact effects from the Bergell pluton. The increase in metamorphic grade of the country rocks toward the west is associated with an increase in the depth of crystallization of the Bergell pluton: Reusser (1987) showed that the pressure of crystallization gradually increases from 5 kbar at the eastern margin to ~7.5 kbar at the westernmost part of the tonalite tail, suggesting

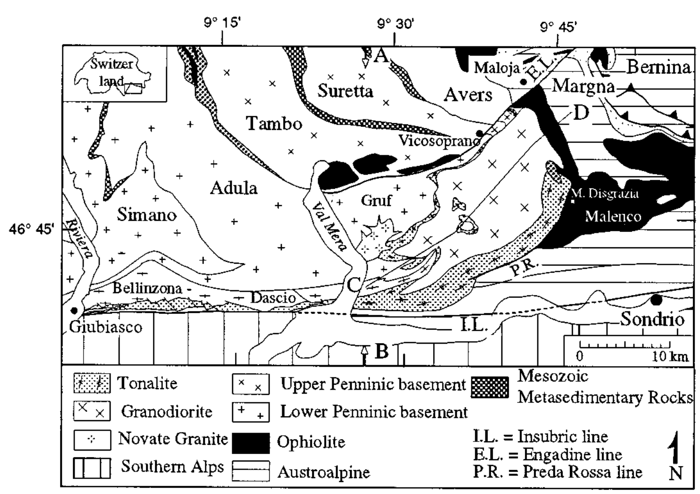


**Figure 1. Geologic map of Bergell area. Profile traces A-B and C-D refer to Figures 2 and 3.**

**Data Repository item 9523 contains additional material related to this article.**

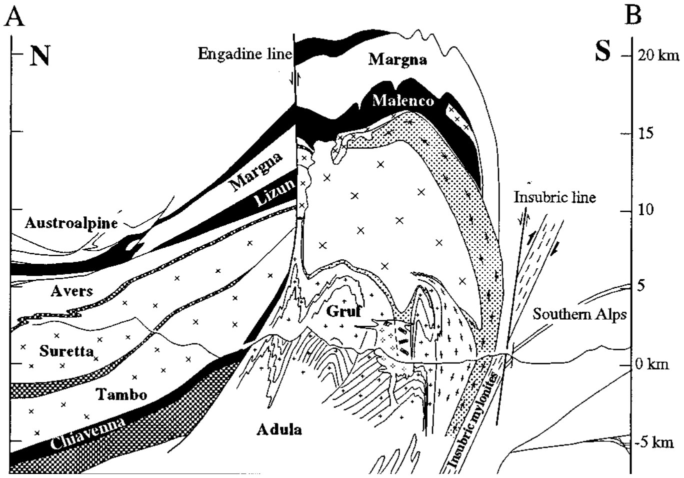


**Figure 2. North-south cross section through Bergell pluton. See Figure 1 for legend.**

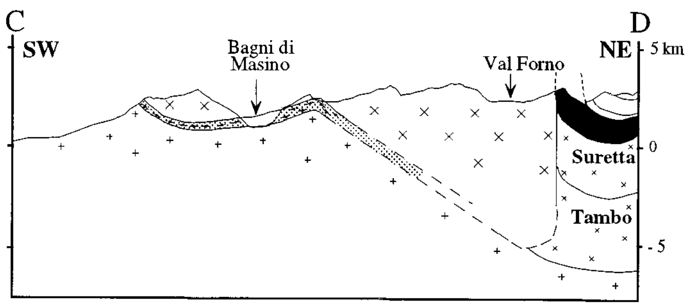


**Figure 3. East-west cross section through Bergell pluton. See Figure 1 for legend.**

postintrusive tilting of the pluton. This confirms the interpretation of Trommsdorff and Nievergelt (1983), based on geological arguments, that an east-west profile through the Bergell pluton is 10 km in crustal depth. The northernmost part of the pluton, which connects the structurally lower intrusive level of the western contact with the structurally higher eastern contact, is discordant and cuts across the Tambo and Suretta nappes (Figs. 1 and 2). The above-mentioned tilting, together with the general east dip of the nappes, provides the constraints for the construction of the east-west and north-south cross sections through the pluton (Figs. 2 and 3). For a comprehensive description of the data and projection methods underlying the profile construction, see Schmid et al. (1995) and Appendix A[1].

