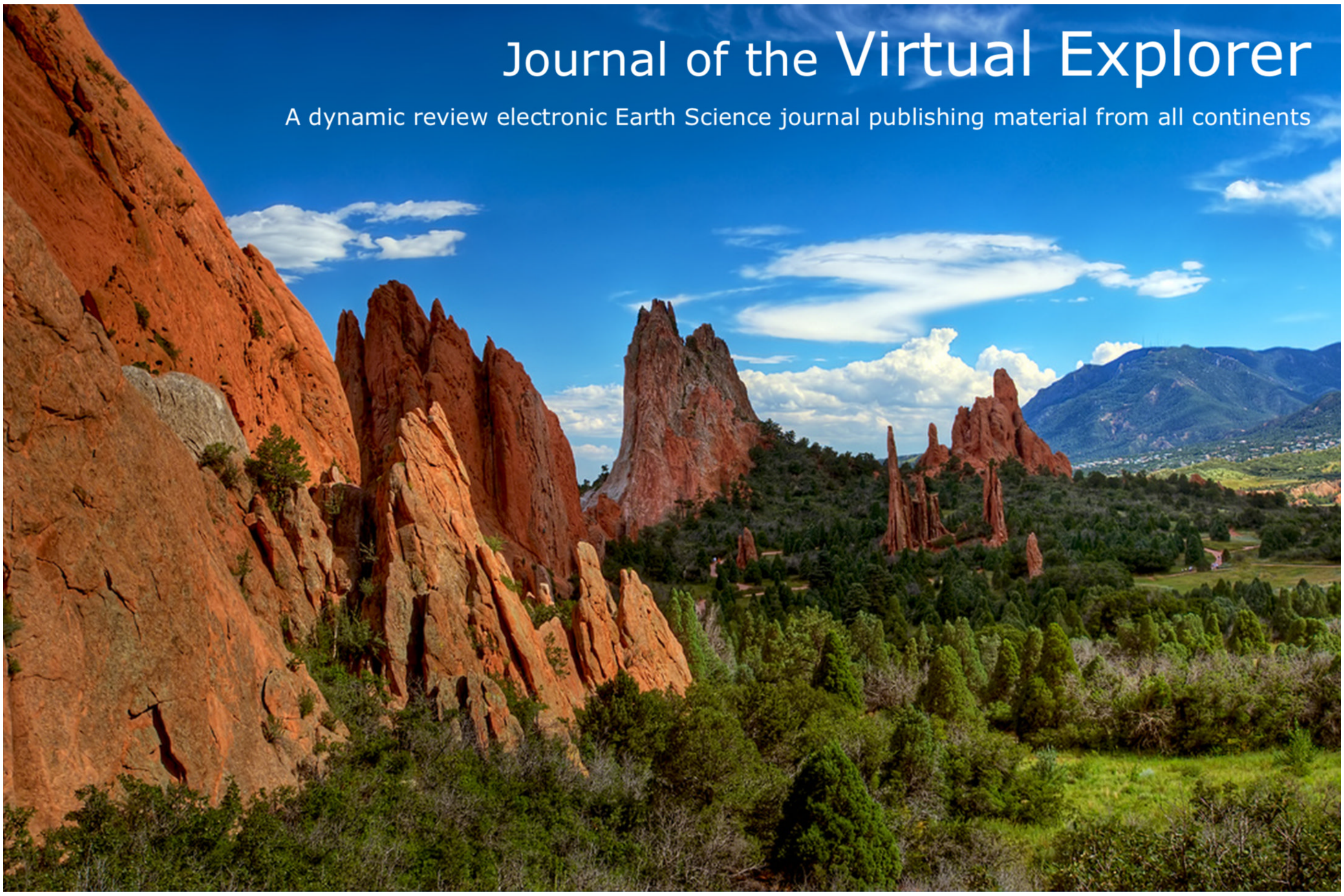

Field Trip to the Base of the Bega Batholith - An Overview

Simon W. Richards, William J. Collins, R.A. Weibe, B. Healy

Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume **26**, paper 1
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Abstract: On this trip we will be examining granite plutons, layered mafic complexes and related country rocks. Why? Hopefully to generate an understanding of granites, which, in turn will help us to decipher the tectonic regime of the region (SE LFB) during their emplacement. Granite plutons and their associated rocks should be viewed as tectonic indicators, just like faults and folds. However, when studied in conjunction with often intensively studied faults and folds and with accurate dating, plutons (including their geochemistry and internal structure) provide a very powerful tool indeed.

