The nature and polygenetic origin of orbicular granodiorite in the Lower Castle Creek pluton, northern Sierra Nevada batholith, California

Arthur Gibbs Sylvester

Department of Earth Science, University of California, Santa Barbara, California 93106, USA

ABSTRACT

Mafic and granodioritic magmas mingled to produce a swarm of microdiorite enclaves in the granodiorite. The enclaves and rare hornfels inclusions were carried upward in an oval-shaped pipe, 30 m long and 15 m wide, probably as a gas-driven mass to a point where an H$_2$O-rich, superheated felsic melt intruded the pipe and the enclave mass, and upon abrupt undercooling, deposited orbicular shells of tangentially oriented microcrystals of sodic plagioclase, quartz, K-feldspar, and biotite on 20% of the enclaves and inclusions now located only against the north margin of the pipe. The mass of orbicular and non-orbicular enclaves was then injected by a quartz monzodiorite magma that now comprises the matrix among the enclaves.

INTRODUCTION

During the course of regional geologic mapping in the Donner Pass region of the Sierra Nevada, several localized swarms of mafic magmatic enclaves were discovered in some of the plutonic rocks that provide good field evidence of the enclaves' origin by magma mingling. Such enclave swarms are relatively common in Sierran granitic plutons (Tobisch et al., 1997; Vernon and Paterson, 2008), and for the purposes of this paper, I accept the field, structural, geochemical, and modeling evidence that mafic enclaves represent globules of mafic magma produced by the mingling of a hot mafic magma with a cooler host granitic magma in the mid- to upper crustal levels of granitic plutons (e.g., Taylor et al., 1980; Vernon, 1983; Reid et al., 1983; Furman and Spera, 1985; Frost and Mahood, 1987; Larsen and Smith, 1990; Foster and Hyndman, 1990; Zorpi et al., 1989; Wiebe, 1991; Barbarin and Didier, 1992; Pitcher, 1993; Wiebe et al., 1997; Barbarin, 2005, and many others).

Much less common, but by no means unique, are concentrations of mafic enclaves with orbicular structure, not only in the Sierra Nevada

batholith (Moore and Lockwood, 1973), but also in plutons worldwide, especially in Scandinavia (e.g., Sederholm, 1928; Simonen, 1966; Lahti, 2005). The orbicules themselves may have cores of other kinds of rocks besides mafic rocks, including metamorphic rock fragments and single crystals or clots of minerals such as K-feldspar megacrysts (e.g., Lahti, 2005).

This paper describes an assemblage and origin of some remarkable orbicular rocks with felsic haloes in a single pipe-like exposure in the granodiorite of Lower Castle Creek pluton in the northern Sierra Nevada batholith (Fig. 1). These orbicular rocks bear similarities to some

of those elsewhere in the Sierra Nevada (Moore and Lockwood, 1973), although they are larger and better developed than most Sierran examples (Fig. 2). Large mafic enclaves with felsic haloes have also been noted but not described by Tobisch et al. (1997, their fig. 8c, p. 333) in the central Sierra Nevada batholith.

TERMINOLOGY

Mafic magmatic *enclaves* (MME in the terminology of Barbarin, 2005; also *autoliths* in the terminology of Pabst, 1928) comprise subrounded globules of mafic microgranular
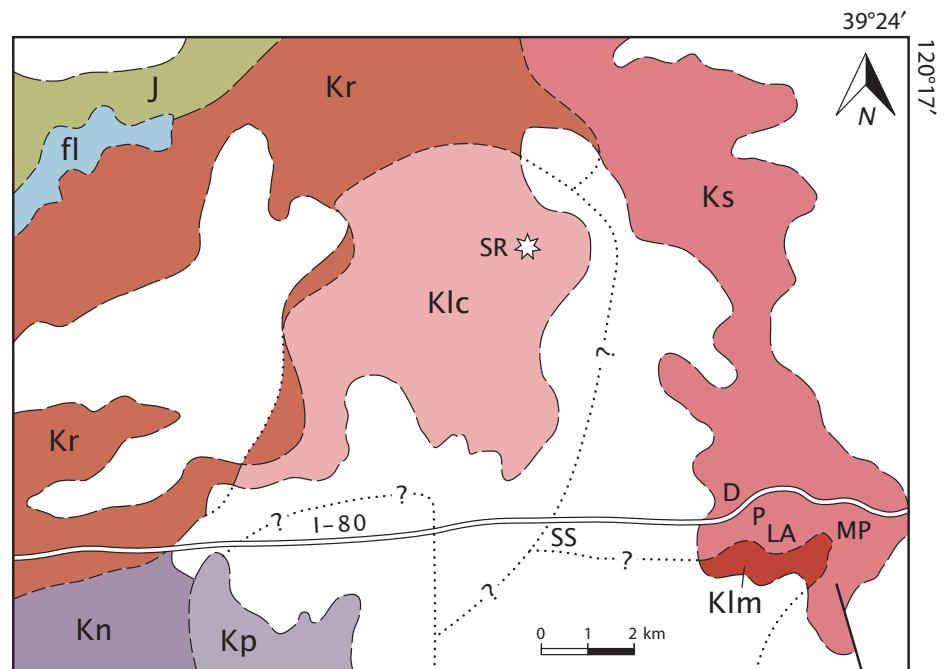

Figure 1. Geologic setting of the Lower Castle Creek pluton (with modifications after Kulow, 1996; Hudson, 1951). Rock units: Klc—granodiorite of Lower Castle Creek; Klm—tonalite of Lake Mary; Kn—Nancy Lake pluton; Kp—granodiorite of Palisade Creek; Kr—Rattlesnake Creek pluton; Ks—granodiorite of Summit Lake; no pattern—Cenozoic and Holocene cover. Localities: SR—Sand Ridge; SS—Soda Springs; DP—Donner Pass; MP—McGlashan Point; LA—Lake Angela; fl—Fordyce Lake. Star—orbicular rock locality.

