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Dike intrusion and deformation during growth of the Half Dome pluton, Yosemite National Park, California

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ABSTRACT

Meter-scale mapping of the Late Cretaceous Half Dome Granodiorite of the Tuolumne Intrusive Suite (TIS) near Tenaya Lake, Yosemite National Park, defines an intricate internal structure that reflects a combination of incremental pluton growth by diking and internal deformation as the pluton grew. At least four ages of dikes of layered granodiorite are defined by crosscutting relations. Because dikes thicker than 1 m invariably contain multiple cycles of layering that field relations indicate record multiple intrusive increments, dozens of discrete intrusive events are likely. The kinematic pattern of dilation across dikes, offset lithologic markers across dikes, shearing of mafic enclaves and magmatic layering, and folding of dikes defines a synintrusive bulk strain field characterized by E-W extension and N-S contraction, with net volume increase in the extension direction. The geometric and kinematic pattern of the deformation are consistent with current understanding of Late Cretaceous Cordilleran tectonics and suggest that regional tectonic dilation played a significant role in making upper-crustal space for the growing pluton. Narrow shear zones offset lithologic markers and produced extreme strains, yet no rock fabric is preserved in the zones. This indicates that late-magmatic to subsolidus recrystallization, previously inferred in the TIS based on textural and mineralogical observations, greatly modified rock textures and obscured both the intricate internal structure of the pluton and the importance of synemplacement deformation.

INTRODUCTION

Large plutons are increasingly recognized to grow by accumulation of small increments (e.g., Glazner et al., 2004; Annen et al., 2006; Bartley et al., 2006; Grocott et al., 2009). However, the shapes and dimensions of individual increments and the processes by which they are emplaced are poorly known. High-precision geochronology is an effective tool for recognition of incremental growth (e.g., Coleman et al., 2004; Condon et al., 2004; Matzel et al., 2006; Michel et al., 2008; Memeti et al., 2011; Tappa et al., 2011; Davis et al., 2012), but it is not a practical means for mapping increments. Field evidence indicates that increments can range in size down to the meter scale (e.g., Stearns and Bartley, 2014) and that visibly uniform rock bodies may contain subtle or cryptic contacts and thus may be highly composite (e.g., Mahan et al., 2003; Bartley et al., 2006; Glazner and Bartley, 2008; Davis et al., 2012). Structural aspects of incremental pluton growth therefore remain obscure. Because incremental growth now is widely accepted as common and perhaps ubiquitous in large plutons, identification of the physical processes by which it proceeds is among the most pressing questions in plutonic geology.

The Half Dome Granodiorite of the Tuolumne Intrusive Suite (TIS; Fig. 1A) provides exceptional opportunities to examine intrusive mechanisms in an incrementally growing pluton. Late Pleistocene glaciation provided extensive unweathered exposures that are readily accessible in Yosemite National Park. Zircon U-Pb geochronology established that the Half Dome pluton grew over at least 3–4 m.y., from 92.8 ± 0.1 to 89.8 ± 0.8 Ma, and this requires that the pluton grew incrementally (Coleman et al., 2004; Glazner et al., 2004).

Geologic and magnetic-susceptibility mapping of ~25 km^2 of the Half Dome Granodiorite near Tenaya Lake at 1:10,000 scale (Fig. 1B; Coleman et al., 2012) defined a kilometer-scale cyclic pattern of N- to NNE-trending rock bodies. The bodies are bounded by sharp contacts, with comparatively uniform and mafic granodiorite (color index ~15–20) on the west side of each contact against heterogeneous but overall very felsic (color index <5) granodiorite on the east side of the contact. Within each cycle, the uniform and more mafic rock grades westward into the heterogeneous felsic rock (Coleman et al., 2012). A similar pattern is also present in the eastern part of the Half Dome Granodiorite (Coleman et al., 2012), and similar zonation has been described in lobes of the granodiorite that extend into country rock (Economos et al., 2010; Memeti et al., 2011). We interpret the kilometer-scale compositional cycles to reflect episodic freezing during incremental emplacement (Coleman et al., 2012). Although U-Pb geochronology indicates that the adjacent Cathedral Peak Granodiorite also grew over ~4 m.y. (Memeti et al., 2011), it lacks such lithologic cycles (e.g., Burgess and Miller, 2008). Whereas both plutons must have grown incrementally, we agree with Burgess and Miller (2008) that partial melt was continuously present during growth of the Cathedral Peak pluton, and we attribute the lack of kilometer-scale lithologic cycles to the absence of freezing episodes.