These rocks are slightly younger (~422 Ma) than those at Cooma (~435 Ma), which lie approximately 70 km to west. At Cooma we viewed some classic metamorphic rocks with well-developed structures and obvious migmatitic leucosomes. In contrast, the structures and rocktypes observed on this trip are unusual. The granite is a classic granodiorite but the migmatites are schlieren migmatites and are quite distinct from the classic layered migmatites (which are metatexites) which are common in high-temperature metamorphic complexes around the world. The migmatites in the Wog Wog River are diatexites: they have lost all their original structure (be it bedding or a tectonic layering) and therefore resemble sedimentary breccias. Hornfelsic xenoliths (mm-m-size) are suspended in a fine-grained, typically foliated leucosome matrix.

On this trip we will be principally examining, discussing and evaluating geological processes. These include the origin of microgranitoid (or microgranular) enclaves, the significance of granitic textures, magmatic versus solid-state deformation (*e.g.*, Paterson *et al.*, 1989), stratigraphy and sedimentary-type structures in plutons, granite emplacement mechanisms (*e.g.* Paterson & Vernon, 1995),

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Aims of the Field Trip

1) To describe and evaluate the interplay of structural, metamorphic and magmatic processes that operate at the base of granitic plutons.

2) To determine the role of the Wog Wog Mafic Complex (WWMC) in the structural, metamorphic and magmatic development of the Kameruka Suite; the orogin of mafic enclaves in the Kameruka pluton and to examine some of the causes of chemical diversity within the Kameruka pluton.

3) Examine depositional systems in plutons as a guide to construction mechanisms.

4) Examine way-up structures in plutons, particularly load casts and flame structures.

5) Review magmatic foliations developed by compaction or magmatic flow.

6) View in-situ magma mixing and mingling processes.

7) Delineate stratigraphic zonation in plutons.

Modified Program

Day 1 – Drive from Canberra, to the Towamba River (~3hrs if all goes according to plan) where we can walk along a felsic (microgranite) dyke that terminates as a diffuse, sub-horizontal layer within the magma chamber. The dyke is representative of many dykes in the pluton and is interpreted as a feeder dyke.