Sylvester

Figure 2. Gray microdiorite enclaves with felsic orbicules of sodic plagioclase-quartz–K-feldspar–biotite encased in quartz monzodiorite matrix. Rare black inclusions, also with felsic orbicules, are Jurassic hornfels. Hammer handle length is 40 cm.

igneous rocks in a granitic matrix. Such enclaves are commonly but irregularly distributed throughout Sierran granitic plutons (Pabst, 1928; Mayo, 1935; Bateman et al., 1963; Link, 1969), especially in plutons of tonalitic or granodiorite composition. Mafic magmatic enclaves are distinguished from *xenoliths* that represent bits of mafic segregations (restite) from the bottoms of plutons (Bateman et al., 1963; Vernon, 1983, 1984; Chappell et al., 1987), or early formed indigenous cumulates of their host magmas (Dodge and Kistler, 1990), or mantle rocks (e.g., Irving, 1980), or of a mafic migmatitic neosome (Hopson and Mattinson, 1994). *Inclusions* are fragments derived from the pluton's country rocks.

Swarms are concentrations of abundant enclaves typically separated by a minimal amount of host matrix (Pabst, 1928, p. 331). Enclave swarms have subsequently been recognized widely in the Sierra Nevada (e.g., Tobisch et al., 1997; Vernon and Paterson, 2008) and in many granitic bodies worldwide (e.g., Gansser and Gyr, 1964; Didier, 1973; Elburg and Nicholls, 1995; Surour and Kabesh, 1998; Arvin et al., 2004). Most workers have concluded that such swarms formed by disaggregation or pillowing of hybrid mafic dikes during injection into a host felsic magma (e.g., Roddick and Armstrong, 1959; Reid et al.,

1983; Frost and Mahood, 1987; Wiebe, 1991; Sylvester, 1998).

Orbs are enclaves or country rock fragments that comprise a *core* typically consisting of plutonic igneous rocks that may range greatly from gabbro to granite and pegmatite (e.g., Enz et al., 1979; Lahti, 2005), and a concentric layer or *orbicule* of radially or tangentially oriented plagioclase and/or K-feldspar associated with quartz and biotite and or amphibole. Contacts between the core and the orbicule and between the orbicule and matrix are typically sharp. A plutonic *matrix* fills the spaces among the orbs; it may be composed of a slightly more mafic phase of the host plutonic rock (Leveson, 1966).

GEOLOGIC SETTING AND NATURE OF LOWER CASTLE CREEK PLUTON

The Lower Castle Creek pluton is an oval-shaped body of hornblende-biotite granodiorite ~9 km long and 8 km wide in the center of what Kulow (1996) termed the Castle Valley pluton assemblage (Fig. 1). Lower Castle Creek dikes intruded the adjacent plutons, and, with a U-Pb age of 110 ± 5 Ma (Kulow, 1996), it is the youngest pluton of the assemblage.

The granodiorite is a medium-grained, light-gray rock composed of euhedral to subhedral plagioclase (≥50%), anhedral poikilitic ortho-

clase (up to 17%), and fine- to medium-grained, subhedral quartz (up to 20%). The remainder of the rock comprises medium- to coarse-grained hornblende and biotite, commonly in mafic aggregates or clots from 5 to 8 mm in width, or in single, anhedral crystals up to 5 mm long. The clotted mafic minerals and its relatively high color index (15–36) distinguish the granodiorite of Lower Castle Creek from the surrounding plutons (Kulow, 1996).

Most of the granodiorite of Lower Castle Creek is homogeneous, but noteworthy outcrops of comb layering, schlieren, and orbicular rocks exist locally especially near its contacts with the Rattlesnake Creek pluton (Kulow, 1996). The mineralogy, fabric, and dimensions of the comb layering are similar to such features elsewhere in the Sierra Nevada batholith (Moore and Lockwood, 1973; Paterson et al., 2008). Discrete mafic enclaves are sparse in the Lower Castle Creek pluton, except in local, rare swarms, and country-rock inclusions have not been found except in the pipe described in this paper.

All of the Castle Creek plutons are cut by aplite dikes up to one meter thick and less commonly by rare diabase dikes from 0.3 m to 5 m thick, which, at their upper extremities within the adjacent Summit Lake and Rattlesnake Creek plutons, have clearly mingled with granodiorite to produce various types of swarms of mafic enclaves, notably at McGlashan Point[1] and Lake Angela[2] near Donner Pass (Fig. 1), and at Rainbow Bend in the southwest part of the Rattlesnake pluton (Pabst, 1928).

NATURE OF THE ORBICULAR ROCKS

The orbicular rocks crop out in a singular exposure of a quartz monzodiorite pipe on the north-facing flank of a small hill at the east end of Sand Ridge, 5 km north of Soda Springs, California (Fig. 1)[3]. The pipe lies well within the interior of the Lower Castle Creek pluton, about one kilometer west of its eastern contact with the older Summit Lake pluton. Orbicular rocks are generally found nearer the margins of plutons (Moore and Lockwood, 1973; Lahti, 2005), but several instances of them being evenly distributed or accumulated throughout an entire pluton have been cited, and some orbicular rocks may

[1]Located at the south end of Rainbow Bridge on Highway 40 at latitude 39.31849N, longitude –120.31849W.

[2]Located on the west slope of Lake Angela at latitude 39.32435N, longitude –120.32855W.

[3]The exposure is located on the north flank of hill 8020 in the northeast corner of the Soda Springs 7.5′ quadrangle at latitude 39.37020N, longitude –120.38503W.

Polygenic origin of orbicular granodiorite

coincide with inclusion- or enclave-rich zones in plutonic rocks (Lahti, 2005).

The quartz monzodiorite pipe is ~30 m long and 15 m wide within the hornblende-biotite granodiorite of Lower Castle Creek (Fig. 3). As such, it is almost an order of magnitude larger than most Sierran pipes described by Tobisch et al. (1997) and Paterson (2009). The contact between the pipe and the granodiorite host is fairly sharp or gradational over a zone ~10 cm (Fig. 4), but locally the contact is a schlieren zone from 20 to 50 cm wide (Fig. 5).