It was apparent during mapping of the Half Dome pluton that each cycle is itself internally composite. The felsic domains of the cycles in particular contain numerous complexities that include bodies of modally layered granodiorite with intricate crosscutting relations. Reconnaissance of other parts

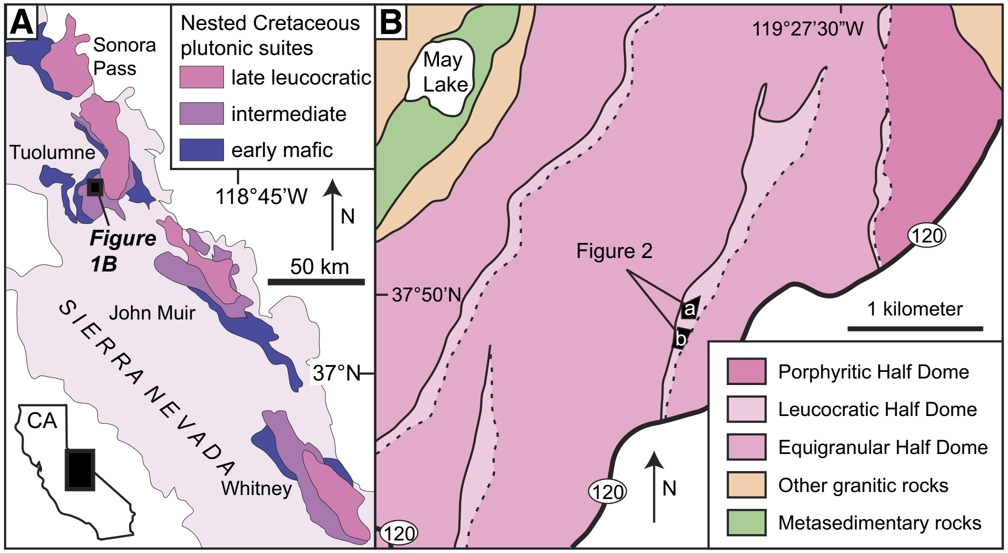

Figure 1. (A) Location of study area. (B) Map of lithologic cycles in part of the Half Dome Granodiorite and location of study area relative to them, after Coleman et al. (2005, 2012). The mapped felsic domains within the Half Dome have gradational eastern contacts and sharp western contacts. We interpret each felsic domain to have formed by in situ differentiation from more mafic granodiorite to its east. The sharp western contact is interpreted to be an intrusive contact against already-solidified Half Dome Granodiorite (see Coleman et al., 2012, for further explanation). CA—California.

of the Half Dome pluton confirmed that the leucocratic portions of cycles are internally complex throughout the pluton. We therefore selected two areas in the best exposed felsic domain for more detailed mapping, with the goals of (1) determining the nature of the complex outcrop-scale structures and the mechanical and petrological processes that produced them and (2) understanding the role that these structures played in formation of the kilometer-scale lithologic cycles and the growth of the pluton as a whole.

