

Mechanical Instabilities and Physical Accumulation of K-feldspar Megacrysts in Granitic Magma, Tuolumne Batholith, California, USA

Scott R. Paterson

Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089-0740, USA

Email: paterson@usc.edu

R. H. Vernon

Department of Earth and Planetary Sciences and GEMOC, Macquarie University, Sydney NSW 2109, Australia

Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089-0740, USA

J. Zak

Department of Geology and Paleontology Charles University Prague, Czech Republic Czech Geological Survey Prague, Czech Republic

Keywords: Crystal accumulation, Crystal concentrations, Granite, K-feldspar megacrysts, Ladder dykes, Mechanical instabilities in magma, Troughs, Tubes

Abstract: Examination of K-feldspar megacrysts in the Tuolumne batholith (TB), Sierra Nevada, California, USA, indicates that they grew from melts, rather than metasomatically. During K-feldspar growth, local mechanical instabilities in the magma were common and resulted in the physical accumulation of K-feldspar megacrysts in schlieren tubes, troughs, irregular clusters, dikes, and small diapirs. Evidence favoring physical accumulation of concentrations of K-feldspar megacrysts includes

- a. clustering of megacrysts in much greater modal proportions than is likely from the magma composition,
- b. imbrication (tiling) of megacrysts,
- c. concentrations below schlieren layers with the layering draping around K-feldspars due to filter pressing,
- d. scattered to locally concentrated megacrysts in schlieren, together with microgranitoid enclaves ("mafic" enclaves) and xenoliths,
- e. dike-like and irregular "slumped" concentrations of megacrysts that in some places intrude other units with few to no megacrysts, and
- f. truncation of internal zoning in K-feldspars by fracturing or contact melting where megacrysts impinge on one another in clusters.

The above features emphasize the widespread occurrence of instabilities and local flow within the TB, as well as the role that these processes play in changing the mineral proportions preserved in frozen magma chambers.

An alternative suggestion that concentrations of megacrysts are formed by in situ growth is opposed by the evidence for physical accumulation, as well as the following observations:

- a. normal zoning of barium in the megacrysts;
- b. lack of molding of megacrysts around one another;
- c. mixing of megacrysts into microgranitoid enclaves ("mafic" enclaves);
- d. evidence for hydraulic equivalence between megacrysts and other minerals; and
- e. draping of schlieren layers around megacrysts.

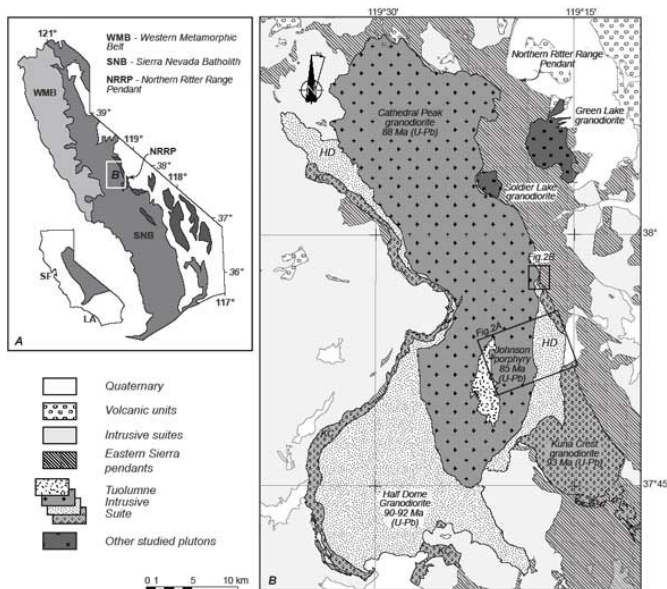
Table of Contents

Introduction	4
Tuolumne Batholith	5
Magmatic crystallization	5
Nucleation and growth	6
Evidence for physical accumulation	7
Discussion	11
Conclusion	15
Acknowledgments	15
References	15

Introduction

This paper is concerned with the development of magmatic, mechanical instabilities in Tuolumne Batholith (TB), Sierra Nevada, California, USA (Figure 1) and the resulting physical accumulation and concentration of K-feldspar megacrysts (phenocrysts).

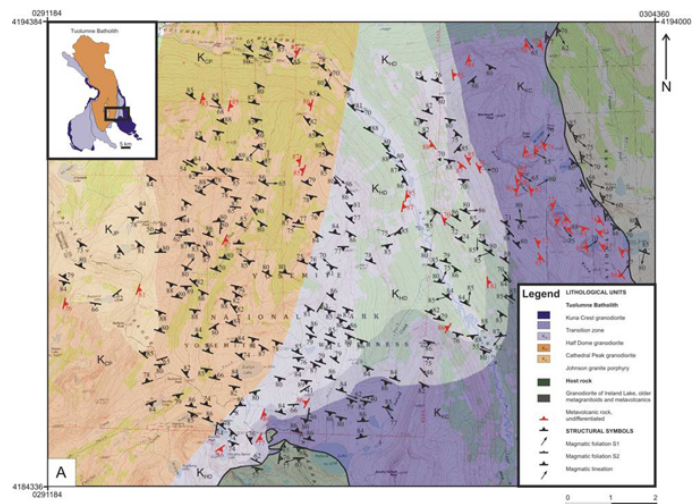
Figure 1. Map of the Tuolumne Batholith



Map of the Tuolumne Batholith showing four main units and their approximate ages. Inset shows location of batholith in the Sierra Nevada Batholith and California. Two boxes outline areas of detailed work shown in Figure 2.

Evidence for physical accumulation of megacrysts in the TB was presented long ago by Gilbert (1906), but a recent suggestion by Higgins (1999) that megacryst concentrations are due to in situ crystallization during open-system conditions has prompted us to re-examine the existing evidence and search for new evidence. We conclude that K-feldspar megacrysts grew from a melt and that a number of processes led to their physical accumulation. In some places, these accumulations in turn were positively buoyant and continued to rise in the magma chamber while concentrating additional megacrysts. These accumulations formed prior to the development of a late magmatic foliation/lineation (Figure 2), that is before final crystallization of magma in the chamber.

Figure 2. Detailed maps of two areas outlined in Figure 1



Detailed maps of two areas outlined in Figure 1 showing the pattern of two magmatic foliations in these areas, one of which cross-cuts internal contacts. Red symbols show orientations of an older approximately margin-parallel foliation. Black symbols show orientations of a slightly younger magmatic fabric that crosscuts all contacts.

- Southern corridor across the four main magmatic units in the TB (Kuna Crest, Half Dome, Cathedral Peak, and Johnson from east to west, respectively); (View, Full size).
- Sawmill Canyon area along the eastern margin of the chamber where the KC and HD phases were cut out by intrusion of the CP phase. (View, Full size).
- Photo of area mapped in Fig. 2a looking west; (View).
- Photo of area mapped in Fig. 2b looking west. (View).

After briefly summarizing the main characteristics of the TB, we provide a review of the evidence for the magmatic origin of K-feldspar megacrysts, mainly because some authors still favor a metasomatic origin [e.g., Dickson, 1996], and then discuss the cause of the large size of the megacrysts — nucleation and growth versus "Ostwald ripening." We then present evidence for megacryst movement and accumulation in granitic magma, and conclude with a discussion of the timing of megacryst growth in the TB, the lack of evidence for grain coarsening or concentration by in situ growth of megacrysts by precipitation from K-rich solutions, and of the physical processes by which the megacrysts were accumulated in the TB.