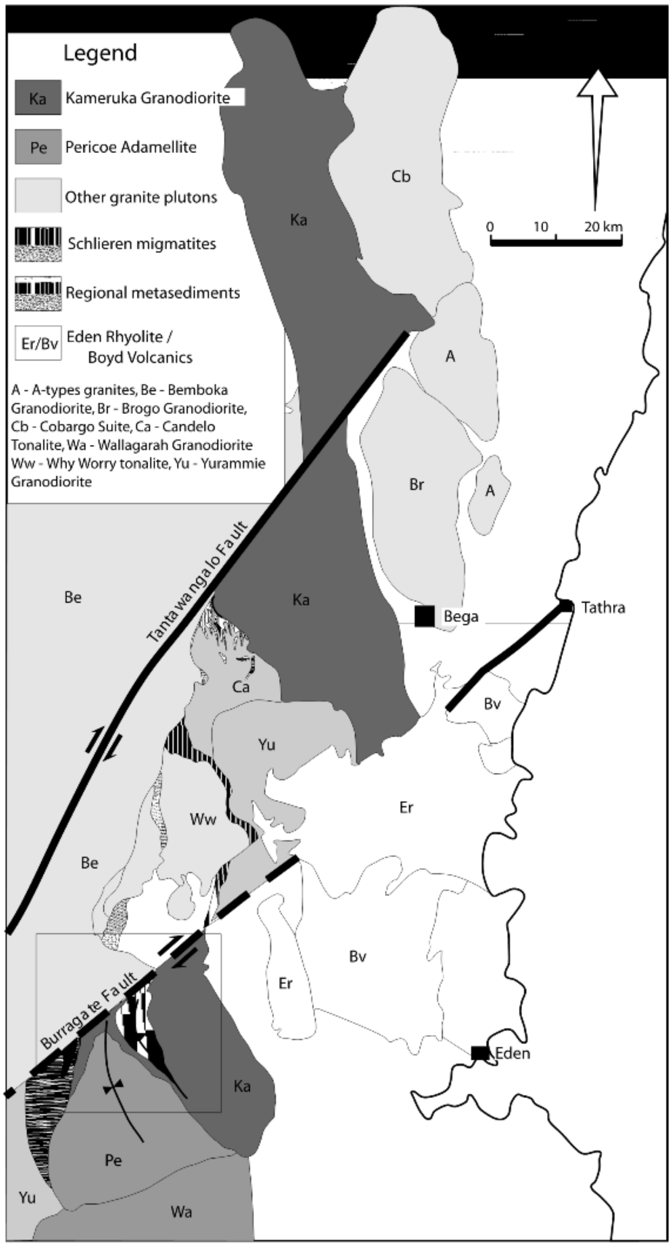
From the Towamba River, we will drive to the lower reaches of the Wog Wog River where we will walk west through inter-sheeted granite and migmatite at the base and below the Kameruka Granodiorite. We will examine shear sense indicators in the migmatites as well as stratigraphic indicators in the granite and migmatites. One of the primary aims of this section has to be to point out the complexity (structural and geoghemical) generated at the base of the pluton. We will also examine some magnificent felsic pipes. From here we will drive to the campsite for a well-deserved beer, BBQ and sleep.

Day 2 –We will begin our traverse in the Wog Wog River, in front of the Campground, heading east toward the base of the Kameruka pluton. The traverse will finish within the Pericoe pluton and at a location known as an “elephants graveyard” where material (mafic enclaves and stoped blocks of countryrock) has come to rest on the pluton floor.

Layered Mafic Intrusions and Stratigraphy in Plutons

Sheet-like bodies of relatively mafic magmatic rock occur in many granitic plutons (Wiebe, 1974; Barbarin 1988; Michael 1991; Blundy & Sparks 1992; Chapman & Rhodes 1992; Wiebe 1993,1994; Fernandez & Gasquet, 1994; Coleman *et al.* 1995). Such bodies vary from km-scale to m-scale, and may be represented as enclave swarms or merely as dispersed, aligned enclaves, such as in many parts of the Kameruka pluton – we are visiting the Kameruka pluton (Figure 1) to view some of these structures.