## GEOMETRY

The east-west change in structural level, as documented by the barometry data (Reusser, 1987), is also shown by the different geometry of the western and eastern contacts of the pluton (Figs. 2, 3, and 4). The western margin represents the floor of the pluton, whereas the eastern margin is subvertical and corresponds to the side.

### Floor of the Pluton

The floor of the pluton is exposed along its western margin and in an erosional window near the middle of the intrusion (Fig. 1). In these areas the intrusive rocks have a foliation parallel to the contact

[1]GSA Data Repository item 9523, Appendix A: Construction of profile C-D, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

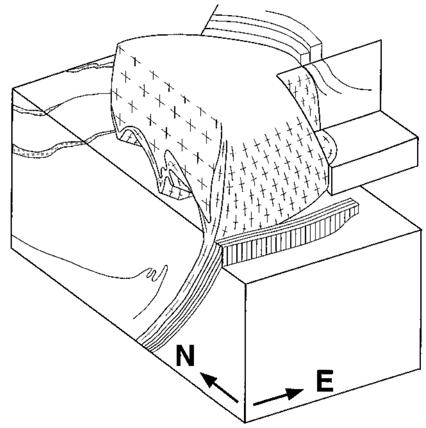


**Figure 4. Block diagram of Bergell pluton (modified from Froitzheim et al., 1994).**

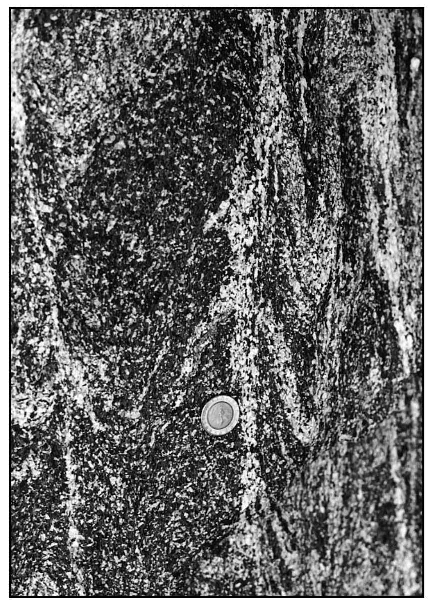

**Figure 5. Folded tonalite with tonalitic veins intruded parallel to axial plane of folds.**

and to the foliation in the underlying country rocks. The western contact dips ~40°E then flattens to subhorizontal in the erosional window (Fig. 3). Consequently, the inward-dipping foliations of the western margin of the main intrusive body do not reflect a funnel geometry, with gradual steepening of the contact at depth, but rather a basin, progressively flattening toward the bottom (Fig. 3). These considerations strongly support the idea that the feeder of the pluton is not hidden underneath the main intrusive body but is represented by the tonalite tail, oriented parallel to the Insubric line.

A major feature of the pluton's floor is that it is folded concordantly with the enclosing rocks over its entire contact length. The folds can be observed at map scale (Fig. 1) as well as on the outcrop (Figs. 5 and 6) and thin-section scale. They have variably plunging axes (east plunging along the western margin and west plunging in the window) and east-west–striking, nearly vertical axial planes (Fig. 2), implying north-south shortening. They are generally tighter toward the south, where they become strongly isoclinal.