REGIONAL CONTEXT

The 1200 km^2 TIS is one of several large-volume zoned intrusive suites emplaced in the Late Cretaceous magmatic arc of the Sierra Nevada (Fig. 1A; Bateman, 1992). Each suite is characterized by heterogeneous mafic granodioritic outer phases that grade inward to a felsic granodioritic to granitic core. All of the suites were intruded at pressures of 100–300 MPa (1–3 kbar; Ague and Brimhall, 1988). Geochronologic data indicate that the TIS was assembled over a period of ~10 m.y. between 95 and 85 Ma (Kistler and Fleck, 1994; Coleman et al., 2004; Memeti et al., 2011), and the coeval Whitney and John Muir Suites grew over similar durations (Hirt, 2007; Davis et al., 2012). There is a significant mismatch between the wall rocks on the east and west sides of the TIS (Bateman, 1992). The eastern wall is dominated by Jurassic metavolcanic rocks and plutons, whereas the west is dominated by ca. 103 Ma plutonic rocks of the Intrusive Suite of Yosemite Valley (Ratajeski et al., 2001), which in turn was intruded into pre-batholithic metasedimentary rocks. The mismatch may reflect intrusion of the TIS into an intrabatholithic shear zone (e.g., Lahren and Schweickert, 1989; Kistler, 1993; Saleeby and Busby, 1993).

METHODS

Two hectare-scale areas of Half Dome Granodiorite that were ~100% exposed by Late Pleistocene glaciation were mapped using a laser total-station surveying system (Fig. 2). The surveying system uses a theodolite and an electronic distance meter to determine the orientation and length of the distance vector from a base station to a handheld mobile reflector carried by the geologist doing the mapping. The system provides locations with cm-level precision. Features down to ~1 m in size were mapped, although areas with particularly intricate meter-scale structure were generalized. Our original intention was to link the two maps shown in Figure 2, but minor oxidization and consequent staining of surfaces in the intervening area conceal subtle petrographic distinctions on which the mapping depended. Below we refer to locations on these maps via UTM easting and northing coordinates (e.g., 282525, 4189825) relative to the NAD83 datum.

The study area lies within federally designated wilderness, and therefore samples could not be collected using mechanized means (e.g., drilling). Sample collection thus is nearly impossible on the smooth glacial slabs mapped in this study. However, the interpretive importance of textural relations of the "Eighth Note" mafic enclave (see below) made it crucial to collect samples from the polished exposure of the enclave and the shear zone that deforms

