DAVID J. LEVESON *Geology Department, Brooklyn College of the City University of New York, Brc lyn, New York 11210*

Origin of Comb Layering and Orbicular Structure, Sierra Nevada Batholith, California: Discussion

Moore and Lockwood (1973) describe three occurrences of comb layering within the Sierra Nevada batholith, California; of these, two are associated with outcrops of orbicular rock. The origin of both the comb layering and the orbicules is attributed to crystallization from an aqueous fluid phase that intermittently separated from an adjacent cooling magma. Evidence cited for igneous origin of the comb layering and orbicules consists mainly of megascopic and mesoscopic structural and textural relations. I suggest that this same evidence may be cited to support a metamorphic origin for these features.

Moore and Lockwood describe comb layering as commonly changing along strike into schlieren layering, and they conclude that both types of layering formed simultaneously. Equally valid conclusions might be that one type of layering developed at the expense of the other through metamorphic recrystallization or replacement, and that the formation of the two types of layering was sequential rather than simultaneous.

Possible origins for schlieren layering postulated by Moore and Lockwood are: (1) magmatic gravity-controlled sedimentation, and (2) mechanical flow sorting. Other possible origins include: (1) mechanical sorting through plastic flow in a solid environment, and (2) metamorphic differentiation through ion migration.

In places, small quartz-K-feldspar pegmatitic pods "cut and thus appear slightly later than the comb layering" (Moore and Lockwood, 1973, p. 7). This suggests that comb layering was subjected to metamorphic alteration, and that schlieren layering may have formed during a metamorphic episode subsequent to comb-layering formation.

Channeling and truncation of schlieren layers are considered by Moore and Lockwood to have originated by cut-and-fill action of flowing magma. Similar features occur in layered gneisses and may be attributed to shear or plastic attenuation.

Comb layering and associated orbicules are found near the contacts of intrusive plutons. Moore and Lockwood envision the concentration of water emanating from a crystallizing magma into a marginal aqueous phase that streams upward along plutonic contacts, thus forming and localizing the phenomena of comb layering and orbicules. Rhythmic character of the precipitates is attributed to changes in pressure, temperature, volume, and composition of the aqueous phase. In the Lonesome Mountain area of the Beartooth Mountains, Montana and Wyoming, metamorphic orbicules commonly occur at or near the contact of amphibolite with granitic gneiss (Leveson, 1963). In Alderney, Channel Islands, comb layering and orbicules occur within olivine diabase at or near its contact with intrusive granodiorite (Leveson, in prep.). In both instances, the presence of rhythmically layered structures may be due to Liesegang-type diffusion processes favored by the juxtaposition of compositionally distinct rock units. Rhythmic precipitation of this nature may take place in metamorphic, migmatitic, and some igneous environments in which there are high levels of diffusion (Leveson, 1966).

Delicately branching plagioclase or hornblende crystals project perpendicularly from the surface of comb layers. According to Moore and Lockwood (1973, p. 15), "It is inconceivable that such fragile crystals could project into a moving fluid of high viscosity without being broken off." They conclude, therefore, that an upward-streaming, low-viscosity, low-density fluid was involved. Using the same logic, an alternate hypothesis is that these crystals formed through a static, metasomatic process. Moore and Lockwood rule out a static environment in favor of a dynamic environ-

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ment because of the presence of broken, "eroded," and transported layering and orbicules. At Orchard Beach, Pelham Bay Park, The Bronx, New York, broken, "eroded," and transported fragments of layered amphibolite are common, produced by tectonic transport in a plastic, solid environment (Leveson and Seyfert, 1969). Similarly, bending of crystals within comb layers that Moore and Lockwood attribute to the influence of moving fluids could be due to differential tectonic transport.

A possible sequence of events alternate to that postulated by Moore and Lockwood is: (1) magmatic intrusion and crystallization; (2) formation of comb layering at intrusive contacts by Liesegang-type rhythmic crystallization under conditions of active diffusion in a water-rich, high-temperature metamorphic environment; (3) disseminated metasomatic replacement of comb layering by quartz and K-feldspar, and metamorphic conversion of some comb layering to schlieren layering; (4) local plastic dismemberment and tectonic transport of comb layering and other rock types, together with shearing that produces "cut-and-fill" structures; (5) intermittent, continued, or renewed metamorphic rhythmic crystallization about diverse rock-type centers of contrasted composition to form orbicules; and (6) rhythmic crystallization alternates with metasomatic replacement that produces unconformities and truncations within rhythmic-layering sequences.