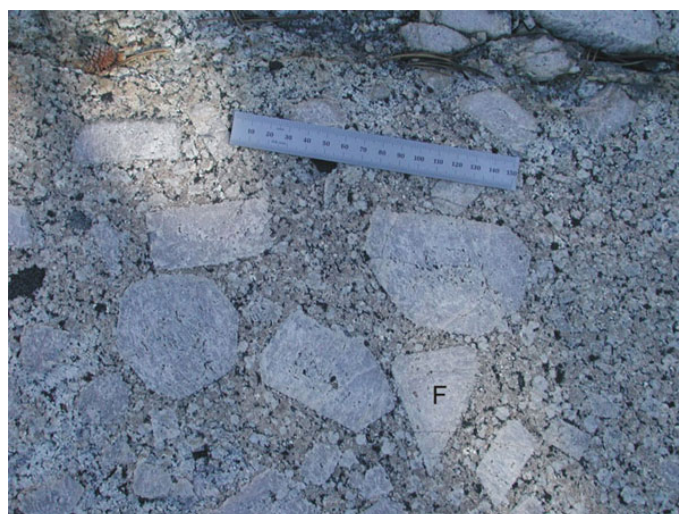
Tuolumne Batholith

The Tuolumne batholith (TB, Figure 1) consists of four recognized phases [Bateman and Chappell, 1979; Bateman, 1992]: (1) an outer granodioritic to tonalitic phase called the Kuna Crest (includes the Glen Aulin and Glacier Point tonalites and Kuna Crest granodiorite), (2) the Half Dome (HD) granodiorite, which consists of an outer equigranular (Khde) and inner porphyritic facies (Khdp); (3) the K-feldspar megacrystic Cathedral Peak (CP) granodiorite, and (4) the Johnson granite porphyry. Bateman and Chappell (1979) argued that this normally zoned intrusive suite formed from a single parent melt by in situ crystal fractionation. However, a subsequent geochemical study of enclaves [Reid et al., 1983] and a REE study by Kistler et al. (1986) showed that at least two separately evolved pulses were required, in part derived from mixing of basaltic and granitic magmas, and that the inner siliceous phases could have no more than 15% mantle component. Recent geochronological work [Kistler and Fleck, 1994; Fleck et al., 1996; Coleman and Glazner, 1997; Coleman et al. 2002] indicates that different pulses in this suite have moderately different ages (up to 1-3 Ma apart) and that the suite was constructed and crystallized over a 7-11 Ma period (~93 Ma to ~85 Ma), supporting the interpretation of Kistler et al. (1986). Because of the distinct geochemical and geochronologic differences between inner and outer pulses, this body is by definition not an intrusive suite, and we therefore use the name Tuolumne Batholith (TB).

Recent detailed mapping and geochronology have suggested that at least the outer pulses may have been constructed incrementally [Miller and Miller, 2003, Glazner et al., 2004], and that complex relationships occur along parts of internal contacts between the four main phases (Figure 2; Zak and Paterson, in review). Additional studies have also confirmed Bateman's (1992) original observation that two magmatic foliations occur in this batholith, and that at least the younger of these two foliations overprint all internal contacts and associated structures [Paterson et al., 2004], as shown in Figure 2.

K-feldspar megacrysts (Figure 3a, 3b) occur in the inner Half Dome, Cathedral Peak, and Johnson phases. We have examined all of these units, but will largely focus on the particularly well developed megacrysts in the Cathedral Peak phase.

Figure 3. K-feldspar megacryst characteristics



- Station CP-Z-831 (UTM: 0288453; 4201870). (View a, b).

Megacrysts in the Cathedral Peak phase showing variable shapes, sizes, weak compositional zoning and rare fragmentation (marked "f");

- Station CP-Z-485 (UTM: 0295831; 4186779). (View c).
- Station CP-740 (UTM: 0297694 44200479). (View d).

Comb layering, involving dendritic crystals of K-feldspar in a relatively mafic layer at high angles to contacts and layering. Also present are K-feldspar megacrysts lying parallel to the layering. The dendritic K-feldspar appears to have nucleated on (1) the walls of the mafic layer, (2) compositional layers (centre) and (3) the top surfaces of K-feldspar megacrysts (above centre). The compositional layering appears to have been deflected around some of the dendritic K-feldspar, but growth of the dendrites appears to have continued after deflection, transecting the layers. This, together with the nucleation of dendrites on megacrysts, suggests that the dendritic K-feldspar grew relatively late in the magmatic history. This may reflect delayed nucleation, caused by destruction of nuclei by superheating, possibly in response to the addition of water to the magma [Vernon, 1985].

Criteria of magmatic crystallization of K-feldspar megacrysts

As discussed in detail by Vernon (1986) and summarized by Vernon (1999) and Vernon and Paterson (2002), the following criteria favor a magmatic origin for K-feldspar megacrysts: (1) euhedral shapes of the megacrysts, compared with typical xenoblastic shapes of K-feldspar porphyroblasts in metamorphic rocks (Figure 3a, b); (2) simple twinning, which is rare to unobserved in metamorphic K-feldspar; (3) oscillatory zoning (especially Ba),

which to our knowledge, is unreported for metamorphic K-feldspar; (4) normal zoning with Ba-rich cores, as expected for melt crystallization; (5) concentrically arranged inclusions (e.g., biotite and plagioclase) parallel to crystallographic planes, as opposed to inclusion trails unrelated to K-feldspar crystallography in metamorphic K-feldspar (Figure 3a , b); (6) euhedral plagioclase inclusions, as opposed to rounded plagioclase inclusions in metamorphic K-feldspar; (7) fractured megacrysts in which the fractures truncate zoning and the megacryst is surrounded by other crystals grown from a melt (Figure 3a , b); (8) evidence that already grown megacrysts were physically accumulated during flow in melt (Figure 4 - 10), as discussed later in the paper; and (9) overprinting of megacryst accumulations by a magmatic foliation. All of these observations are readily applied to megacrysts in the TB (Figure 3 , 4).

Figure 4. K-feldspar megacryst accumulation in general clusters



- a. CP-179 (UTM: 0287557 4194677) Cluster of K-feldspar megacrysts, nearly all of which are independent, euhedral, zoned crystals, without molding. The cluster has no obvious boundary. 15 cm ruler for scale; (View).
- b. CP 766 (UTM: 0280769; 4211678) Normal distribution of k-feldspars and planar cluster of K-feldspar megacrysts, some of which touch but without molding. The cluster has no obvious boundary. Brunton for scale; (View).
- c. CP-Z-294 (UTM: 0297260;4207191) Clusters inside and outside local schlieren zone. Clusters elongate parallel to schlieren zone. Late aplite dike cuts clusters and schlieren. ~25 cm hammer for scale; (View).
- d. CP-280 (UTM: 0298065 4206296): Megacryst cluster in CP near eastern margin with metavolcanic

host rock. metavolcanic xenoliths, which have rotated with respect to the host rock, also occur. 15 cm ruler for scale; (View)

- e. CP-281 (UTM: 0298025 4206295) Tiling of K-feldspar megacrysts in a cluster in CP phase where it has intruded metavolcanic host rocks. Molding relationships are again absent. 15 cm ruler for scale; (View).
- f. CP-804 (UTM: 0281644 4210647) K-feldspar megacrysts and local megacryst cluster in mafic (hornblende-rich) layer in CP . 15 cm ruler for scale; (View).
- g. HD-CP 640 (UTM: 0288529 4198378) Looking N along strike of contact that dips steeply to right between HD and CP granodiorites: thus cliff face is approximately parallel to contact. An accumulation of K-feldspar megacrysts in CP immediately at contact. Height of face approximately 7 m; (View).
- h. HD-CP 641 (UTM: 0288567 4198416) Horizontal face near photo Fig. 4g, showing same contact between CP and HD phases. K-feldspar clusters from CP, one with accumulation of enclaves, occur in HD and are now detached from CP. ~36 cm hammer for scale. (View).

Nucleation and growth versus "Ostwald ripening" of K-feldspar

The simplest explanation for the large size of K-feldspar megacrysts in granites is that they develop at conditions of unusually low nucleation-to-growth ratio, presumably at low degrees of supersaturation, as suggested by Swanson (1977). The experiments of Fenn (1977) indicate pronounced reductions in the nucleation rate of alkali feldspar in hydrous felsic melts. The nucleation difficulty does not appear to be connected with the major-element chemical composition of the magma, as megacrystic granites may be compositionally identical to adjacent non-megacrystic granites [Bateman & Chappell 1979].