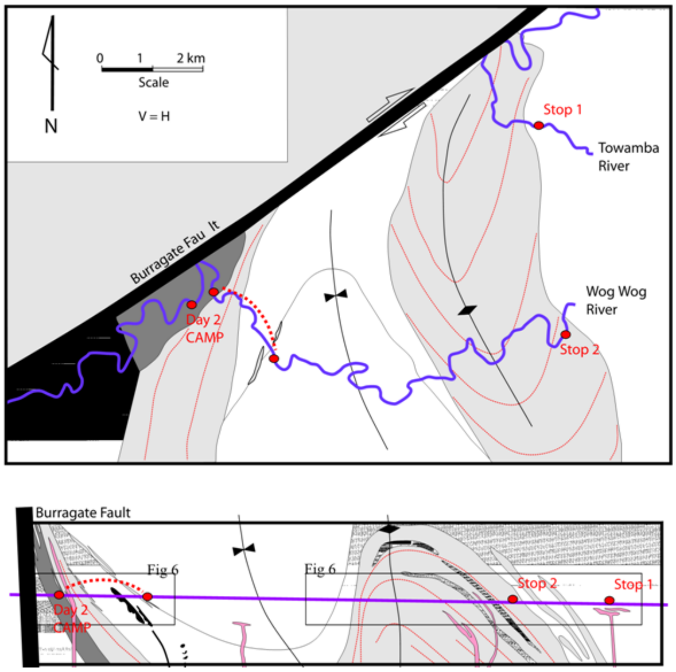
Figure 1. Bega Batholith



Geological map of the Bega Batholith

Individual sheets or lenses may be chilled on the base, which commonly displays prominent convex downward lobate structures that closely resemble sedimentary load cast structures (Wiebe 1974, 1993). These structures range from metres to tens of metres in diameter. The base is commonly perforated by flame structures and veins of leucogranite, which provide way-up indicators (Wiebe 1974). This felsic material appears to represent interstitial liquid, which was filter-pressed from the underlying granitic crystal mush and rose upward into the overlying mafic body. Compaction of the underlying crystal mush may lead to the development of feldspar-rich cumulates, in which individual crystals are moulded into the basal part of the overlying mafic layer (Figure 3b). In some mafic layers, pipe structures have formed as cylindrical diapirs of crystal mush, which rose vertically from the underlying granitic crystal mush into the overlying unconsolidated mafic layer (Chapman & Rhodes 1992). Where they have not been affected by slumping or magmatic flow in the host mafic layer, they appear to provide a record of the vertical during consolidation of the mafic layer and, hence, can be used to indicate the initial dip of the floor and the amount of tilting since deposition (Wiebe 1993).

Figure 2. Map and location of stops visited on this trip



The cross section gives a general overview of the structure of this part of the pluton. Apparent 'folding' of the pluton has resulted in exposure of the base of the pluton in a number of localities, two of which we shall be visiting.

Figure 3. Flat lying mafic enclaves

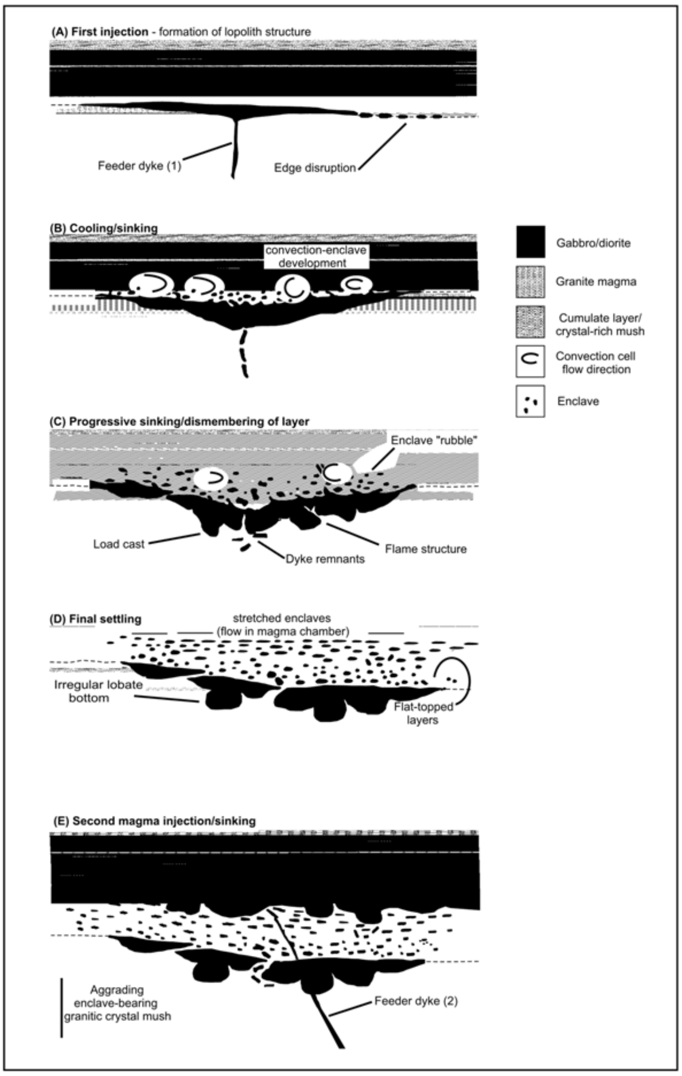
3a) Flat lying mafic enclaves of varying compositions hosted within the Kameruka Granodiorite close to the eastern margin of the pluton. 3b) Feldspar rich cumulate at the base of a mafic layer showing crystals moulding onto the base. 3c) Classic cresent-shaped channel deposit of enclaves in Kameruka pluton.