In conclusion, I do not claim that my "scenario" is correct or that Moore and Lockwood's conclusion is wrong, but I wish to point out the difficulty of arriving at a unique solution to the problem based upon the type of evidence presented. What is needed is the development of criteria to test the validity of all reasonable hypotheses. Also, the use of terminology with genetic connotations, such as "channeling," should be avoided in the descriptive phases of an investigation, for it decreases the likelihood that the investigator will successfully escape the confines of his own inevitable, initial bias.

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JAMES G. MOORE
JOHN P. LOCKWOOD
U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025

Origin of Comb Layering and Orbicular Structure, Sierra Nevada Batholith, California: Reply

We welcome the opportunity to reply to the thoughtful discussion by Leveson (1973) of our paper on comb layering and orbicular structure (Moore and Lockwood, 1973). Leveson has suggested that the comb layering and orbicular structure may have formed at the expense of other rocks, including schlieren layering, through metamorphic recrystallization or replacement, and that the formation of the two types of layering was sequential rather than simultaneous. Admittedly, the distinction between origin by crystallization from an aqueous fluid (our hypothesis) and metamorphic recrystallization (Leveson's hypothesis) is difficult or impossible when any restricted small rock unit is considered. However, we feel that the unique contribution of our study has been the establishment by detailed mapping of the structural relations between comb layering, schlieren layering, orbicules, and the parent pluton, and the construction of a rather simple new model which accounts for these relations.

In order to keep this discussion within reasonable bounds, we will restrict our reply to the specific items raised in Leveson's discussion (1973). The following five items represent Leveson's proposed hypotheses. Unless specified otherwise, page and figure numbers refer to Moore and Lockwood (1973).

1. Replacement origin of comb layering: We have demonstrated by detailed mapping that comb layering changes on strike into schlieren layering and, moreover, occupies a unique structural position (steep overturned troughs; Figs. 6, 7). Also, the direction of growth of both types of layering is the same (younging toward the parent pluton or away from wall rock; Figs. 6, 7, and 15), as indicated by channeling and cross-bedding in schlieren layering (Fig. 4) and branching of crystals in comb layering (Fig. 2). Hence, if (as Leveson suggests) the comb layering formed by a later metamorphic recrystallization of the schlieren layering, why should the crystals indicate a growth direction of the comb layering in the same sense as the schlieren layering formed earlier?

Also, since Leveson would bend the crystals of the comb layering upward by plastic flow, he would have to invoke a second period of plastic flow much later than the one he calls on to produce the channeling of the original schlieren layering.

The lateral transition of comb layering to schlieren layering has been carefully observed and described (p. 4, Figs. 6, 7), and in no place did we see evidence of replacement textures indicating metamorphic recrystallization and replacement of schlieren layering by comb layering. Rather the "comb layers thin, divide, and curve near their ends" (p. 4). The curves at the end of the comb layers (Fig. 7) are characteristic and suggestive of the margins of the fluid-filled channels we propose.

The close spacial association of orbicules with laterally continuous comb layers at Fisher Lake (Fig. 18) and the remarkable similarity of layers in the orbicules to those in the continuous layers suggest strongly that they were produced by the same processes. Many of the orbs within a small area contain distinctive sequences of layers, and commonly these distinctive sequences can be identified in adjacent comb layering. However, in such samples, these orbs occur only on the younger side of the laterally continuous comb layering. The orbs on the older side are enclosed by layers that have no correlation with those of the throughgoing comb layers. These relations suggest that while the comb layering was being deposited on a wall, adjacent xenoliths suspended in fluid were simultaneously being coated by the same layers. If metamorphic processes were operative, why would they not recrystallize the outer shells of the orbicules on the other (older) side of the comb layering?

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Also, why do just some of the orbicules on the young side show the distinctive layers? We would argue that those orbicules that correspond in layering were suspended (and coated) near the comb-layered wall, whereas those that do not were brought in from either higher or lower in the fluid-filled channel.

2. Origin of schlieren layering through (a) mechanical sorting through plastic flow in a solid environment, or (b) metamorphic differentiation through ion migration: The first mechanism would presumably take place by intragranular deformation and external rotation of grains and would produce granoblastic textures and deformation structures—even when recrystallization is involved. Actually, the schlieren layering shows marked oscillatory zoning of plagioclase and hypidiomorphic texture. The schlieren layers occur on the margins of the pluton and invariably young toward it, suggesting that they are clearly related to it and form by inward consolidation simultaneously with continued movement of the parent pluton.

The second mechanism, that of metamorphic differentiation through ion migration, would require a very complex model to produce the channeling and cross-bedding (Fig. 4), while maintaining the growth direction toward the parent pluton (Figs. 6, 7).