Eighty percent of the enclaves in the pipe are quite ordinary rounded or subrounded mafic magmatic enclaves, generally 5–15 cm in longest dimension grading upward to outsized individuals of 20 cm (Fig. 6). Enclave packing is moderate to tight, their axial ratios are ~2:1, and they lack preferred orientation. All consist of fine-grained microdiorite and are now more feldspathic than their inferred initial diabasic composition because of extensive chemical exchange with the quartz monzodioritic matrix and perhaps also with granodiorite of the host pluton, a common phenomenon among mafic enclaves in other Sierran granitic plutons (Pabst, 1928; Barbarin, 1990; Sisson et al., 1996) and elsewhere (e.g., Zorpi et al., 1991).

The remaining 20% of the enclaves in the quartz monzodiorite pipe are orbicular mafic magmatic enclaves and rare, angular fragments of hornfels characterized by felsic orbicules (Fig. 7). The hornfels stems from locally and widely exposed country rocks of the Jurassic Sailor Canyon Formation. The orbicular rocks are concentrated exclusively at the north margin of the pipe (Fig. 3) right up to its sharp contact with the host pluton, whereas the contact between the orbicular and the nonorbicular enclaves in the pipe is gradational over a few centimeters. The orbicular enclaves are moderately packed; their axial ratios are from 1:1 to 3:1, and they are generally twice as large as the nonorbicular enclaves.

The felsic orbicules are typically symmetrical and well developed, ranging in thickness from 7 to 40 mm; most are ~20 mm thick. Each orbicule maintains its thickness around its enclave, at least in the two-dimensional exposures afforded by the outcrop. In most instances, the orbicules are in direct contact with their cores and, thus, are concentric to the edge of the semirounded enclaves (Fig. 2). Orbicules of some enclaves touch or overlap in a shared arrangement (Fig. 8) as if stuck together, flattened, or molded and thinned against one another, suggesting they were plastic and agglutinated in the magmatic state. Some of the microdiorite cores have a slice of granodiorite between them and their orbicule (Fig. 9), demonstrating that mingling

Figure 3. Field sketch map of the distribution of orbicular and nonorbicular microdiorite enclaves in quartz monzodiorite pipe within host hornblende-biotite granodiorite, cut by a fault. Orbicular enclaves are not drawn to scale.
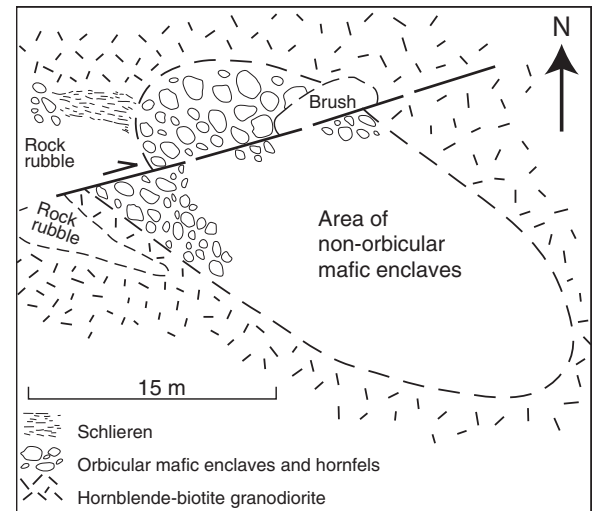

Figure 4. Dashed line demarcates contact between host hornblende-biotite granodiorite (left) and quartz monzodiorite pipe (right) with its microdiorite orbs. Bar scale is 15 cm long.

of granodiorite and the mafic protolith occurred before formation of the orbicules, and that separation of the enclaves from granodiorite was not always complete before being mantled with a felsic orbicule.

Regardless of the composition of the core, the orbicules are identical in mineralogy, fabric, and layer stratigraphy. Thus, the orbicules consist of ~75% microcrystalline sodic plagioclase, 20% quartz, and 5% K-feldspar. Discontinuous, wispy biotite-rich platelets and layers define a foliation that is tangential to the margin of each

core (Fig. 10). Whereas the crystals in orbicules described by other writers are usually characterized by a radial fabric (e.g., Fig. 11), tangential fabrics are relatively common in orbicules composed mainly of felsic minerals and biotite (Lahti, 2005), and are probably due to epitaxis controlled by the minimum interfacial energy achieved by crystal-lattice arrangements.

Closer examination of the layers in the orbicules reveals that several orbs in a small area, a couple meters square, contain a distinctive white layer of anhedral K-feldspar and quartz

Sylvester

Figure 5. Schlieren zone between quartz monzodiorite with microdiorite orbs (right) and host granodiorite (left) is located only along part of the contact between the pipe and the granodiorite. Hammer handle length is 40 cm.

Figure 6. Swarm of rounded and subrounded mafic magmatic enclaves (right), in various stages of hybridization, is encased in quartz monzodiorite in sharp contact with the enclave-free granodiorite host (beneath hammer) at the southeast end of quartz-monzodiorite pipe (Fig. 3).

located about one-third of the thickness from the inner margin of the orbicule (Figs. 10 and 12). Like a distinctive tree ring, this layer indicates that some of the orbicules experienced a common depositional event when the orbicules had achieved about one-third of their growth. In none of the orbicules are inner layers partly missing or transected by unconformities; all in all, the felsic layers are concentric with the core.

DISCUSSION

The diverse rock types, ranging from microdiorite enclaves to granodiorite plutonic host to felsic orbicules to quartz monzodiorite matrix in the pipe, imply that a multiplicity of synplutonic magma injection events occurred to form the remarkable assemblage of orbicular and nonorbicular rocks. The following events may be inferred from the field relationships: (1) mingling of the microdiorite protolith and granodiorite to form a swarm of discrete microdiorite enclaves; (2) variable hybridization of the mafic enclaves with the host granodiorite; (3) injection of a felsic melt or aqueous fluid that deposited orbicules on 20% of the enclaves and on rare hornfels inclusions that at some point were spatially separated from the other 80%; and (4) infusion of quartz monzodiorite melt to form the matrix among both the orbicular and nonorbicular rocks.