The abundance of simple twinning in igneous K-feldspar [Eggleton 1979], compared with its rarity to absence in K-feldspar that has grown in the solid state [Vernon 1999] also suggests that the development of viable nuclei of K-feldspar in magmas may be difficult. For example, K-feldspar crystals occurring both as phenocrysts and in the groundmass of trachytes invariably have simple twinning, which is also very common in K-feldspar megacrysts in granite [Vernon 1986]. Twinned nuclei may assist precipitation of K-feldspar in magmas, by the re-entrant at the twin interface assisting attachment of atoms to the nucleus, or because of concentrations of dislocations along the twin plane [Baronnet 1984].

The occurrence of megacrystic K-feldspar in comb layers, locally seen in a number of spots in the TB (Figure 3c , 3d), has been explained by delayed nucleation [Vernon , 1985]. If so, it also reflects the general difficulty of K-feldspar nucleation in granitic melts.

Higgins (1999) suggested that megacrysts of K-feldspar in the TB were formed by coarsening ("textural coarsening" or "Ostwald ripening") of much smaller, earlier formed crystals, rather than resulting from low nucleation-to-growth ratios during their crystallization. "Ostwald ripening" may occur after nuclei of a new mineral are produced; larger nuclei grow at the expense of smaller nuclei, over a much longer time than it takes for nucleation to occur [e.g., Ostwald, 1901; Lovett et al ., 1978]. If a few nuclei dissolve, nearby nuclei grow, which induces diffusion towards the instability, promoting further crystal growth there [Lovett et al ., 1978; Tikare & Cawley, 1998]. The surviving pieces of crystalline material grow into observable crystals. "Ostwald ripening" reflects the greater solubility of very small crystalline particles, compared to larger ones [Buckley, 1961; Voorhees, 1992], in response to the tendency to reduce the total interfacial free energy of all the particles of that phase [Baronnet, 1984, p. 224]. Because the surface energies of particles are not large enough to drive diffusion over large distances, surface energy is an important driving force for dissolution in the liquid only when crystals are very small, in the micrometre or nanometre size range [Jackson, 1967; Martin & Doherty, 1976; Baronnet, 1982; Lasaga, 1998, p. 514; Cabane et al ., 2001]. Crystals large enough to be observed in the light microscope are much more stable than submicroscopic particles [Martin & Doherty 1976, pp.174-176].

"Ostwald ripening" produces a population of viable nuclei that can grow into crystals, affecting the crystal size distribution (CSD) produced during subsequent crystal growth [Eberl et al., 2002]. Thus, CSD plots skewed towards larger grain sizes may suggest that "Ostwald ripening" has occurred [e.g., Miyazaki , 1991; Kile et al ., 2000; Zieg & Marsh, 2002, p. 99]. The inference of Higgins (1999) that "Ostwald ripening" accounts for the large size of the TB megacrysts was based on two CSD plots (from six stations). However, the validity of the current CSD approach has been challenged by Pan (2001), on the basis that $\ln(n)$ versus L plots involve inherited correlation. The current approach has been defended by Schaeben et al. (2002) and Marsh & Higgins (2002), but Pan (2000a, 2000b) has also defended his objections to the approach.

Higgins (1999) inferred two linear CSD plots, one for the megacrysts, the other for groundmass K-feldspar grains. Higgins (1999) inferred that the plots represent grain coarsening without movement of crystals after their growth, whereas evidence listed in the next section indicates common movement of megacrysts in granodiorite magma. An alternative interpretation of the plots of Higgins (1999) could be that physical accumulation of megacrysts has occurred, producing a single plot kinked or skewed towards larger grain sizes (Marsh, 1988), rather than two separate plots.

In contrast to an "Ostwald ripening" interpretation, Berger & Roselle (2001) found that the CSD of K-feldspar megacrysts in migmatite leucosomes reflects the interplay between nucleation and growth rates at the initial stage of crystallization, not later grain coarsening. Furthermore, Cabane et al. (2001) found that coarsening is inappropriate for quartz grains larger than 1 mm in granitic melts. Extrapolating from their experimental results, Cabane et al. (2001) found that grain sizes produced by "Ostwald ripening" of quartz after 1 Ma would range from 12 to 70 μ m, depending on the water content of the liquid. This suggests that K-feldspar megacrysts of up to 25 mm are unlikely to be due to "Ostwald ripening".

This does not preclude "Ostwald ripening" at the nucleation and very early growth (submicroscopic) stages, establishing the number of viable nuclei or submicroscopic crystal particles, as mentioned previously . For example, Cabane et al. (2001) inferred that "Ostwald ripening" may occur in the later stages of nucleation events, removing many nuclei. However, the process cannot be observed, except in experiments.

Evidence for physical accumulation of megacrysts

Evidence presented by others that K-feldspar megacrysts in granitoids commonly move as independent crystals and so do not necessarily represent in situ growth includes the following: (1) accumulation, either as (a) abundant, megacryst-rich layers in granites [Vernon 1986; Wiebe 1994, 1996; Healy et al. 2000; Wiebe et al. 2002] or (b) flow-sorted layers ("schlieren") in granites (commonly with graded-bedding and cross-bedding), together with mafic minerals, xenoliths and microgranitoid enclaves [Gilbert 1906; Cloos 1936; Phillips 1968, p. 180; Wilshire 1969, p. 244; Wahrhaftig 1979; Barrière 1981; Vernon 1986, pp. 7-8; Abbott 1989; Reid et al . 1993; Tobisch et

al. 1997; Clarke and Clarke 1998; Weinberg et al. 2001]; (2) the common alignment of megacrysts in magmatic structures, as reviewed by Vernon (1986, pp. 5-7); (3) physical incorporation of megacrysts in more mafic magma during magma mixing [Reid et al. 1983; Vernon 1983, 1990, 1991]; and (4) "log jam" accumulations of K-feldspar megacrysts in the narrower parts of channels in magma chambers [Clarke and Clarke 1998; Weinberg et al. 2001].

Evidence that K-feldspar megacrysts in the TB have moved and/or accumulated physically includes the following (also see Gilbert 1906). The processes that we infer to have caused these accumulations will be outlined in the discussion section.

1. Locally K-feldspar megacrysts cluster in much greater modal proportions than is expected for the composition of the magma (Figure 4a-h).
2. Imbrication (tiling) of megacrysts is locally preserved (Figure 4b , 4c , 4e , Figure 9d).
3. Megacrysts may concentrate in dike-like bodies (Figure 5), which in some places intrude other intrusive units with few to no K-feldspar megacrysts (Figure 5c).
4. Scattered to locally concentrated megacrysts commonly occur in schlieren along channel margins, together with microgranitoid enclaves and xenoliths (Figure 6a-h). In many places, the most aligned K-feldspar megacrysts occur in the more mafic (hornblende-rich) layers (Figure 6a-e , 6h), indicating hydraulic equivalence between megacrysts and hornblende.
5. Concentrations rich in K-feldspar megacrysts commonly occur in "ladder dikes" or "schlieren tubes" (Figure 7a-d) or in elliptically shaped "plumes" (Figure 8a-d). Some of these plumes consist of up to 80% modal percent of K-feldspar megacrysts (Figure 8a , 8b , 8d), much greater than could possibly occur from direct crystallization of any normal magma composition. Others have concentrations of mafic minerals along their surfaces (Figure 8a , 8b), and still other plumes have distorted overlying schlieren layers (10e), indicating continued movement of megacryst clusters.
6. Xenoliths (i.e., wall-rock fragments) and microgranitoid enclaves occur in the schlieren troughs, tubes, plumes and other K-feldspar megacryst concentrations (Figure 4d , Figure 8d , 10d , 10f), suggesting a connection between the process by which the xenoliths/enclaves were displaced and the associated megacrysts were concentrated.
7. Megacryst concentrations in the CP phase occur in the megacryst-free outer equigranular HD phase near margins where the two units are juxtaposed (Figure 4h).
8. Schlieren layers are indented by or drape megacrysts, suggesting differential compaction around existing megacrysts (Figure 9a-c).
9. Megacrysts that impinge on one another in clusters (Figure 9b , d) locally show truncation of internal zoning, indicative of contact melting (Park & Means 1996), provided that cores with concentric zones are present in both crystals [Vernon et al., 2004]; otherwise, impingement during growth or epitactic nucleation of one crystal on the other are equally plausible interpretations of this relationship [Vernon, 2004; Vernon et al., 2004].
10. Megacrysts in clusters indent or are wrapped by microgranitoid enclaves, indicating that the megacryst was present and stronger than the enclaves during subsequent strain of the magma (Figure 10d).
11. K-feldspar megacrysts have been physically incorporated into more mafic magma, as indicated by K-feldspar megacrysts in microgranitoid enclaves or mafic-felsic mingled zones (Figure 4f , 6g , 9b) in TB granitoids [Reid et al. 1983].
12. K-feldspar megacrysts are locally aligned parallel to the external margin with the host rock, to internal margins between pulses, or parallel to overprinting magmatic foliations (Figure 2 , 6 , 7) indicating that flow or strain aligned already existing K-feldspar megacrysts.