Upper margins of sheets may be sharp gradational to the overlying granite (Wiebe, 1974). Thick mafic layers generally have unchilled tops and commonly show evidence for mechanical mixing with the overlying granite. For example, the size and proportion of feldspar or quartz xenocrysts commonly increases toward the top of the mafic layer (Wiebe 1974). It is most likely that convective stirring in both layers led to mechanical mixing and break-up of the top of the mafic layer (Wiebe 1974). In the overlying granite, the occurrence of enclaves that decrease in size and abundance upward from the top of the mafic layer provide further evidence for convection and mixing (Wiebe, 1974; Barbarin 1988).

The contrasting character of the bases and tops of individual mafic sheets strongly suggests that thick sequences of parallel mafic sheets in granite formed by sequential deposition of each mafic layer at the interface between a crystal-rich base of a granitic chamber (an aggrading chamber floor) and a crystal-poor, liquid interior. Because these basally chilled mafic layers rest on rocks ranging from gabbro to granite (Wiebe 1993, 1994), their level of emplacement into the granitic bodies cannot be related to neutral buoyancy. Instead, the level of emplacement is probably controlled by the rapid change in rheology from a crystal-rich material beneath the active chamber to a crystal-poor liquid in the interior. These were described by Wiebe (1993, 1994) as Mafic And Silicic Layered Intrusions (MASLI).

Wiebe and Collins (1998) provided a general model for the formation of MASLI systems in granite dominated magma chambers (Figure 4). After the mafic injection enters the magma chamber, it spreads laterally at a level of rheological contrast (Figure 4). Once the sheet begins to cool its density increases and it sinks into the underlying crystal mush, generating overlying "eddy" currents which are capable of ripping mafic magma globules off the upper surface (Figure 4). With progressive sinking, load casts and flame structures develop in the mafic sheet (Figure 4), which tends to develop a flat top during settling (Figure 4). Further cooling results in complete solidification of the mafic sheet and entrainment in an enclave-rich granitoid crystal mush. Flow in the overlying magma chamber produces stretched enclaves and a magmatic foliation (Figure 4) in the mush. With repeated injections, the pluton aggrades as a sequence of crystal mushes that provide a stratigraphic record within the intrusion (Figure 4).

Figure 4. Stages of formation of MASLI system



Model showing the progressive stages of formation of a MASLI system (from Weibe and Collins, 1998)

In occurrences that they studied, Wiebe and Collins (1998) saw no evidence to suggest that these sheets were emplaced as sills at random levels in the package of layers. Thus, they considered that such a sequence of interlayered mafic and granitic rocks preserves a stratigraphic record of magma chamber processes that were active during the crystallization of the granite intrusion. Indeed, the apparent sedimentary character of some plutons is enhanced by the presence of channel deposits, which are crescent shaped accumulations of poorly sorted enclaves that are convex-down (Figure 4).

The Bega Batholith

The 420-400 Ma old Bega Batholith is the largest I-type batholith in the LFB, comprising 8940 km2 if the Moruya suite is included (Chappell 1996). It extends some 300 km from east of Canberra in the north to Bass Strait in the south and is composed of >130 plutons which have been divided into 50 suites, which can be grouped into 7 supersuites (Beams 1980). The supersuite extend as narrow linear arrangements of chemically related plutons, aligned N-S, parallel to the batholith trend (Figure 1) and that of the major structural trends of the low-grade country-rocks of Ordovician metasediment.

The two central supersuites of the batholith are Candelo and Kameruka, covering an area of 1200 km2 and 1350 km2, respectively. Candelo is dominated by tonalite and granodiorite, whereas Kameruka is dominated by granodiorite and monzogranite. Candelo Suite granites are distinguished by the presence of conspicuous hornblende crystals, interstitial quartz, and a paucity of K-feldspar megacrysts. The Kameruka granodiorite is a spectacular, coarse-grained rock with distinctive pink K-feldspar (4-10 cm) megacrysts, white rectangular plagioclase (1-4 cm) and rounded grey quartz grains (~ 1 cm). We focus on the Kameruka pluton and associated plutons of the suite.