It is reasonable to infer that the swarm of mafic magmatic enclaves originated by mingling of parent hornblende-biotite granodiorite magma with a mafic magmatic intrusion for two reasons: (1) thin sections of the microdiorite reveal the presence of quartz ocelli, acicular apatite, and fritted plagioclase, three mineral habits that are distinctive of mingled mafic rock (Angus, 1962; Reid et al., 1983; Castro et al., 1990; Vernon, 1990; Sylvester, 1998), and (2) because the mingling process is clearly displayed at a few locations elsewhere in the region as described above, as well as in other high-level Sierra Nevadan plutons (e.g., Reid et al., 1983; Frost and Mahood, 1987; Barbarin, 1990, 2005; Coleman et al., 1995; Sisson et al., 1996), and as described elsewhere, especially by Wiebe (1991), Barbarin and Didier (1992), and Pitcher (1993), among many others. The presence of orbs with a microdiorite core having a partial rind of granodiorite (Fig. 9) indicates that mingling occurred before the formation of the orbicular shell, but it also indicates that some of the enclaves were not completely disassociated from their granodiorite host when the orbicules formed.

The felsic orbicules are evidence that discrete infusion of melt followed hybridization of

Polygenic origin of orbicular granodiorite

the mafic enclaves. The rounded shapes of the mafic enclaves and the tangential layering in the orbicules imply that the orbicular structures formed in the magmatic state. The irregular, polygonal shape of the rare hornfelsic inclusions implies that they were solids, that they obtained their shapes by fracture, and that they retained their shapes even when entrained in the granodiorite magma.

Nucleation of the orbicules occurred directly on the margins of solid enclave and hornfels cores. The contact between the orbicules and the quartz monzodiorite matrix is invariably sharp, which indicates an abrupt, in situ change in the conditions of crystallization. It is especially noteworthy that the orbicules lack dispersed crystals having the shape, size, and distribution of those in the quartz monzodiorite matrix or granodiorite of the pluton, indicating that orbicule formation was a discrete event in the interval between enclave formation and matrix crystallization.

The sharp outer contact of the orbicules indicates that both orbicular and nonorbicular enclaves and inclusions were coherent and mutually separable before their incorporation in the quartz monzodiorite matrix. Some of the orbicules are merged (Fig. 8), indicating they were plastic enough to agglutinate during the time of orbicule formation. The K-feldspar and/or quartz rings within the orbicules (Figs. 10 and 12) indicate compositional fluctuations of felsic melt in the pipe, probably due to fluctuations in temperature and pressure. The orbicules cannot have formed by metasomatic reaction between their microdioritic cores and the quartz monzodiorite matrix (Thompson and Giles, 1974; but see also Enz et al., 1979), because the orbicules are equally developed around hornfels.

In order for orbicules to form so nicely and neatly on just some of the enclaves, however, their spatial separation is required at their place of origin or during transport through the pipe, perhaps as a gas-driven fluidized mass, to a site where the pipe encountered a felsic melt. Direct evidence of such a gas-driven mechanism is lacking at the outcrop, but fluidization is commonly postulated to explain transport of fragmented rocks in pipes in shallow epizonal plutons (e.g., Platten, 1984; Burnham, 1985; Ross et al., 2002). The felsic melt was probably an aplite dike that supplied the mineral components for the orbicules.

The fourth event was infusion of quartz monzodiorite into the mixture of orbicular and nonorbicular enclaves and inclusions. Restriction of this heterogeneous mass to the confines of the pipe and plastic deformation of some the orbs suggest that the mixture was transported as a mobilized aggregate through the

Figure 7. Hammer bridges the gap between two halves of a hornfels inclusion separated from its felsic orbicule by a rind of granodiorite; black feature in center of image is a shadow between the two halves.

Figure 8. Two mafic enclaves conjoined by a felsic orbicule. Pencil for scale. Photo by Amber Miniami.

Sylvester

Figure 9. Felsic orbicule encloses mafic enclave together with its partial orbicule of grano-diorite, all surrounded by quartz monzodiorite.

Figure 10. Detail of felsic orbicule with a thin, white layer of microcrystalline K-feldspar and quartz. Inner edge (top) of orbicule is against the mafic core; upper edge is against quartz monzodiorite matrix. Tangential mineral layering within orbicule is defined by discontinuous concentrations of biotite. Photo by Amber Miniami.

host granodiorite. Schlieren along part of the pipe margin (Fig. 5) are local evidence of flow between the mass of enclaves in the pipe and the host granodiorite.

Although the orbs are not closely associated with comb-layered structures in the Lower Castle Creek pluton, they share enough features with well-developed orbs described elsewhere in the literature to suggest the processes of formation may be similar (Tom Sisson, 2006, written commun.). These shared features include: (1) a spatial concentration of preexisting mafic enclaves, such as provided by an enclave swarm; (2) a restricted size range of the mafic enclaves, probably due to mechanical sorting during flow; (3) coating of the enclave cores with an anomalous abundance of one or a few mineral phases; and (4) the presence of a rare metamorphic fragment in some of the enclave swarms, supporting mechanical concentration as a possible cause of the sorting observed in the pipe.

Concentration of the orbs to just part of the pipe demands discussion (Fig. 3). Moore and Lockwood (1973) noted that comb-layering and orbicular structures are largely restricted to structural traps along pluton walls into which upwardly migrating, "low density, solute-rich aqueous fluids" were channeled. Thus orbicular and nonorbicular mafic enclaves exist in close proximity in Lower Castle Creek pipe, but orbs evidently formed only in that part of the pipe where sufficient felsic fluids or melt were available. On the other hand, because the orbicular enclaves are generally larger than those lacking orbs, flow sorting or mechanical concentration may have occurred during transport in the pipe to their present position. Thus a sharp boundary between orbs and the host granodiorite, and the close proximity of orbicular and nonorbicular enclaves, cannot be due to an in situ change in the conditions of crystallization (Vernon, 1985). Alternatively, the orbicular and nonorbicular enclaves formed spatially and perhaps temporally separate from one another and then were joined as two separate intrusions in the pipe. Compelling field evidence is lacking to choose between the two alternatives.