### Side of the Intrusion

In contrast to the western and southern part of the Bergell pluton, the eastern border has discordant intrusive contacts, overprinted by a foliation that extends parallel to the pluton margin (Drescher-Kaden and Storz, 1926). Gently east dipping structures in the enclosing rocks steepen abruptly in proximity to the pluton's border, forming an asymmetric synform (Fig. 3). The axial trace of this synform is parallel to the intrusive contact (Spillmann, 1993). The presence of this synform is restricted to the contact of the

Figure 6. Base of Bergell pluton (western contact). Bergell tonalite lies concordantly on top of migmatitic gneisses and contact is folded. Field of view is 130 cm wide.

pluton, and its axial plane is parallel to the pluton margin. Therefore, Spillmann (1993) suggested that this structure formed in response to the emplacement of the Bergell pluton. Increasing aspect ratios of mafic enclaves toward the intrusion's contact show that a strain gradient is present from the internal part of the main intrusive body toward its margin. Deformation extends into the enclosing rocks, as indicated by the folding of granitoid dikes from the intrusion. The axial plane of these folds is parallel to the contact and to the main foliation in the contact aureole.

Features similar to those described above are commonly cited in the literature on "ballooning plutons" (see Pitcher, 1992, for review). In fact, previous work on the eastern margin of the Bergell linked deformation along the eastern contact to ballooning, generated by the intrusion of the granodiorite into the core of the main body (Conforto-Galli et al., 1988; Spillmann, 1993).

Paterson and Tobisch (1988) pointed out that some features typical of deformation surrounding such a pluton may not be due to the expansion of the pluton, but rather to postemplacement regional deformation. In the case of the eastern contact of the Bergell, deformation must be attributed to the forceful intrusion of the partially molten pluton for the following reasons. (1) The east-west strike of the youngest regional structures (e.g., east-west–striking axial planes of the folds; Spillmann, 1993) in this area indicates a north-south shortening direction, incompatible with the north-south–oriented foliation of the eastern Bergell margin. (2) North-south–oriented structures, as found along the eastern Bergell margin, have not been observed anywhere else in this area. Therefore, they cannot be correlated with any known phase of regional deformation. (3) A transition from magmatic to high-temperature deformation (see below) can be observed, although alpine regional metamorphism only reached greenschist facies conditions.

### Root Zone

The tail of the pluton (the southwestern extension of the tonalite) is an east-west–striking, steeply north dipping (60°–80°), ~1-km-thick tabular body of tonalite. Foliation in the tonalite is parallel to the contact and to that in the Insubric mylonite belt. Hornblende barometry (Reusser, 1987) indicates that the western end of this tail represents the deepest part of the pluton. Seismic data show that steeply north dipping reflectors, probably correlating with the Insubric mylonite belt and tonalite tail, extend to a depth of 20 km (Holliger and Kissling, 1991). The steep attitude of hornblende lineations in the northern part of the dike, where magmatic fabrics are still discernable, rules out the possibility that the tail of the pluton was formed by dextral shearing of a preexisting main intrusive body along the Insubric line.

Therefore, the continuation of the western Bergell at depth is likely to maintain a subvertical orientation. Consequently, this part of the pluton can be considered to represent the feeder of the main intrusive body. However, the present-day shape of the feeder is not necessarily identical with the primary geometry of the melt as it intruded the crust. In order to create space for the melt in a compressive environment, tensile and/or dilatant shear fractures (Clemens and Mawer, 1992; Davidson et al., 1994) that gave rise to dikes may have developed. These initial dikes probably developed at some angle to the present orientation of the feeder. Subsequent synmagmatic deformation along the Insubric line may have produced the interconnection of the dikes, which became reoriented subparallel to the shear-zone boundary, thus acquiring the present-day shape. Both the brittle deformation leading to the formation of the initial dikes and the synmagmatic "ductile" deformation of the dikes contribute to the ascent of the melt.

## TIMING OF THE DEFORMATION

### Folding of the Pluton Floor

All along the western contact, microstructures indicate a good shape preferred orientation of hornblende, plagioclase, and biotite, without internal crystal plastic deformation of the individual grains. These fabrics suggest that the foliation in the tonalite developed during the magmatic stage (Paterson et al., 1989). Close to the intrusive contact, this magmatic foliation is folded. The microstructures of these folds show that the limbs, as well as the hinge region of the folded layers, preserve a fully magmatic fabric, with no overprint of solid-state deformation. Thus, we infer that folding was also synmagmatic. This interpretation is supported by other observations. Some folds in the tonalite show slightly more differentiated tonalitic veins, injected parallel to the axial planes (Fig. 5). Calc-silicate layers in the limb of a fold have formed boudinage structures in the tonalitic matrix, which shows no evidence of solid-state deformation.