Kameruka Pluton

The Devonian Kameruka Granodiorite (Figure 1) is a relatively large (570 km) and well-studied I-type pluton in the central part of the Bega Batholith, which is part of the Kameruka Suite (Beams 1980; Chappell *et al.* 1991; Chappell 1996). U/Pb dating on zircon from the pluton has revealed an age of around 420-425 Ma (Healy pers. comm. 2004). The pluton consists mainly of coarse-grained biotite granodiorite and is characterised by the presence of alkali-feldspar megacrysts up to 10 cm in length (Figure 5a). The Kameruka pluton extends from Cobargo in the north to Towamba in the south, a distance of ~100 km, but only reaches a maximum width of 12 km in the Bega Valley. The elongate, orogen parallel nature of the pluton suggests a strong structural control on emplacement – we will be addressing the nature of pluton emplacement over the two days.

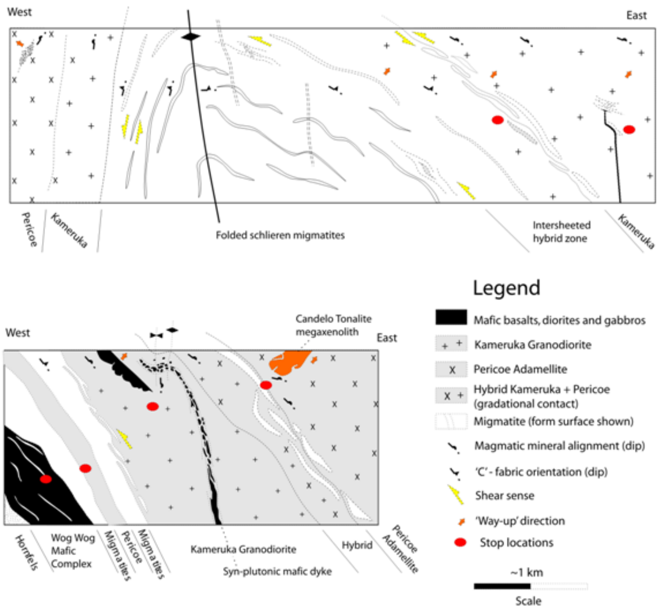
Figure 5. Kameruka Pluton

5a) White ovoid pseudomorphs after K-feldspar in Kameruka pluton. 5b) Double enclave with xenocryst poor core and xenocryst rich rim. 5c) Complex heterogeneous enclave showing at least four mixing stages, including an outer feldspar-rich rind contiaining rounded enclaves. It is gradational with the host granite. 5d) “Layered” enclaves consisting of xenocryst- rich and -poor sheets. It resembles some enclave layers at Illawambra

Excellent exposures within the Bega River provide a complete east-west traverse through the pluton. The western contact of the Kameruka Granodiorite dips moderately (50-700) to the east; sub-concordant with deformed (syn-migmatitic), migmatitic Ordovician metasediments. The eastern contact is much steeper, sharp and characterised by low-grade (relative to migmatites that characterise the western contact) hornfels.

The thickness of the pluton can be crudely estimated from the internal structures. They consist mainly of a locally, but well-developed feldspar foliation, swarms of mafic enclaves, sparse large tabular bodies of diorite, and planar boundaries between megacryst-rich and –poor phases of the granite. These features occur sporadically throughout the studied section and consistently dip moderately to steeply to the east. They tend to be steeper in the west (50-70 degrees) and shallower to the east (50-20). The internal features imply that the pluton dips eastward and has a thickness of 7-10 km. Reconstructions of the internal geometry of the pluton combined with detailed gravity has shown that the pluton is wedge-shaped, exhibiting a steep root on the eastern side, shallowing progressively to the west where the base of the pluton is exposed in the Wog Wog River (see Figure 2, Figure 4 and Figure 6 at end of the guide)

Figure 6. Characteristic Features



Details of some of the characteristic features we will be observing on this trip. The top cross-section is applicable to stops on the first day in the Towamba River and Lower Wog Wog River. The lower cross section shows features observed on the second day in the upper Wog Wog River.