Vernon (1985) argued cogently that both comb-layering and orbicular structures require the absence of nuclei in a melt, and that superheating is an effective way to destroy nuclei, as he maintained experiments show (e.g., Donaldson, 1977). He stated further that absence of nuclei also delays crystallization and allows a significant degree of undercooling to occur, which, in turn, forces development of compositional layering (Donaldson, 1977). Thus injection of a superheated melt into a pluton during

Polygenic origin of orbicular granodiorite

its late stages of crystallization may supply the components for orbicule formation. Undercooling would force crystallization of the melt's components upon solid objects such as enclaves and inclusions, or on refractory crystals or megacrysts during a hiatus between superheating and the onset of complete crystallization of the plutonic host (Vernon, 1985; Ort, 1992).

The initial superheating may have been supplied to a late-stage aplitic melt by upward infusion of a plume of still-molten quartz monzodiorite from the bottom of the cooling granodiorite pluton or by fluidization that provided the gas-drive for the enclaves during their transport up the pipe. The undercooling of the felsic melt and consequent deposition of the orbicules may have been occasioned by rapid ascent of the pipe contents to a regime of lower temperature and pressure, perhaps by an abrupt volcanic venting (see Ort, 1992). Then following formation of the orbs, quartz monzodiorite intruded and mobilized both the suspended orbs and nonorbicular enclaves and carried them farther upward in the pipe.

That the orbicules have a tangential fabric rather than the more common radial fabric may be due to the kinetics of epitaxial crystallization, a low degree of supersaturation, or to concentration gradients at the enclave margins. If the orbicules crystallized from an aqueous fluid (Moore and Lockwood, 1973; Donaldson, 1977) or from a superheated felsic melt such as aplite, then fluid concentrations in a partially molten system are controlled by local reactions between minerals and liquid. Concentration gradients in the liquid may move material to or away from the boundary from both sides of the boundary, not simply across it (Lundstrom et al., 2005). Thus water and/or K_2O may concentrate at an enclave boundary, favor crystallization of biotite there, and provide a sink for any additional H_2O or K_2O in the system.

Assuming the enclaves represent hot, crystal-poor mafic magma (say 1050–1200 °C) that is injected by a cooler, felsic magma (say 750–850 °C), then significant thermal gradients on the order of 300–400 °C will exist initially, at least over a few centimeters or tens of centimeters between the enclaves and the felsic melt. Eventually the thermal gradients will flatten over geologically short times, depending on the geometry and frequency of injection of mafic magma to maintain high temperatures. In the meantime, a thermal gradient will set up around each hot mafic enclave, which then allows nonequilibrium Soret diffusion to occur in the surrounding mush, so that Si, K, Na, and, to a lesser extent, Al, all from a felsic melt or aqueous fluid, may concentrate around the enclaves, whereas Ca, Fe, Ti, and Mg move away.

Figure 11. Spheroidal mafic enclave in granodiorite of Summit Lake, ~1 km west of Summit Lake with core of heterogeneous, coarsely crystalline hornblende and plagioclase. Ring-shaped orbicule, consisting of fine-grained, radially oriented hornblende and plagioclase, exhibits comb structure, wherein the long axes of crystals are perpendicular to the core margin.

Processes that probably cause enclaves to concentrate in swarms ("log jams" in the terminology of Tobisch et al., 1997, and illustrated but not described by Paterson, 2009, in his fig. 18c, p. 520) include convergent flow in fractures or pipes, velocity gradient sorting, and flow perturbations due to boundary irregularities such as overhangs in walls near the roof of the host pluton (Moore and Lockwood, 1973). The size of the Lower Castle Creek pipe is larger than most of those described elsewhere (e.g., Tobisch et al., 1997; Paterson, 2009) and may be unique in that regard. The question of how mafic enclaves accumulate in the first place, so as to be in a position to rise in a pipe and form swarms, is a topic of debate and continued study (e.g., Tobisch et al., 1997; Wiebe et al., 1997; Wiebe and Collins, 1998).

ORIGIN

The orbicular rocks in this study evince a complex history of formation that requires an equally complex interpretation. Initial formation of mafic enclaves involved mingling of mafic magma and granodiorite deep in the granodiorite magma chamber. Different from all other mingled magma interactions in the Castle Creek plutons, however, is the addition of a third melt phase, a highly mobile, H_2O-saturated felsic melt that ascended from depth and may have had the same source as neighboring aplite dikes. These aplites may represent the low-melt fraction generated during injection of late-stage basaltic melts into hot, nearly solid host granodiorite. Such an aplitic melt could be superheated and invade a swarm
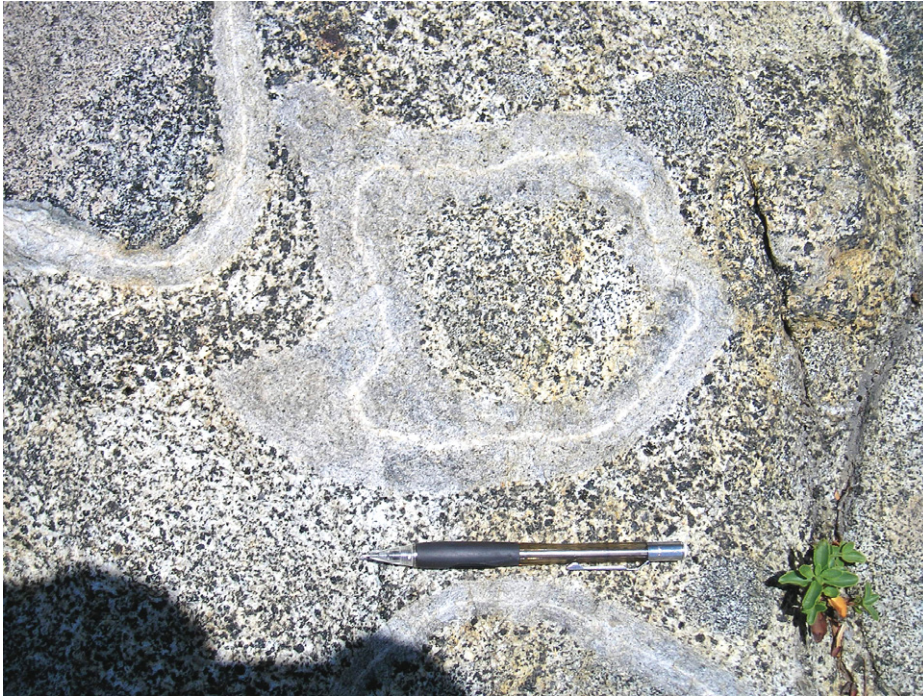
Sylvester