Figure 5. K-feldspar megacryst accumulations in dike-like bodies



- a. CP 179 (UTM: 0287557 4194677) Elongate (>10 meters by 0.5 to 1 m) megacryst cluster with sinuous and diffuse margins, in CP granodiorite. 15 cm ruler for scale; (View).
- b. SM M 310 (UTM: 0298325 4203484) K-feldspar megacryst-rich dike intruding schlieren-type layering in CP granodiorite, subsequently intruded by a late aplite dike. Some megacrysts are locally tiled, although most occur as independent crystals. 15 cm pencil for scale; (View).
- c. J 162 (UTM: 0291943 4193796) Megacryst-rich dike of CP granodiorite intruding Johnson granite porphyry. The megacrysts decrease near the dike margins, suggesting a possible Bagnold effect. ~36 cm hammer for scale; (View).
- d. SM CP-403 (UTM: 0298525 4203748) megacryst-rich dike of CP granodiorite cutting a metavolcanic raft along eastern margin of batholith, with weak alignment of megacrysts parallel to dike walls. Small veins of CP phase with few or no megacrysts extend out from dike. 36 cm hammer for scale. (View).

Figure 6. K-feldspar megacryst accumulation in troughs



- a. SM M Z-329 (UTM: 0298300; 4203320) Three sets of cross-cutting schlieren troughs with trough axes plunging gently (~12 o) away from viewer. Late aplite dike cuts all three sets. Oldest set to right is folded and deflected (along with middle set) by diapiric rise of K-feldspar megacryst-rich layer at base of cliff face. Middle trough set offset by magmatic fault (see next photo). this fault does not offset youngest set, nor the CP diapir at base of cliff. All three sets show strongly aligned megacrysts in mafic (hornblende and biotite) layers and decreasing alignment away from these layers (e.g. base of the troughs). Cliff face about 7 m high; (View).
- b. SM MZ-329 (UTM: 0298300; 4203320) Close-up of middle schlieren trough set shown in Photo A. Well aligned megacrysts in mafic schlieren; magmatic fault offsets the schlieren locally truncates the megacrysts. Megacryst-rich CP phase at base. 15 cm ruler for scale; (View).
- c. CP 292 (UTM: 0297209 4205369) Aligned and unaligned K-feldspar megacrysts in schlieren trough. Axis of trough nearly vertical; so layering dips steeply. See Fig. 6D for close-up. 15 cm ruler for scale; (View).
- d. CP-292 (UTM: 0297209 4205369) Close-up of megacrysts in schlieren in Fig. 6C. 15 cm ruler for scale; (View).
- e. CP-Z-256 (UTM: 0298326; 4204274) Schlieren at the base of troughs with strongly aligned K-feldspar megacrysts. Trough cut-offs and grading of mafic minerals both indicate younging to left. Megacryst alignment decreases away from base of troughs. ~25 cm hammer for scale; (View).
- f. CP-167 (UTM: 0289838 4194967) Faint schliere marks internal margin, with megacryst accumulation immediately above schliere. 15 cm ruler for scale; (View).
- g. SM-HD 335 (UTM: 0298191 4203473) Base of trough where both K-feldspar megacrysts and large

euhedral hornblende crystals have accumulated. 15 cm ruler for scale; (View).

- h. CP Z-255 (UTM: 0298401; 4204132) Large schlieren troughs locally cut by magmatic faults (immediately to left of person) and intruded by slightly younger CP phase. aligned megacrysts in schlieren presumably were present before magmatic faulting and reintrusion by CP granodiorite. (View).

Figure 7. K-feldspar megacrysts in tubes



Tubes differ from troughs by having the boundary-parallel schlieren entirely enclosed (thus forming elliptical patterns) in sections perpendicular to the tube axis; tube axes in the TB almost always plunge at angles greater than 70°:

- a. SM M 352 (UTM: 0298485 4203607). Large schlieren tube in hybrid HD phase with aligned megacrysts in the schlieren. Tube axis near vertical. ~36 cm hammer for scale.; (View).
- b. CP 167 (UTM: 0289838 4194967) Subhorizontal and steeply dipping surfaces through a schlieren tube. Megacrysts are aligned in both schlieren in the approximately vertical "feeder pipe" and schlieren forming elliptical sections in the subhorizontal plane. Megacrysts are also concentrated in the center of the tube (subhorizontal face). 15 cm ruler for scale; (View).
- c. CP-291 (UTM: 0297095 4205422) Subhorizontal and steeply dipping surfaces through a steeply plunging schlieren tube. Megacrysts occur only in the center of the tube. 31 cm map case for scale.; (View).
- d. CP 535 (UTM: 0288450 5197268) Horizontal cut through steeply plunging, migrating schlieren tube, the "snail structure" of Weinberg et al. (2001) The largest crystal faces of K-feldspar megacrysts are aligned parallel to schlieren, but long axes of megacrysts show some variation in orientation. 15 cm ruler for scale. (View).

Figure 8. K-feldspar megacrysts in plumes



Plumes are relatively homogeneous columns with fewer or no schlieren layers, and also almost always have steeply plunging axes in the TB:

- a. CP167 (UTM: 0289838 4194967) Concentration of megacrysts in sharply bound plume known as "The Mummy." Mafic minerals are concentrated along side and upper margin of plume. 36 cm hammer for scale.; (View).
- b. CP 649 (UTM: 0288577 4197802) Vertical and subhorizontal (top and bottom of photo) surfaces through a vertically plunging megacryst-rich plume. In subhorizontal surfaces, plume forms elliptical pattern. A small amount of enrichment in mafic minerals occurs along the plume margins. Megacrysts show weak alignment in a subhorizontal direction, as though vertical compaction had occurred in the plume. 36 cm hammer for scale.; (View).
- c. SM CP 349 (UTM: 0298488 4203738) Small schlieren tubes and troughs along margin of large (~15 m diameter) vertically plunging megacryst-rich plume (lower right corner of photo). These secondary tubes and troughs occur elsewhere along the margin of this plume suggesting a genetic relationship. 36 cm hammer for scale; (View).
- d. SM CP 349 (UTM: 0298488 4203738) Close-up of K-feldspar megacryst-rich plume in lower-right

corner of area shown in Fig. 7g. forming 80% of rock. Small xenoliths of host rock are also present. One interpretation is that the megacryst accumulation (plus accompanying volatiles?) was more buoyant and thus drove upward motion in tube, thereby supporting the xenoliths. Even with this high percentage of megacrysts, molding relationships are rare to absent. 15 cm ruler for scale. (View).

Figure 9. Compaction around K-feldspar megacrysts



- CP 292 (UTM: 0297209 4205369) Schlieren layer indented by or draping megacrysts. Mafic layer thins and disappears at points of greatest deflection (upper corners of some megacrysts). 36 cm hammer for scale; (View).
- CP-Z-294 (UTM: 0297260;4207191) Deflection of schlieren by K-feldspar megacrysts. Rare truncated corners (e.g., arrows) where megacrysts touch may result in contact melting. ~5 cm camera lens for scale; (View).
- CP 805 (UTM: 0281704 4210788) Subhorizontal alignment of K-feldspar megacrysts in a vertical plume. 15 cm ruler for scale; (d) (UTM: not available) Megacryst cluster, in which some megacrysts in contact may have undergone contact melting (arrows). Inclusions are aligned parallel to crystal faces of some megacrysts. Late quartz-filled fractures also present. 15 cm ruler for scale. (View).