Enclave swarms (Figure 3c) and individual enclaves display a range of small-scale features suggesting that they were deposited on a loosely packed mixture of crystals and interstitial melt (i.e. the floor of a magma chamber). Larger, chilled mafic enclaves typically have slab-like or pillow-like shapes and are strongly moulded around underlying feldspar megacrysts, which are commonly very tightly packed beneath these enclaves. In many swarms, individual enclaves are commonly moulded around each other, leaving only a very small residual matrix of megacryst-rich granodiorite (we will examine some of these enclave-rich "deposits"). All of these features suggest that compaction occurred immediately after deposition of the enclaves, while most of them were still soft (partly liquid). Where way-up criteria is available, swarms consistently indicate top to the east.

Significance of Variable Enclave Compositions

Enclaves display abundant evidence of several stages of mixing; an important part of the geochemical and tectonic story. Double enclaves are common and most enclaves contain some megacrysts identical in size and shape to crystals in the Kameruka granodiorite (Figure 5). Alkali-feldspar megacrysts in the enclaves are commonly rounded in shape and typically have very broad rims consisting of inter-grown small, normally zoned, subhedral to euhedral plagioclase crystals with interstitial quartz. Adjacent enclaves have widely different proportions and sizes of megacrysts, suggesting that mixing occurred both locally, but more importantly, remotely, prior to deposition.

The proportions and character of the feldspar megacrysts vary widely on the scale of the entire intrusion and, more locally, within large, well-exposed stream outcrops. Near the western margin of the intrusion, alkali-feldspar megacrysts are generally homogeneous, evenly distributed and lack rims of sodic plagioclase. Further to the east, stratigraphically above some major swarms of mafic enclaves, alkali-feldspar megacrysts are generally more scarce and unevenly distributed: most show plagioclase rims of varying thickness and are extremely similar to mantled K-feldspar found within the enclaves. These relations strongly suggest that the common mantles on alkali-feldspar at higher structural levels in the Kameruka were caused by the input of higher temperature, mafic magma as preserved in enclave swarms. Thus, it is likely that mafic input only affected local volumes of the magma chamber, and that batches of magma with different crystallization histories did not mix completely.

Summary

Because depositional features in the Kameruka Granodiorite occur throughout the studied section and provide a consistent sense of top to the east, we interpret the western margin as the base of the intrusion and the eastern margin as the roof. This interpretation is consistent with the contrast in metamorphic grade of the country-rocks, from migmatitic in the west to hornfelsic in the east. The evidence for way-up structures mentioned above suggests that the pluton formed by floor aggregation and thus provides a stratigraphic record of events (*e.g.* crystallization, replenishment of mafic and felsic magmas, and mixing) in a granodioritic magma chamber.

Base of the Kameruka Pluton

Pluton Geometry and Regional Cross-section

The Kameruka Pluton is a N-S trending, wedge-shaped pluton (cross-section) aligned parallel to the regional structural trend of the eastern Lachlan Fold Belt and of the Bega Batholith (Figure 1). The Pericoe Adamellite is the other pluton of the Kameruka Suite; it is a small (60 km2) body mapped as a separate pluton by Beams (1980), lying to the west of Towamba (Figure 2). A narrow rim of Kameruka granite was noted by Beams (1980) in its western side. We will now focus on the Kameruka pluton in the vicinity of Towamba, where mapping demonstrates that Pericoe is the upper part of a regional synform or basin-shaped depression in the Kameruka pluton.