Figure 12. Irregularly-shaped felsic orbicule with internal thin layer of K-feldspar and quartz surrounding a mixed core of quartz monzodiorite and almost completely hybridized mafic enclave. Photo by Amber Miniami.

of mafic enclaves that were mechanically and spatially separated by gas-driven ascent in a pipe. During undercooling of the aplitic melt in a restricted part of the pipe, or in a separate mass of enclaves altogether, mafic enclaves and rare hornfels inclusions were nuclei for deposition of orbicules. If from an aqueous fluid, then deposition may have been facilitated by the Soret effect. The entire mass of enclaves, inclusions, and orbs were then intruded by quartz monzodiorite, and the whole mass then continued upward in a pipe as a mobilized aggregate through its granodioritic host magma to solidify at its present level in the pluton. Differential flow between the pipe and the host granodioritic magma is evinced by schlieren along part of the pipe margin. Elsewhere, late-stage felsic melts also coursed through fractures in the pluton and solidified as aplite dikes.

As Vernon (1985) concluded, the rarity of orbicular rocks, by this interpretation, implies that superheated and undercooled melts are also rare in granitic plutons, because most granitic magmas contain enough nuclei to permit normal crystallization. This interpretation also requires transfer of a hot, more mafic phase of a granitic pluton via a pipe to a higher, cooler level. Such pipes and heat-transfer structures, with or without enclaves or orbs, are indicative of late-stage convective instabilities in granitic

plutons (Weinberg et al., 2001; Vernon and Paterson, 2008; Paterson, 2009) and are probably more common but more complicated than previously realized. Lastly, the interactions of four compositionally distinct magmas to produce the distinctive rocks and structures in the Lower Castle Creek pipe represent a rare, but by no means unusual, example of magma mingling in granitic plutons.

REFERENCES CITED

Angus, N.S., 1962, Ocellar hybrids from the Tyrone igneous series, Ireland: Geological Magazine, v. 94, p. 2–27.
Arvin, M., Dargahi, S., and Bababei, A.A., 2004, Mafic microgranular enclave swarms in the Chenar granitoids stock, NW of Kerman, Iran: Journal of Asian Earth Sciences, v. 24, no. 1, p. 105–113, doi:10.1016/j.jseaes.2003.09.004.
Barbarin, B., 1990, Plagioclase xenocrysts and mafic magmatic enclaves in some granitoids of the Sierra

Nevada batholith, California: Journal of Geophysical Research, v. 95, B11, p. 17,747–17,756, doi:10.1029/JB095iB11p17747.
Barbarin, B., 2005, Mafic magmatic enclaves and mafic rocks associated with some granitoids of the central Sierra Nevada batholith, California: Nature, origin, and relations with the hosts: Lithos, v. 80, p. 155–177, doi:10.1016/j.lithos.2004.05.010.
Barbarin, B., and Didier, J., 1992, Genesis and evolution of mafic microgranular enclaves through various types of interaction between coexisting felsic and mafic magmas: Transactions of the Royal Society of Edinburgh. Earth Sciences, v. 83, p. 145–153.
Bateman, P.C., Clark, L.D., and Huber, N.K., Moore, J.G., and Reinhart, C.D., 1963, The Sierra Nevada batholith—A synthesis of recent work across the central part: U.S. Geological Survey Professional Paper 414-D, p. D1–D46.
Burnham, C.W., 1985, Energy release in subvolcanic environments: Implications for breccia formation: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 80, p. 1515–1522, doi:10.2113/gsecongeo.80.6.1515.
Castro, A., de la Rosa, J.D., and Stephens, W.E., 1990, Magma mixing in the subvolcanic environment, petrology of the Gerena interaction zone near Seville, Spain: Contributions to Mineralogy and Petrology, v. 106, p. 9–26, doi:10.1007/BF00306405.
Chappell, B.W., White, A.J.R., and Wyborn, D., 1987, The importance of residual source material (restite) in granite petrogenesis: Journal of Petrology, v. 28, no. 6, p. 1111–1138.
Coleman, D.S., Glazner, A.F., Miller, J.S., Bradford, K.J., Frost, T.P., Joye, J.L., and Bach, C.A., 1995, Exposure of a Late Cretaceous layered mafic-felsic magma system in the central Sierra Nevada batholith, California: Contributions to Mineralogy and Petrology, v. 120, p. 129–136, doi:10.1007/BF00287110.
Didier, J., 1973, Granites and Their Enclaves: Elsevier, Amsterdam, 393 p.
Dodge, F.C.W., and Kistler, R.W., 1990, Some additional observations on inclusions in the granitic rocks of the Sierra Nevada: Journal of Geophysical Research, v. 95, B11, p. 17,841–17,848, doi:10.1029/JB095iB11p17841.
Donaldson, C.H., 1977, Laboratory duplication of comb layering in the Rhum pluton: Mineralogical Magazine, v. 41, p. 323–336, doi:10.1180/minmag.1977.041.319.03.
Elburg, M.A., and Nicholls, I.A., 1995, Origin of microgranitoid enclaves in the S-type Wilson's Promontory batholith, Victoria: Evidence for magma mingling: Australian Journal of Earth Sciences, v. 42, no. 4, p. 423–435, doi:10.1080/08120099508728212.
Enz, R.D., Kudo, A.M., and Brookins, D.G., 1979, Igneous origin of the orbicular rocks of the Sandia Mountains, New Mexico: Summary: Geological Society of America Bulletin, v. 90, p. 138–140, doi:10.1130/0016-7606(1979)90<138:IOOTOR>2.0.CO;2.
Foster, D.A., and Hyndman, D.W., 1990, Magma mixing and mingling between synplutonic mafic dikes and granite in the Idaho-Bitterroot batholith, Chap. 20, in Anderson, J.L., ed., The Nature and Origin of Cordilleran Magmatism: Geological Society of America Memoir 174, p. 347–358.
Frost, T.P., and Mahood, G.A., 1987, Field, chemical, and physical constraints on mafic-felsic magma interaction in the Lamarck Granodiorite, Sierra Nevada, California: Geological Society of America Bulletin, v. 99, no. 2, p. 272–291, doi:10.1130/0016-7606(1987)99<272:FCAPCO>2.0.CO;2.
Furman, T., and Spera, F.J., 1985, Co-mingling of acid and basic magma with implications for the origin of mafic I-type xenoliths; Field and petrochemical relations of an unusual dike complex at Eagle Lake, Sequoia National Park, California, USA: Journal of Volcanology and Geothermal Research, v. 24, p. 151–178, doi:10.1016/0377-0273(85)90031-9.
Gansser, A., and Gyr, T., 1964, Über Xenolithschwärme aus dem Bergeller Massiv und Probleme der Intrusion: Eclogae Geologie Helvetica, v. 57, p. 577–598.
Hopson, C.A., and Mattinson, J.M., 1994, Chelan Migmatite Complex, Washington: Field evidence for mafic magmatism, crustal anatexis, mixing and protodiapiric