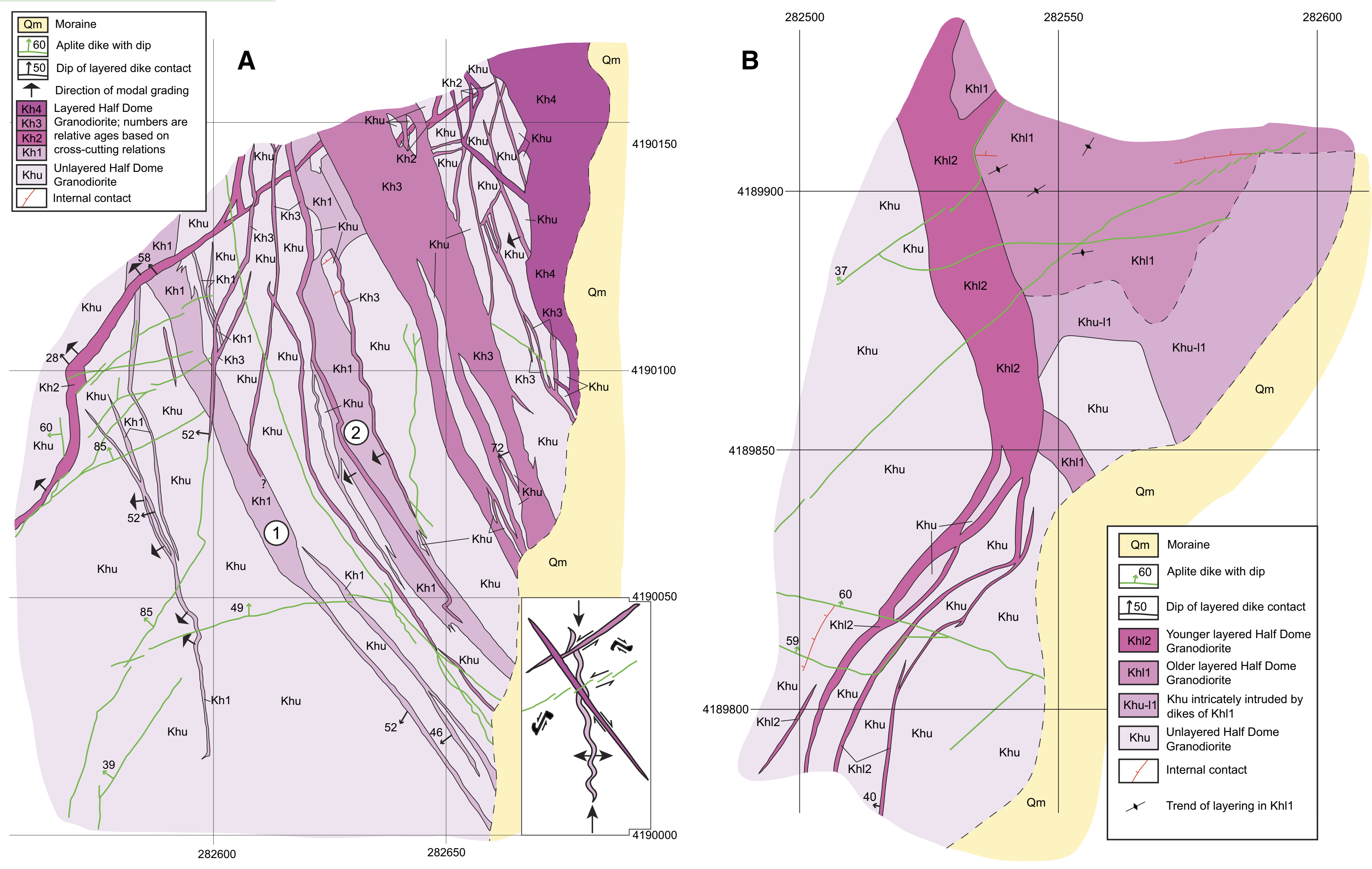

Figure 2. Detailed geologic maps of the internal anatomy of the felsic domain of a lithologic cycle in the Half Dome Granodiorite. Location grid gives UTM coordinates relative to the NAD83 datum, zone 11S. Inset in the lower corner of (A) shows kinematic pattern defined by observed deformation features including opening of, lateral offsets across, and en echelon arrays of dikes; folding of dikes; and shearing of markers such as mafic enclaves.

it. We achieved this by chiseling tiny chips from faint bumps on the surface, and thus sample locations were entirely dictated by locations of such bumps. The typical size of a sample chip was <1 cm in its longest dimension and <2 mm thick. This is too small to fabricate a standard thin section for optical petrography but sufficient to make a polished mount for scanning electron microscope (SEM) study.

OBSERVATIONS

Lithology

All rocks exposed in the study area are assigned to the Half Dome Granodiorite, which by definition is composed of medium- to coarse-grained granodiorite that contains prominent euhedral hornblende phenocrysts (Bateman, 1992). The areas shown in Figures 2A and 2B lie approximately midway between the outer and inner contacts of the Half Dome Granodiorite as mapped by Bateman et al. (1983), within the equigranular facies and just outside of the mapped gradational transition to a markedly porphyritic inner facies that grades into the K-feldspar megacrystic Cathedral Peak Granodiorite (Bateman et al., 1983; Johnson and Glazner, 2010). The study area crosses the mafic-to-felsic transition within one of the kilometer-scale lithologic cycles mapped by Coleman et al. (2012). In the map area, the Half Dome Granodiorite includes two general varieties: (1) unlayered granodiorite that is relatively homogeneous with a color index of 15–20; commonly contains abundant ovoid to irregularly shaped mafic enclaves; and is isotropic to faintly layered, foliated, and/or lineated, generally with a broadly E-W to NE-SW strike and/or bearing (Figs. 2B and 3A; Bateman et al., 1983); and (2) strongly modally lay-