According to the internal structures of the Kameruka pluton in the Bega region, the base is to the west and top is to the east. The eastern margin of the pluton is subconcordant to steep, east-dipping structures, overprinted by a narrow hornfelsed aureole, whereas the western margin is dominated by moderately E-dipping migmatites. Similar relations are observed in the Towamba area, but further west in the Wog Wog River (Figure 2), the relatively simple geometry of the Kameruka pluton changes. There, internal features and the enveloping structure of the underlying migmatites indicate that the pluton has a geometry similar to a gently S-plunging asymmetric, west-verging antiform, however, thee is very little evidence of deformation (post full-crystallisation compressive deformation) within the pluton. However, the presence of leucosomes and granite in the axial plane of scattered, open folds is evidence to suggest that the pluton has undergone a minor degree of late-syn-emplacement deformation. We can discuss the significance of this feature over the two days.

In the upper Wog Wog River, migmatitic layering and foliation are concordant to E-dipping gabbroic sheets of the WWGC (adjacent to the campsite), however, both of these structures are discordant to N-trending, tight, upright fold structures in the underlying lower grade metasedimentary rocks. These structures are correlatable with the regional D1 and D2 structures outside the Bega Batholith, which have developed in low-grade, greenschist facies metasediments. Therefore, the east-dipping migmatitic foliation is S3.

The overall geometry of the pluton is best described from west to east along the Wog Wog River (X-section, Figure 2 and Figure 6). Southeastward from the Burragate Fault, low-grade, folded metasedimentary units underlie the E-dipping, E-younging, inter-sheeted Wog Wog Gabbro Complex (WWGC – Day 2 stop 1). Overlying the WWGC and separating it from the Kameruka Granodiorite is a km-wide zone of stromatic metatexites and schlieren diatexites, structurally concordant with the WWGC. The migmatites lie stratigraphically below a concordant (east-dipping) km-thick sheet of Kameruka Granodiorite, a succession that is repeated in the lower Wog Wog River. The granodiorite throughout this section contains a high degree of inter-sheeting between different phases together with a large number of mafic bodies (we will walk through this section on Day 2). Farther to the east (up-section) a 600m-wide complex zone (contact) between the Kameruka and overlying Pericoe pluton is exposed. The contact zone is marked by the presence of an 'elephants graveyard' including the large block of Candelo Tonalite

(Day 2 final stop).

Several km downstream, the eastern margin of the Pericoe pluton is steeply west dipping and is gradational with a narrow sheet of Kameruka granite which itself grades rapidly into a steep, west-dipping zone of schlieren migmatites. The migmatites here have a well-developed foliation and shear sense indicators that show west-side-down (normal) movement.

Farther east, the migmatites fold over an open, gently south plunging antiform where they dip to the east again, below the basal contact of the Kameruka Pluton in the lower Wog Wog River (Figure 2) (Day 1 Stop 2).

Way-up structures are present in the WWGC, in the Kameruka pluton, in the contact zone and in the Pericoe pluton. All suggest that the rocks are "right way up" and confirm that the Pericoe pluton is a basin-shaped structure overlying the Kameruka pluton (Figure 2).

Acknowledgements and General Comments

This field guide has been designed to be informative. Consequently, I have placed most emphasis on the evidence, not the model or the interpretation. As geologists, however, we always enjoy trying to reconcile some of the evidence in the framework of a “model” so some interpretation is necessary. Within each section, I have provided some questions or queries worth discussing when we are on the outcrop. The objective of this field trip isn’t to point out great looking rocks (which would be fun but eventually become monotonous) but to try and spark some positive discussion about the evidence and what it means in terms of the bigger picture.

The information in this guide has been collected over several years by a number of people including Bryce Healy, Paul Ellison, Dianne Barrett and Mark Brokelsby; all undertook at least part of their honors research here. Additionally, Bill Collins and I ran a field trip to the SE

LFB and parts of the Wog Wog River (mainly the WWMC) were included in that trip. I have incorporated some of that information into this guide but our interpretations of the information have also changed slightly, so much of the information in this guide is also new. Additionally, I have included, at the end of the guide, a copy of a paper that will be published in Transactions of the Royal Society of Edinburgh this year. The paper contains our interpretations and tectonic model for generation and emplacement of the Bega Batholith and its implications for orogenesis of the eastern LFB. I have included it at the end so that discussion over the two days is not model driven or model influenced.

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