Discussion

Timing of K-feldspar megacryst growth in the TB: Experiments indicate that granodioritic magma becomes saturated in other minerals, such as hornblende, biotite and plagioclase, before K-feldspar [Piwinski & Wyllie, 1970; Clemens & Wall, 1981]. Therefore, the K-feldspar in megacrystic granodiorites must have grown larger than the other minerals because of its much lower ratio of nucleation rate to growth rate in the magma concerned, not because it

began to crystallize earlier than the other minerals [Vernon, 1986]. Experiments have shown that in typical felsic magmas, about 60-70 per cent of the magma is still melt when K-feldspar nucleates [Clemens & Wall, 1981; Winkler & Schultes, 1982], and this provides enough room for the K-feldspar megacrysts to develop [Vernon, 1986]. The zonally arranged, much smaller inclusions of plagioclase and biotite (Figure 3a, Figure 3b, Figure 9d) reflect the much higher ratios of nucleation rate to growth rate of these minerals, which were crystallizing during growth of the K-feldspar. Field observations in the TB noted above indicate that many K-feldspar megacrysts had grown prior to being concentrated and/or aligned into general clusters (Figure 4), in dike-like bodies (Figure 5), schlieren troughs (Figure 6), schlieren tubes (Figure 7) and small plumes (Figure 8). Some megacryst plumes continued to move as diapirs (Figure 8a-d, Figure 10e) or by slumping along internal contacts within the chamber (Figure 4g, Figure 4h, Figure 6h). In some places K-feldspar megacrysts with fully developed zoning were either fractured (Figure 3b) or partly dissolved during contact melting (9b, 9d). Furthermore schlieren layering, defined by a modal increase of mafic minerals (Figure 9a, Figure 9b), may be deflected around megacrysts and/or concentrated around them requiring that the megacrysts already existed, in order to act as buttresses during the deflection.

All these structures are in turn overprinted by a magmatic foliation and steep lineation (Figure 2, Figure 10), which requires that at least many K-feldspar megacrysts had grown prior to the late formation of magmatic fabrics and final crystallization. We have also observed additional "cross-cutting" or relative timing relationships that place further constraints on the timing of K-feldspar megacryst growth in the Johnson granite, CP granodiorite, and HD granodiorite, respectively (Figure 10). Angular of the K-feldspar-bearing CP phase (Figure 10a) and individual K-feldspar megacrysts, presumably from the CP (10b), occur in the Johnson granite porphyry, which is typically fine grained and free of megacrysts. Thus megacrysts and/or megacryst-rich pieces of granodiorite existed before incorporation into the Johnson granite. Some schlieren tubes in the CP phase have K-feldspar megacrysts aligned parallel to the tube margins and are cut by felsic dikes that grade into leucocratic patches rich in K-feldspar megacrysts (Figure 10c). Both the tube and leucocratic patches are locally overprinted by a magmatic foliation. This indicates early alignment of K-feldspar megacrysts parallel to the

trough walls, subsequent formation of K-feldspar – rich patches, and finally formation of the late magmatic foliation.

Figure 10. Timing relationships arranged from younger to older



Timing relationships arranged from younger to older, that is from the central Johnson granite porphyry to HD granodiorite:

- a. J 160: (UTM: 0291272 4194254) Angular xenolith (arrow) of CP phase in Johnson granite porphyry. The angular shape and truncation of K-feldspar grains indicate that this is a solid fragment of CP broken off after K-feldspar growth and transported into the Johnson granite. 8 cm knife for scale; (View).
- b. J 160 (UTM: 0291272 4194254) K-feldspar megacrysts (arrows) that we interpret as having been transported from the CP granodiorite into the Johnson granite porphyry. 8 cm knife for scale; (View).
- c. CP 111 (UTM: no data) Schlieren tube in CP phase with K-feldspar megacrysts aligned parallel to the tube margins. This tube is cut by felsic dike that grades into leucocratic patch rich in megacrysts. Both these features are overprinted by a magmatic foliation parallel to the 15 cm ruler; (View).
- d. CP 281 (UTM: 0298025 4206295) An accumulation of K-feldspar megacrysts, some touching but with no molding, and of microgranitoid enclaves in a patch of CP granodiorite (possibly part of a former dike) surrounded by late aplite and intruding volcanic host rock along the eastern margin of the TB. Megacrysts indent or are wrapped by host enclaves (arrows). 36 cm hammer for scale; (View).
- e. SM MZ 429 (UTM: 0298590 4203427) megacryst-rich dike of CP that has intruded magmatically folded schlieren layers, some with aligned megacrysts, and sheets of mingled HD and CP granodiorites. Dike was thickened and diapirically rose into layers and sheets. Our interpretation is that CP

magma was more buoyant, and thus rose and deformed adjacent layers. 15 cm ruler for scale; (View).

- f. HD-CP 460 (UTM: no data) Contact (marked with line) between HD and CP granodiorites. Microgranitoid enclave with K-feldspar megacryst occurs near mingled zone along contact. A magmatic foliation, parallel to the 15 cm ruler, cuts across contact and overprints the enclave; (View).
- g. CP 738 (UTM: 0297500 4200149) K-feldspar crystal cut by aplite vein. ~4 cm chapstick for scale. Some minerals in enclave are also parallel to this foliation; (h) CP SP kspars-aplite-2 (UTM: no data) K-feldspar megacrysts protruding into or transecting a late aplite dike. Dark rims on megacrysts were drawn with pen to emphasize crystal margins. 15 cm ruler for scale. (View).

Another example in the CP is the accumulation of K-feldspar megacrysts and megacryst-indented microgranitoid enclaves in a patch of CP granodiorite both of which are now in a late aplite dike that has intruded the volcanic host rock along the eastern margin of the TB (Figure 10d). This requires initial clustering of megacrysts and microgranitoid enclaves in the CP and then transport within the aplite dike. Along the contact between the CP and HD granodiorites, we have observed several other relationships. In a sheeted and mingling zone in the Sawmill Canyon area (Figure 2b) K-feldspar megacryst-rich dikes of the CP intruded into magmatically folded schlieren, some with aligned K-feldspar megacrysts, and sheets of mingled HD and CP granodiorites (Figure 10e). Some of these dikes began to thicken and diapirically intrude the surrounding layers and sheets. One interpretation is that the CP magma was more buoyant and thus rose and deformed adjacent layers.

Whatever the correct interpretation, it requires the alignment of megacrysts in the schlieren prior to diapiric rise of megacryst rich masses. We have also found microgranitoid enclaves with K-feldspar megacrysts in mingled zones along the HD-CP granodiorites contact: this contact and the enclaves are overprinted by a magmatic foliation (Figure 10f) as are other microgranitoid enclaves in the HD granodiorite. These observations imply early mingling of enclaves and K-feldspar megacrysts, juxtaposition of the CP-HD magmas, and finally overprinting by late strain prior to final crystallization. And finally, K-feldspar megacrysts are typically cut by late magmatic veins (Figure 10g). We are aware of only a few possible exceptions to the above observations and interpretations. For example, some megacrysts transect aplitic veins (Figure 10h).

However, aplites may form relatively early in the pluton history by fracturing of the incompletely crystallized host granite magma [e.g., Pitcher and Berger, 1972, p. 221; Hibbard & Watters, 1985]; if so, the megacrysts could have nucleated in either the vein magma or the host granite magma, or could have grown on existing K-feldspar crystals in either magma, and then continued to grow across the contact between both magmas [Vernon, 1986, p. 24]. Alternatively, if the aplite was formed late in the history of the pluton, this structure could represent continued growth of an existing K-feldspar megacryst into relatively late magma filling the vein [Vernon, 1986].

A similar explanation may account for dendritic aggregates of K-feldspar megacrysts transecting schlieren (Figure 3c,d); i.e., the megacrysts could have continued growing into magma with flow layering under conditions of strong supercooling. Evidence against concentration of megacrysts by in situ growth: Higgins (1991) suggested that concentrations of K-feldspar megacrysts in the TB granitoids are due to "Ostwald ripening", which he inferred to have dissolved existing K-feldspar crystals, making flow channels available for K-rich melt to precipitate and therefore concentrate K-feldspar megacrysts by in situ growth in the channels. An alternative explanation is that interstitial melt has been removed, passively concentrating the megacrysts — i.e., a "log jamb" situation (e.g., Clarke & Clarke 1998; Weinberg et al. 2001). Moreover, the evidence discussed in the previous sections indicates that K-feldspar megacrysts in granodiorites commonly move as large independent crystals and concentrate mechanically, rather than being the result of crystallization in situ.