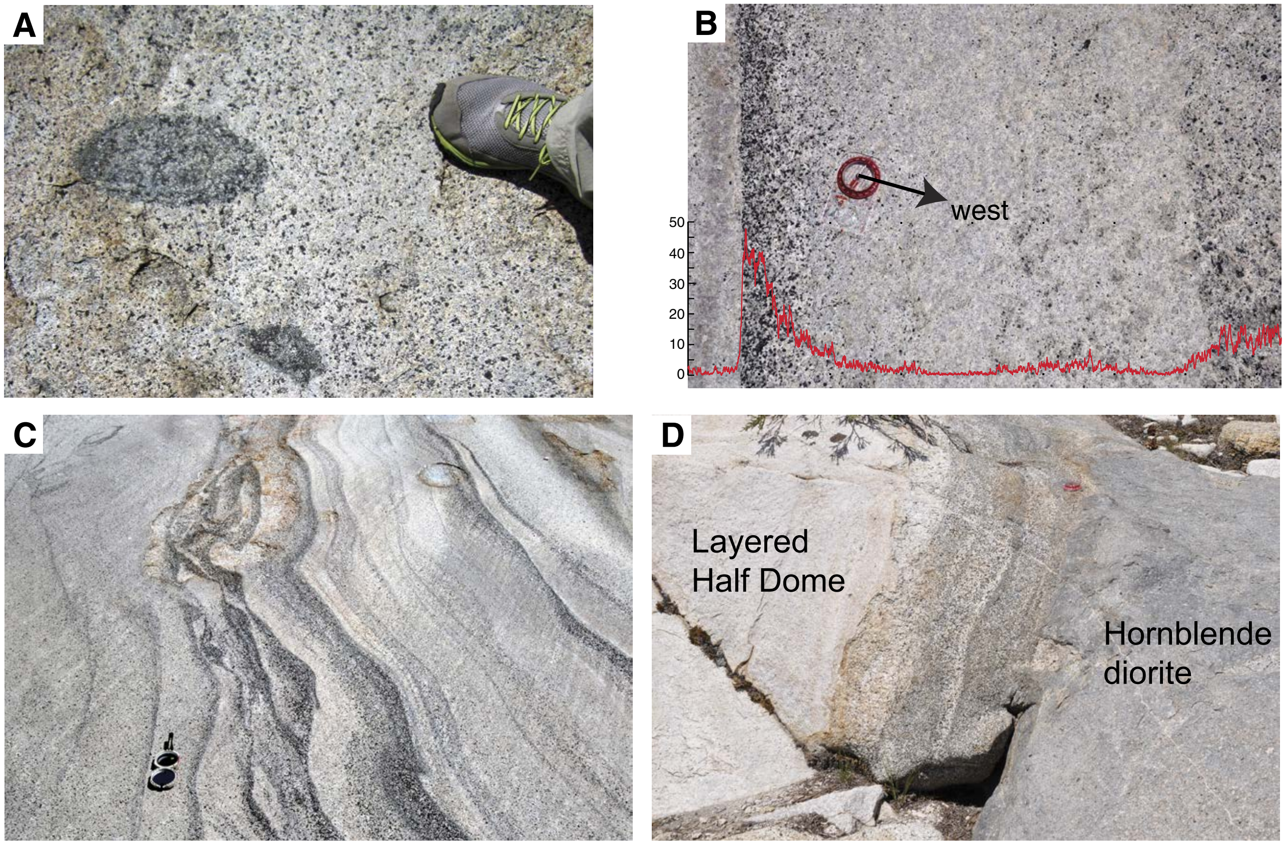

Figure 3. Lithologic variations in the study area. The compass used for scale in the photographs is oriented to indicate north. (A) Typical unlayered Half Dome Granodiorite with mafic enclave. (B) Modally layered, leucocratic Half Dome Granodiorite. Note sharp contact at eastern edge of mafic layer and westward gradation into leucogranite. The superimposed plot shows percent dark minerals (color index; scale shown at left edge of photograph) as a function of distance across photograph. (C) Layering in a thick dike. Note cyclic repetition of compositionally graded layers similar to the one shown in B, with sharp contacts on the right-hand (east) sides of dark layers and gradational contacts on left-hand (west) sides. Folding of some compositional layers is apparent (also see Fig. 5A). (D) Dark-gray hornblende-plagioclase porphyry body within a modally layered dike; modal layering in the adjacent Half Dome Granodiorite is oriented parallel to the contact.

ered granodiorite, much of which is very leucocratic (color index [CI] <5) but contains layers with CI >30; contains sparse or no mafic enclaves; and rarely contains a visible preferred mineral orientation (Fig. 3B).

Bateman (1992) and Gray (2003) described the petrography of the Half Dome Granodiorite. Modal compositions of the equigranular facies plot predominantly within the granodiorite and granite fields on a quartz-alkali feldspar-plagioclase (QAP) diagram (Bateman, 1992). Distinguishing characteristics of the unit are abundant euhedral hornblende crystals up to 20 mm long and wedge-shaped titanite crystals up to 4 mm across. Hornblende and biotite are present in subequal amounts, and color index can range from 15 to less than 5 in any particular area. The equigranular facies is generally medium grained (2–4 mm), but blocky K-feldspar and hornblende crystals up to 25 mm in size can give the rock a porphyritic texture. In thin section, the predominant texture is hypidiomorphic granular with euhedral hornblende, biotite, and titanite, subhedral plagioclase, anhedral to subhedral K-feldspar, and anhedral quartz. Plagioclase is locally sericitized, and biotite locally contains kink bands and commonly is partially replaced by chlorite and granular titanite. Most quartz crystals show minor checkerboard subgrains that reflect a small amount of high-temperature dislocation creep (Hirth and Tullis, 1992).