Axial planes and fold hinges of synmagmatic folds are parallel to those in the country rocks (Fig. 6). These folds can be traced for several kilometres from the pluton and formed in response to a major late Alpine deformation phase recorded in the southernmost Penninic units (backfolding of the nappe pile, related to movements along the Insubric line). Thus, we infer that the regional north-south shortening that folded the base of the intrusion acted during the magmatic stage of the Bergell intrusion.

### Deformation Along the Eastern Contact

Deformation along the eastern margin of the pluton produced a foliation in the intrusive rocks parallel to the contact. Although solid-state deformation is always present, a magmatic foliation can be recognized locally.

Dynamic recrystallization of plagioclase and the stable magmatic mineral assemblage of the tonalite indicate that solid-state deformation took place under high-temperature conditions (amphibolite facies). Because regional metamorphism at the time of the intrusion was at greenschist facies conditions at the eastern contact, this high-temperature deformation must be related directly to the emplacement of the Bergell pluton. Contact-metamorphic minerals in the enclosing rocks (e.g., andradite) grew in pressure shadows of porphyroclasts, indicating that deformation was synchronous with contact metamorphism. These observations indicate that deformation along the eastern margin of the pluton was synmagmatic.

### Deformation of the Root Zone

At the northern contact of the root zone, solid-state deformation is only weakly developed and microstructures show a magmatic shape preferred orientation, including a foliation as well as a lineation, that parallel those in the country rocks and the contact of the pluton. The preserved east-west–striking magmatic foliation parallel to the contact of the tonalite tail indicates that the east-west elongation of the root zone is a primary feature that does not result from the deformation of a bloblike pluton. Country rocks north of the tonalite tail are high-grade mylonites with an east-west–striking, steeply north dipping foliation and downdip stretching lineations. Kinematic indicators give top-to-the-south shear sense (northern block up). This movement corresponds to back thrusting of the Central Alps along the Insubric line. Because the magmatic foliation and lineation are parallel to the mylonitic foliation and lineation, the initial stages of back thrusting were synmagmatic. Therefore, we infer that the tonalite was intruded along the Insubric line during back thrusting of the Central Alps, which occurred in an overall transpressive regime according to Schmid et al. (1989).

## DISCUSSION AND CONCLUSIONS

The Insubric line controlled the ascent of the magma. Therefore, the rather concentric shape of the main body of the intrusion results only from final emplacement processes.

Many features of the upper part of the Bergell intrusion are typically found in ballooning plutons: i.e., circular to elliptical shape, foliation trajectories parallel to the pluton contact, strain increase toward the contact, deflection of foliation trajectories and contacts in the enclosing rocks, concentric zonation (although incomplete), and synkinematic growth of contact-metamorphic minerals. In contrast, most of the features present at the base of the pluton do not correspond to any ballooning model, but rather to a contact folded in the magmatic stage during regional deformation.

The synmagmatic character of folding of the base and ballooning at the side of the intrusion suggests coeval shortening at depth and expansion at higher structural levels in the crust. Such a process is best explained by a "vertical escape" of the crystal mush, which was being squeezed at the bottom. Because the viscosity and density of the granitoid melt are lower than that of the enclosing rocks, shortening will cause preferential escape of the melt upward, where ballooning is observed. Therefore, ballooning of the upper part of the pluton was not caused solely by buoyancy forces, but rather was induced by regional deformation affecting a deeper structural level of the pluton.

The development of an emplacement model based on the study of this particular pluton does not allow us to generalize this model to other plutons. However, the Bergell is, to our knowledge, the only documented pluton emplaced by a process of forceful emplacement, whose floor can also be observed at the same time. That this floor shows regional synmagmatic shortening suggests that other ballooning plutons might also be tectonically squeezed at their bottoms, although the outcrop conditions only show a "posttectonic slice" of the pluton.

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