As noted by Gilbert (1906, p. 322) and Wilshire (1969, 244), the K-feldspar megacrysts typically do not interpenetrate (Figure 3a, Figure 3b, Figure 4a-e, Figure 6g, Figure 9b, Figure 9d, Figure 10d), even where in contact, but almost always remain separate in the concentrating process; simultaneous, in situ growth of K-feldspar crystals would be likely to produce molding of one megacryst around another. Where local contact does occur, compositional zoning is truncated (Figure 9b, Figure 9d), which can indicate contact melting [Park & Means 1996]. Furthermore, K-feldspar megacrysts in the TB show normal zoning in Ba [Kerrick, 1990], as do many K-feldspar megacrysts [Vernon, 1986].

In contrast, dissolving early-formed small crystals should add progressively more Ba to the larger crystals though the effect may be minor, in view of the probable

small size of the crystals inferred to have been dissolved. In a few places, the most abundant, aligned K-feldspar megacrysts occur in the most mafic (hornblende-rich) schlieren (Figure 6, Figure 7), even around folded layers, indicating hydraulic equivalence between the two minerals at the sizes concerned. The model of Higgins (1999) produces layers rich in K-feldspar, not hornblende. Moreover, if the megacrysts were formed in situ from percolating K-rich melt, there would be little constraint on them to grow with such a strong parallel alignment. In addition, a K-rich granitic melt would also be expected to precipitate some biotite, plagioclase and quartz with the K-feldspar.

It is also difficult to explain magmatic fabric characteristics by the Higgins model. We infer that the slightly younger magmatic foliation/lineation, which cuts contacts between intrusive units in the TB (Figure 2), recorded strain increments superimposed on a relatively static chamber [Paterson et al., 2003]. In the CP granodiorite and the Johnson granite porphyry, this regional magmatic foliation/lineation is in places defined by K-feldspar megacrysts, suggesting that they were present in the magma prior to fabric formation, and subsequently have been re-oriented due to regional strain while a melt was still present in the system.

A final argument is that mafic schlieren (Figure 6, Figure 9a-b) and microgranitoid enclaves (Figure 10d) commonly are indented by K-feldspar megacrysts. In the Higgins (1999) model, the megacrysts would have to physically push aside the mafic layer or enclave during their growth. Below we suggest an alternative interpretation that extraction of melt occurred, leading to collapse of the mafic layer or enclave around the strong megacrysts.

Types of processes that physically moved/accumulated K-feldspar megacrysts: In an earlier section we noted structures associated with the physical movement and/or accumulation of K-feldspar megacrysts in the TB (also see Gilbert 1906). We now speculate on the processes that are implied by these structures/accumulations.

1. Where K-feldspar megacrysts are concentrated, the magma between the megacrysts must have been preferentially removed. We infer this to have taken place by a "filter-pressing" mechanism [e.g., Kerr and Tait 1986; Park and Means 1996; Weibe 1996; Clarke & Clarke 1998; Weinberg et al. 2001]. We suggest that the fracturing (Figure 3a, b) and contact melting (Figure 9a, d) of K-feldspar megacrysts in clusters

- imply that zoned megacrysts grew, and then were physically accumulated during removal of magma, during which some impinged on one another, possibly causing the cracking or contact melting. The "pressing" was driven by buoyancy, but the details varies from place to place. For example, we interpret the deflection of schlieren layering around megacrysts (Figure 6c, 6d, 9a, 9b, 9c) as a result of filter pressing driven by sinking of the overlying layer, which would increase the proportion of the mafic minerals (as the more felsic melts rise). Alternatively, megacryst-rich plumes may rise and cause filter pressing on their upper surfaces along which concentrations of mafic minerals form (Figure 6a, 8a, 8b, 10e). Concentrations of megacrysts in dikes (Figure 5) may partly result from melts draining off as flow in the dikes slow and the dike wall collapse inwards.
2. Imbrication (tiling) of megacrysts presumably occurred during magmatic strain caused by flow [Blumenfeld, 1983; Paterson et al., 1989; Paterson et al. 1998; Vernon 2000], leading to concentration of megacrysts as they piled up behind obstacles or more slowly moving megacrysts (Figure 4b, 4c, 4e, 9d). Again the magma between the megacrysts must be "removed" and thus move at a faster velocity than the megacrysts [e.g., Koide and Bhattacharji 1975; Bergantz 2000].
 3. The general clusters preserve little evidence of how they formed. They typically are not associated with preserved evidence of flow [e.g., schlieren layers, boundaries, etc] and occur in a variety of different settings in the chamber. Only rarely are they associated with dikes indicating that melt drained off (Figure 10c). However we think it likely that these clusters reflect regions where K-feldspar megacrysts "piled up" during general flow in combination with removal of the magma between crystals as described above.
 4. We interpret schlieren troughs, including grading in the schlieren and cross-cutting of one trough by another (Figure 6), to be equivalent to sedimentary troughs and grading and thus to reflect local magma flow channels [e.g., Barrière 1981; Bateman 1992]. The scattered to locally concentrated K-feldspar megacrysts, along with mafic minerals and microgranitoid enclaves in the trough-bounding schlieren layers (Figure 6, 7) indicate hydraulic equivalence of these objects. Koide and Bhattacharji (1975) and Weinberg et al. (2001) ascribed this kind of layering to shear sorting, and Barrière (1981) discussed possible boundary effects that lead to sorting of minerals during such shear flow.
 5. The "schlieren tubes" (Figure 7) and diapirically rising "plumes" (Figure 6a, 8, 10e) are interpreted by Weinberg et al. (2001) to form by compositional and thermal instabilities that drive local flow in closed channels through a crystal mush. Our observations strongly support their interpretations and add some additional information. Almost all tube and plume axes plunge greater than 70° in the TB suggesting gravity played a dominant role in their formation. The rare exceptions typically have evidence that the tubes/plumes "fell over" and collapsed into the surrounding magma. The tubes typically cut through older layering (if present), and in a few places we have observed their 3D forms (Figure 7b, 7c). Some of the plumes consist of up to 80% modal percent of K-feldspar megacrysts (Figure 8) indicating that liquid was removed from the plume by a "filter pressing" mechanism. Others distort overlying schlieren layers (Figure 6a, Figure 10e) and have concentrations of mafic minerals along their upper surfaces (Figure 8a, b), again suggesting a filter pressing mechanism during rise of the plumes. We suggest that shear-flow sorting and filter pressing mechanisms led to the K-feldspar concentrations, which in turn led to additional compositional buoyancy driving further upward motion. Both tubes and plumes are overprinted by a magmatic fabric, indicating that these features represent local flow before the magma reached its solidus.
 6. Megacryst concentrations in dike-like bodies with diffuse (Figure 5q) or sharp (Figure 5c, d) boundaries may reflect different processes. We interpret bodies with sharp boundaries as true dikes in which magma was flowing along a crack formed in a crystal-rich magma. Some of these dikes extend at least 100s meters suggesting that magma viscosities in the dike were not high and thus that the magma in the dikes originally had a greater proportion of melt and/or was volatile-rich. In these dikes, liquid was driven off into megacryst poor veins, by filter pressing through the dike walls, or by flow along the dike as the dikes cooled, collapsed and concentrated the megacrysts. However, we cannot determine to what degree

megacrysts were concentrated before entering the dikes as opposed to concentration of megacrysts by loss of liquid during late freezing and shrinking of the dikes. Dike-like megacryst concentrations with diffuse boundaries (Figure 5a) may represent zones of local "filter pressing" and megacryst accumulation , or may be former planar dikes in a crystal mush, the dikes having been deformed by continued flow of the mush. may rise into surrounding materials by thermal or compositional buoyancy-driven motion (Figure 6a , 6h , 10e).