3. Rhythmically layered comb layering and orbicules formed by Liesegang-type diffusion processes favored by juxtaposition of compositionally distinct rock units: The Fisher Lake locality is characterized by orbicules with nucleii of widely differing composition, including hornblende-hypersthene diorite, masses of mafic minerals, and angular chunks of comb-layered diorite (p. 13, Fig. 3). Also, the nucleii themselves contain layers of strongly differing composition (Fig. 3). The outer layering of the orbicules (particularly the innermost layer adjacent to the nucleii), however, is the same regardless of the composition of the nucleii or their layers, indicating that the composition of the nucleii had no effect on the development of the outer layers.

How then can "Liesegang-type diffusion favored by juxtaposition of compositionally distinct rock units" explain the lack of control of nucleii composition—particularly since crystal branching shows that the layers of orbicules grew from the inside outward (p. 4)?

4. Delicately branching plagioclase and hornblende crystals formed by static metasomatic processes: Leveson suggests that the rhythmically layered comb layering formed by Liesegang-type diffusion and that the branching crystals within the layers formed by metasomatic processes—the two mechanisms presumably operating together or in sequence. We have shown that the branching crystals indicate growth toward the parent pluton (comb layering), toward the outside of orbicules (in orbicules), and toward the center of dikes (Fig. 20). Moreover, in all of these environments, the crystals may be either hornblende or plagioclase. Such a pattern can be readily explained if the one-sided comb layering represents encrustation on the wall of a fluid-filled channel bounded on one side by magma; the orbicules represent layers on xenoliths bobbing within a fluid-filled channel, and the symmetrical comb layers represent deposition on the walls of a fluid-filled crack. Explaining these local situations by metasomatic processes in solid rock requires very special conditions operating over short distances, especially in view of the fact that the growth direction of branching crystals in comb layering is toward the parent pluton in layers of differing composition. The botryoidal pattern of symmetrical comb layers on the walls of dikes such as that at Fisher Lake (Fig. 20) implies growth into a void rather than metasomatic crystallization. The general perpendicular rooted character of the dendritic crystals on their growth surface is typical of crystals growing inward from chamber walls (or outward from nucleii as in the case of the orbicules) toward a nourishing solution, rather than the patterns usually attributed to metasomatic crystallization in solid rock. Moreover, as at Volcanic Lakes (p. 5 and Figs. 2, 12) and Fisher Lake (Fig. 21), we provide evidence that the crystals grew in a regime that continually bent them upward *during growth*, a regime that was clearly not static. Leveson's suggestion that the bending of crystals within comb layers could be due to later differential tectonic transport requires that such transport be confined to narrow dikes (Fig. 21) and to affect some layers, but not others, in a layered sequence (yet always upward on the young side). Such relations can be explained more simply by an upward-streaming fluid bending the crystals upward while nourishing their growth.

5. Broken, eroded, and transported layering and orbicules due to "differential tectonic transport in a plastic, solid environment": The

sharp angular nature of fragments of comb layering and layered orbicules at Fisher Lake (Figs. 3B, 19) do not imply breakage in a "plastic, solid environment," especially when these fragments are very similar in composition to the surrounding rock, which, according to Leveson's hypothesis, would have entirely different, more plastic, rheological properties.

The layering unconformities in orbs such as those shown in Figure 3A can be rather easily explained by a process of (1) accretion of layers completely around a xenolith totally suspended in a fluid, (2) erosion and truncation of the layers on each side but not the end (upper right) by rubbing on the walls of the fluid-filled channel, and (3) continued accretion of the same kind of layers on top of the truncated eroded layers, but precisely conformable on the uneroded layers. Explaining such details by (1) Liesegang diffusion, (2) tectonic erosion in a plastic environment, and (3) continued Liesegang diffusion is difficult to comprehend.

A characteristic of many orbicular occurrences, only briefly described in our paper at the Devils Bathtub locality (p. 11, Fig. 17), is the restriction of closely packed orbs in a pipe. The transport and dumping of these orbs by an aqueous fluid which later drained away, leaving very little matrix material, can account for the geometry of the occurrence better than "differential tectonic transport in a plastic, solid environment."

CONCLUSIONS

Orbicular rocks always form in localized occurrences, generally a few tens of meters in maximum dimensions, and consequently they are an interesting curiosity. For this reason, they have been the subject of many excellent detailed mineralogic and geochemical studies. The restricted distribution of the orbicules in itself suggests a special origin such as the aqueous fluid model we propose. Development of that model, however, required an understanding of the relations of the orbicules to other rock types (including the little-studied comb layering first described in detail in 1960 by Taubeneck and Poldervaart) by detailed mapping in well-exposed, relatively unmetamorphosed terrane as is found in the glaciated core of the Sierra Nevada. We find great difficulty in applying Leveson's "scenario" to the body of data accumulated on the Sierra Nevada occurrences.

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