Polygenic origin of orbicular granodiorite

emplacement, *in* Swanson, D.A., and Haugerud, R.A., eds., Geologic Field Trips in the Pacific Northwest: Seattle, Department of Geological Sciences, University of Washington, 1994 Geological Society of America Annual Meeting, p. 2K1–2K21.

Hudson, F.S., 1951, Mount Lincoln–Castle Peak area, Sierra Nevada, California: Geological Society of America Bulletin, v. 62, p. 931–952, doi:10.1130/0016-7606 (1951)62[931:MLPASN]2.0.CO;2.

Irving, A.J., 1980, Petrology and geochemistry of composite ultramafic xenoliths in alkalic basalts and implications for magmatic processes within the mantle: American Journal of Science, v. 280-A, p. 389–426.

Kulow, M.J., 1996, Geology, petrology, age, and intrusive relations of Cretaceous plutons in the Donner Lake–Cisco Grove area, northern Sierra Nevada, California [M.A. thesis]: Fort Worth, Texas, Texas Christian University, 122 p.

Lahti, S.I., ed., 2005, Orbicular Rocks in Finland, with contributions from Paul Raivio and Ilkka Laitakari: Geological Survey of Finland, 177 p.

Larsen, L.L., and Smith, E.I., 1990, Mafic magmatic enclaves in the Wilson Ridge pluton, northwestern Arizona: Implications for the generation of a calc-alkaline intermediate pluton in an extensional environment: Journal of Geophysical Research, v. 95, p. 17,693–17,716, doi:10.1029/JB095iB11p17693.

Leveson, D.J., 1966, Orbicular rocks: A review: Geological Society of America Bulletin, v. 77, p. 409–426, doi:10.1130/0016-7606(1966)77[409:ORAR]2.0.CO;2.

Link, A.J., 1969, Inclusions of the Half Dome quartz monzonite, Yosemite National Park, California [M.S. thesis]: Evanston, Illinois, Northwestern University, 113 p.

Lundstrom, C., Boudreau, A., and Pertermann, M., 2005, Diffusion-reaction in a thermal gradient: Implications for the genesis of anorthitic plagioclase, high alumina basalt, and igneous mineral layering: Earth and Planetary Science Letters, v. 237, p. 829–854, doi:10.1016/j.epsl.2005.06.026.

Mayo, E.B., 1935, Some intrusions and their wall rocks in the Sierra Nevada: Journal of Geology, v. 43, p. 673–689.

Moore, J.G., and Lockwood, J.P., 1973, Origin of comb layering and orbicular structure, Sierra Nevada batholith, California: Geological Society of America Bulletin, v. 104, p. 1048–1058.

Ort, M.H., 1992, Orbicular volcanic rocks of Cerro Panizos: Their origin and implications for orb formation: Geological Society of America Bulletin, v. 84, p. 1–20.

Pabst, A., 1928, Observations on inclusions in the granitic rocks of the Sierra Nevada: University of California Publications in Geological Sciences, v. 17, p. 325–386.

Paterson, S.R., 2009, Magmatic tubes, pipes, troughs, diapirs, and plumes: Late-stage convective instabilities in compositional diversity and permeable networks in crystal-rich magmas of the Tuolumne batholith, Sierra Nevada, California: Geosphere, v. 5, no. 6, p. 496–527, doi:10.1130/GES00214.1.

Paterson, S.R., Zak, J., and Janousek, V., 2008, Growth of complex magmatic zones during recycling of older magmatic phases: The Sawmill Canyon area in the Tuolumne batholith, Sierra Nevada, California: Journal of Volcanology and Geothermal Research, v. 177, p. 457–484, doi:10.1016/j.jvolgeores.2008.06.024.