7. We are aware of three possible interpretations of the megacryst concentrations derived from the CP phase that now reside in the megacryst-free outer HD phase (Figure 4h): (a) previous accumulations slumped off a reasonably crystallized CP margin into the HD magma; (b) previous accumulations along a margin between two magmas diapirically rose into the HD magma; and (c) magma mingling occurred between the two magmas driven by flow along the margin [e.g., Bergantz 2000] . At present the CP is considered to be younger than the HD [e.g., Coleman et al. 2004] , and we thus favor one of the latter two interpretations.
8. The introduction of K-feldspar megacrysts into microgranitoid enclave magmas by magma mixing (commonly before the formation of enclaves by magma mingling) implies the existence of separate megacrysts at a relatively early stage of the history of the host magma. Arguments in favor of magma mixing, rather than in situ growth of K-feldspar megacrysts in enclaves have been discussed by Reid et al. (1983) and Vernon (1983, 1986, 1990, 1991).
9. The alignment of megacrysts reflect late strain in the chamber which realigned already existing K-feldspar megacrysts and possibly brought them together during strain as interstitial melt was driven off.

Conclusion

Our study indicates the following conclusions:

1. K-feldspar megacrysts in the TB grew from a the liquid portion of a magma at conditions of unusually low nucleation-to-growth ratio, presumably at low degrees of supersaturation. We see no evidence of subsolidus growth, nor that grain coarsening played a

significant role beyond the nucleation and microscopic stage of growth.

2. There is ample evidence of the physical accumulation by several processes (filter pressing, flow sorting, buoyant rise, mixing/mingling) of K-feldspar megacrysts during which the concentration of K-feldspar megacrysts increased from a few volume percent to as high as 80 volume percent and resulted in concentrations in irregular patches, troughs, tubes, plumes, dikes, and enclaves.
3. Clustering of K-feldspar megacrysts cannot be explained by potassium-rich fluid fluxes, particularly where the megacrysts occur in more mafic layers or in very high in more mafic layers or in very high concentrations. The lack of molding relationships and local evidence of contact melting when megacrysts collide in clusters support this conclusion.
4. Evidence of the physical accumulation of the megacrysts has several implications for internal chamber processes. In the TB, numerous, local instabilities preferentially collected certain minerals and formed local compositions and structures. Thus the modes of rocks in the TB do not reflect the original magma compositions [see also Healy et al., 2000, Weibe et al., 2002]. The compositional and structural heterogeneity also argues against widespread convection, at least late in the chamber evolution, and instead implies that local gradients existed in the TB, although the nature of these gradients remain unclear [[Zak and Paterson, in review]. Moreover, the megacryst concentrations indicate that the megacrysts and surrounding magmas did not share the same flow history [e.g., Bergantz, 2000] further complicating the physical meaning of magmatic fabrics [Paterson et al. 1998; Healy et al. 2000].

Acknowledgments

SRP and JZ acknowledge support of National Science Foundation grant EAR-0073943 (to Paterson) and grant No KJB3111403 (to Zak) of the Czech Academy of Sciences. We thank ... ?? for critically reviewing the typescript.

References

- Abbott, R.N. (1989) Internal structures in part of the South Mountain batholith, Nova Scotia, Canada. *Bulletin of the Geological Society of America* 101: 1493-1506.
- Baronnet, A. (1982) Ostwald ripening in solution. The case of calcite and mica. *Estudios geológicos* 38: 185-198.
- Baronnet, A. (1984) Growth kinetics of the silicates. A review of basic concepts. *Fortschritte Mineralogie* 62: 187-232.
- Barrière, M. (1981) On curved laminae, graded layers, convection currents and dynamic crystal sorting in the Ploumanac'h (Brittany) subalkaline granite. *Contributions to Mineralogy and Petrology* 77: 217-224.
- Bateman, P.C. (1992) Plutonism in the Central Part of the Sierra Nevada Batholith, California: United States Geological Survey Professional Paper 1483, 186 p.
- Bateman, P.C. & Chappell, B.W. (1979) Crystallization, fractionation, and solidification of the Tuolumne Batholith, Yosemite National Park, California. *Bulletin of the Geological Society of America* 90: 465-482.
- Bergantz, G.W. (2000) On the dynamics of magma mixing by reintrusion: implications for pluton assembly processes. *Journal of Structural Geology* 22: 1297-1309.
- Blumenfeld, P. (1983) Le "tuilage des mégacristaux," un critère d'écoulement rotationnel pour les fluidités des roches magmatiques: application au granite de Barbey-Sérour (Vosges, France). *Bulletin de la Société géologique de France* 25: 309-318.
- Buckley, H.E. (1961) *Crystal Growth*. Wiley, New York, 571 pp.
- Cabane, H., Laporte, D. & Provost, A. (2001) Experimental investigation of the kinetics of Ostwald ripening of quartz in silicic melts. *Contributions to Mineralogy and Petrology* 142: 361-373.
- Clarke, D.B. & Clarke, G.K.C. (1998) Layered granodiorites at Chebutco Head, South Mountain batholith, Nova Scotia. *Journal of Structural Geology* 20: 1305-1324.
- Clemens, J.D. & Wall, V.J. (1981) Origin and crystallization of some peraluminous (S-type) granitic magmas. *Canadian Mineralogist* 19: 111-131.
- Cloos, E. (1936) Der Sierra Nevada Pluton in Californien. *Neues Jahrbuch für Mineralogie, Geologie und Paläontologie* 76 part B: 355-450.
- Coleman, D.S. & Glazner, A.F. (1997) The Sierra Crest magmatic event; rapid formation of juvenile crust during the Late Cretaceous in California. *International Geology Review* 39: 768-78.
- Coleman, D.S., Glazner, A.F., & Gray, W. (2002) U-Pb geochronologic evidence for incremental filling of the Tuolumne Intrusive Suite magma chamber. *Geological Society of America Abstracts with Programs* 34: 269.
- Eberl, D.D., Kile, D.E. & Drits, V.A. (2002) On geological interpretations of crystal size distributions: Constant vs. proportionate growth. *American Mineralogist* 87: 1235-1241.
- Eggleton, R.A. (1979) The ordering path for igneous K-feldspar megacrysts. *American Mineralogist* 64: 906-911.
- Fenn, P.M. (1977) The nucleation and growth of alkali feldspars from a hydrous melts. *Canadian Mineralogist* 15: 135-161.
- Fleck, R.J., Kistler, R.W., & Wooden, J.L., (1996) Geological complexities related to multiple emplacement history of the Tuolumne intrusive suite, Yosemite National Park, California: *Geological Society of America Abstracts with Programs* 28: 65-66.
- Gilbert, G.K. (1906) Gravitational assemblage in granite. *Bulletin of the Geological Society of America* 17: 321-328.
- Glazner, A.F., Bartley, J.M., Coleman, D.S., Gray, W., & Taylor, R.Z. (2004) Are plutons assembled over millions of years by amalgamation from small magma chambers? *GSA Today* 14: 4-11.
- Healy, B.C., Collins, W.J., Richards, S.W. & Wiebe, R.A. (2000) Chemical effects of squeezing a crystal mush during compressive deformation: the Kamberuka pluton, Lachlan Fold Belt. *Geological Society of Australia Abstracts* 59: 216.
- Hibbard, M.J., and Watters, R.J. (1985). Fracturing and diking in incompletely crystallized granitic plutons. *Lithos* 18: 1-12.
- Higgins, M.D. (1999) Origin of megacrysts in granitoids by textural coarsening: a crystal size distribution (CSD) study of microcline in the Cathedral Peak Granodiorite, Sierra Nevada, California. In: Castro, A., Fernández, C. & Vigneresse, J.-L. (eds): *Understanding Granites: Integrating New and Classical Techniques*. Geological Society of London Special Publication 168: 207-219.
- Jackson, K.A. (1967) A review of the fundamental aspects of crystal growth. In: Peiser HS (ed.): *Crystal Growth*. Pergamon, Oxford, 17-24.
- Kerr, R.C., & Tait, S.R. (1986) Crystallization and compositional convection in a porous medium with application to layered igneous intrusions. *Journal of Geophysical Research* 91: 3591-3608.
- Kerrick, D.M. (1990) K-feldspar megacrysts from a porphyritic quartz monzonite central Sierra Nevada, California. *American Mineralogist* 54: 839-848.
- Kile, D.E., Eberl, D.D., Hoch, A.R. & Reddy, M.M. (2000) An assessment of calcite crystal growth mechanisms based on crystal size distributions. *Geochimica et Cosmochimica Acta* 64: 2937-2950.
- Kistler, R.W., & Fleck, R.J. (1994) Field guide for a transect of the central Sierra Nevada, California: *Geochronology and isotope geology: United States Geological Society Open-File Report* 94-267.

- Kistler, R.W., Chappell, B.W., Peck, D.L., & Bateman, P.C., (1986) Isotopic variation in the Tuolumne Intrusive Suite, central Sierra Nevada, California. *Contributions to Mineralogy and Petrology* 94: 205-220.
- Koide, H., & Bhattacharji, S. (1975) Flow differentiation in igneous dikes and sills: profiles of velocity and phenocryst concentration. *Bulletin of the Geological Society of America* 83: 3443-3448.
- Marsh B.D. (1988) Crystal size distribution (CSD) in rocks and the kinetics and dynamics of crystallization I. Theory. *Contributions to Mineralogy and Petrology* 99: 2772-291.
- Marsh B.D., Higgins M.D. (2002) Inherited correlation in crystal size distribution: Comment and reply. *COMMENT. Geology* 30: 284-285.
- Martin J.W., Doherty R.D. (1976) *Stability of Microstructure in Metallic Systems*. Cambridge University Press, Cambridge, 298 pp.
- Miller, J.S., Miller, R.B., Wooden, J., & Miller, B. (2003) A complex magmatic injection zone in the Half Dome granodiorite, Tuolumne Intrusive Suite, Sierra Nevada Batholith, CA. *Geological Society of America Abstracts with Programs* 35: 18.
- Miller, R.B., & Miller, J.S., (2003) Emplacement of the Tuolumne Intrusive Suite, Sierra Nevada Batholith. *Geological Society of America Abstracts with Programs* 35: 18.
- Miyazaki, K. (1991) Ostwald ripening of garnet in high P/T metamorphic rocks. *Contributions to Mineralogy and Petrology* 108: 118-128.
- Pan Y. (2001) Inherited correlation in crystal size distribution. *Geology* 29: 227-230.
- Pan Y. (2002a) Inherited correlation in crystal size distribution: Comment and reply. *REPLY. Geology* 30: 283-284.
- Pan Y. (2002b) Inherited correlation in crystal size distribution: Comment and reply. *REPLY. Geology* 30: 285-286.
- Park Y. & Means D. (1996) Direct observation of deformation processes in crystal mushes. *Journal of Structural Geology* 18: 847-858.
- Paterson, S.R., Onezime, J. Teruya, L. & Zak, J. (2003) Quadruple-pronged enclaves: their significance for the interpretation of multiple magmatic fabrics in plutons. *Journal of the Virtual Explorer*, Volume 11: <http://virtualexplorer.com.au/2003/general/paterson/>
- Paterson SR, Vernon RH, Tobisch OT (1989) A review of criteria for the identification of magmatic and tectonic foliations in granitoids. *Journal of Structural Geology* 11: 349-363.
- Paterson, S.R., Fowler, T.K., Schmidt, K., Yoshinobu, A. & Yuan S. (1998) Interpreting magmatic fabric patterns in plutons. *Lithos* 44: 53-82.
- Phillips E.R. (1968) Some plutonic rocks from a northern part of the New England Batholith. *University of Queensland Papers, Department of Geology* 6: 159-206.
- Pitcher W.S., Berger A.R. (1972) *The Geology of Donegal: A Study of Granite Emplacement and Unroofing*. Wiley, New York.
- Piwinskii A.J. & Wyllie P.J. (1970) Experimental studies of igneous rock suites; a zoned pluton in the Wallowa Batholith, Oregon. *Journal of Geology* 76: 205-234.
- Reid J. B., Evans O.C. & Fates D.G. (1983) Magma mixing in granitic rocks of the central Sierra Nevada, California. *Earth and Planetary Science Letters* 66: 243-261.
- Reid J. B., Murray D.P., Hermes O.D., & Steig E.J. (1993) Fractional crystallization in granites of the Sierra Nevada: How important is it? *Geology* 21: 587-590.
- Schaeben H., van den Boogaart K., Mock A., & Breitzkreuz C. (2002) Inherited correlation in crystal size distribution: Comment and reply. *COMMENT. Geology* 30: 282-283.
- Swanson S.E. (1977) Relation of nucleation and crystal-growth rate to the development of granitic textures. *American Mineralogist* 62: 966-978.
- Tobisch O.T., McNulty B.A., & Vernon R.H. (1997) Microgranitoid enclave swarms in granitic plutons, central Sierra Nevada, California. *Lithos* 40: 321-339.
- Vernon, R.H. (1983) Restite, xenoliths and microgranitoid enclaves in granites (Clarke Memorial Lecture). *Journal and Proceedings of the Royal Society of New South Wales* 116: 77-103.
- Vernon R.H. (1985) Possible role of superheated magma in the formation of orbicular granitoids. *Geology* 13: 843-845.
- Vernon R.H. (1986) K-feldspar megacrysts in granites — phenocrysts, not porphyroblasts. *Earth-Science Reviews* 23: 1-63.
- Vernon R.H. (1990) Crystallization and hybridism in microgranitoid enclave magmas: microstructural evidence. In: Sawka, W.N. & Hildebrand, R.S. (eds): *Mafic inclusions in granites*. *Journal of Geophysical Research* 95: 17849-17859.
- Vernon R.H. (1991) Interpretation of microstructures of microgranitoid enclaves. In: Didier, J. & Barbarin, B. (eds): *Enclaves and Granite Petrology*, Elsevier, Amsterdam, 277-291.
- Vernon R.H. (1999) Quartz and feldspar microstructures in metamorphic rocks. *Canadian Mineralogist* 37: 513-524.
- Vernon R.H. (2000) Review of microstructural evidence of magmatic and solid-state flow. *Electronic Geosciences* 5:2.
- Vernon R.H. (2004) *A Practical Guide to Rock Microstructure*. Cambridge University Press, Cambridge.
- Vernon R.H., Johnson, S.E. Melis E.A. (2004) Emplacement-related microstructures in the margin of a deformed tonalite pluton: the San José pluton, Baja California, México. *Journal of Structural Geology*, in press.

- Vernon R.H., Paterson S.R. (2002) Igneous origin of K-feldspar megacrysts in deformed granites of the papoose Flat pluton, California , USA . *Electronic Geosciences* 7: 31-39.
- Wahrhaftig C. (1979) Significance of asymmetric schlieren for crystallization of granites in the Sierra Nevada batholith, California . *Geological Society of America Abstracts with Programs* 11: 133.
- Weinberg R.F., Sial, A.N., &Pessoa, R.R. (2001) Magma flow within the Tavares pluton, northeastern Brazil : Compositional and thermal convection. *Bulletin of the Geological Society of America* 113: 508-520.
- Wiebe R. A., Blair, K. D., Hawkins D. P. &Sabine, C. P. (2002) Mafic injections, in situ hybridization, and crystal accumulation in the Pyramid Peak granite, California. *Bulletin of the Geological Society of America* , 114 , 909-920.
- Wiebe R.A. (1994) Silicic magma chambers as traps for basaltic magmas: the Cadillac Mountain intrusive complex, Mount Desert Island , Maine . *Journal of Geology* 102: 423-437.
- Wiebe R.A. (1996) Mafic-silicic layered intrusions: the role of basaltic injections on magmatic processes and the evolution of silicic magma chambers. *Transactions of the Royal Society of Edinburgh : Earth Sciences* 87: 233-242.
- Wilshire H.G. (1969) Mineral layering in the Twin Lakes Granodiorite, Colorado . *Geological Society of America Memoir* 115: 235-261.
- Zieg, M.J. &Marsh, B.D. (2002) Crystal size distributions and scaling laws in the quantification of igneous textures. *Journal of Petrology* 43: 85-101.