Pitcher, W.S., 1993, The mingling and mixing of granite with basalt: A third term in a multiple hypothesis, Chapter 9, *in* Pitcher, W.S., The Nature and Origin of Granite: New York, Blackie Academic and Professional, p. 117–139.

Platten, I.M., 1984, Fluidized mixtures of magma and rock in a late Caledonian breccia dyke and associated breccia pipes in Appin, Scotland: Geological Journal, v. 19, p. 209–226, doi:10.1002/gj.3350190302.

Reid, J.B., Evans, O.C., and Fates, D.G., 1983, Magma mixing in granitic rocks of the central Sierra Nevada, California: Earth and Planetary Science Letters, v. 66, p. 243–261, doi:10.1016/0012-821X(83)90139-5.

Roddick, J.A., and Armstrong, J.E., 1959, Relict dikes in the Coast Mountains near Vancouver, B.C.: The Journal of Geology, v. 67, p. 603–613, doi:10.1086/626621.

Ross, P.S., Jébrak, M., and Walker, B.M., 2002, Discharge of hydrothermal fluids from a magma chamber and concomitant formation of a stratified breccia zone at the Questa porphyry molybdenum deposit, New Mexico: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 97, p. 1679–1699, doi:10.2113/97.8.1679.

Sederholm, J.J., 1928, On orbicular granites, spotted and nodular granites, etc., and on the rapakivi texture: Commission Géologique de Finlande, Bulletin 83, 105 p.

Simonen, A., 1966, Orbicular rock in Kuru, Finland: Commission Géologique de Finlande, Bulletin 222, p. 93–107.

Sisson, T.W., Grove, T.L., and Coleman, D.S., 1996, Hornblende gabbro sill complex at Onion Valley, California, and a mixing origin for the Sierra Nevada batholith: Contributions to Mineralogy and Petrology, v. 126, p. 81–108, doi:10.1007/s004100050237.

Surour, A.A., and Kabesh, M.L., 1998, Calc-alkaline magmatism and associate mafic microgranular enclaves of Wadi Risasa area, southeastern Sinai, Egypt: Annals of the Geological Survey of Egypt, v. 21, p. 35–54.

Sylvester, A.G., 1998, Magma mixing, structure, and reevaluation of the emplacement mechanism of Vrådal pluton, central Telemark, southern Norway: Norsk Geologisk Tidsskrift, v. 78, p. 259–276.

Taylor, T.R., Vogel, T.A., and Wilband, J.T., 1980, The composite dikes at Mount Desert Island, Maine: An example of coexisting acidic and basic magmas: The Journal of Geology, v. 88, p. 433–444, doi:10.1086/628526.

Thompson, T.B., and Giles, D.L., 1974, Orbicular rocks of the Sandia Mountains, New Mexico: Geological Society of America Bulletin, v. 85, p. 911–916, doi:10.1130/0016-7606(1974)85<911:OROTSM>2.0.CO;2.

Tobisch, O.T., McNulty, B.A., and Vernon, R.H., 1997, Microgranitoid enclave swarms in granitic plutons, central Sierra Nevada, California: Lithos, v. 40, p. 321–339, doi:10.1016/S0024-4937(97)00004-2.

Vernon, R.H., 1983, Restite, xenoliths and microgranitoid enclaves in granites: Journal and Proceedings, Royal Society of New South Wales, v. 116, p. 77–103.

Vernon, R.H., 1984, Microgranitoid enclaves in granites; globules of hybrid magma quenched in a plutonic environment: Nature, v. 309, no. 5967, p. 438–439, doi:10.1038/309438a0.

Vernon, R.H., 1985, Possible role of superheated magma in the formation of orbicular granitoids: Geology, v. 13, p. 843–845, doi:10.1130/0091-7613(1985)13<843:PROSMI>2.0.CO;2.

Vernon, R.H., 1990, Crystallization and hybridization in microgranitoid enclave magmas: Microstructural evidence: Journal of Geophysical Research, v. 95, p. 17,849–17,859, doi:10.1029/JB095iB11p17849.

Vernon, R.H., and Paterson, S.R., 2008, Mesoscopic structures resulting from crystal accumulation and melt movement in granites: Transactions of the Royal Society of Edinburgh. Earth Sciences, v. 97, p. 369–381.

Weinberg, R.F., Sial, A.N., and Pessoa, R.R., 2001, Magma flow within the Tavares pluton, northeastern Brazil: Compositional and thermal convection: Geological Society of America Bulletin, v. 113, p. 508–520, doi:10.1130/0016-7606(2001)113<0508:MFWTTP>2.0.CO;2.

Wiebe, R.A., 1991, Co-mingling of contrasted magmas and generation of mafic enclaves in granitic rocks, *in* Didier, J., and Barbarin, B., eds., Enclaves and Granite Petrology: Developments in Petrology: Amsterdam, Elsevier, p. 393–402.

Wiebe, R.A., and Collins, W.J., 1998, Depositional features and stratigraphic sections in granitic plutons: Implications for the emplacement and crystallization of granitic magma: Journal of Structural Geology, v. 20, p. 1273–1289, doi:10.1016/S0191-8141(98)00059-5.

Wiebe, R.A., Smith, D., Sturm, M., King, E.M., and Seckler, M.S., 1997, Enclaves in the Cadillac Mountain Granite (coastal Maine): Samples of hybrid magma from the base of the chamber: Journal of Petrology, v. 38, p. 393–423, doi:10.1093/petrology/38.3.393.

Zorpi, M.J., Coulona, C., and Orsinib, J.B., 1989, Magma mingling, zoning and emplacement in calc-alkaline granitoid plutons: Tectonophysics, v. 157, no. 4, p. 315–329, doi:10.1016/0040-1951(89)90147-9.

Zorpi, M.J., Coulona, C., and Orsinib, J.B., 1991, Hybridization between felsic and mafic magmas in calc-alkaline granitoids—A case study in northern Sardinia, Italy: Chemical Geology, v. 92, p. 45–86, doi:10.1016/0009-2541(91)90049-W.