As in many other granitic rocks, the mineral compositions require substantial low-temperature re-equilibration and recrystallization. For example, K-feldspar compositions around Or_{90} (Gray, 2003) require exsolution of albite component down to temperatures on the order of 400 °C with a consequent volume loss of up to 25% (Johnson and Glazner, 2010). Magnetite, the only Fe-Ti oxide found in these rocks, is essentially pure Fe_3O_4 with no Ti peak visible in X-ray spectra. Magnetite crystals in volcanic rocks of comparable composition typically have 10–15 mol% ulvöspinel (e.g., Whitney and Stormer, 1985). The lack of Ti in magnetite probably reflects consumption of ilmenite and ulvöspinel in reactions to form Ti-rich phases such as titanite and biotite.

The ovoid enclaves in the equigranular Half Dome Granodiorite consist of the same minerals as the host but in different proportions. The enclaves generally have sharp contacts with the host granodiorite and are generally hornblende diorite in composition (Gray, 2003). Mineral grains in the enclaves are somewhat smaller than in the host and typically range from 0.1 to 1 mm. Plagioclase ± hornblende phenocrysts up to 10 mm across range from sparse to abundant.

Mineral textures and compositions in the strongly layered granodiorite resemble those in the unlayered granodiorite. The modal layering is defined by varying proportions of mafic and felsic minerals, all of which have roughly uniform grain size. An individual layer is commonly bounded by sharp contrasts in color index, between which the rock grades from more mafic adjacent to the eastern contact to more felsic at the western contact (Figs. 3B and 3C). Modal layering within each mapped body is oriented generally parallel to its contacts but is locally discordant.

Numerous aplite, leucogranite, and pegmatite dikes intrude the Half Dome Granodiorite (e.g., Fig. 2A), and the most leucocratic portions of the layered granodiorite resemble such dikes in color index. Probably as a result, Kistler's (1973) map of the Hetch Hetchy Reservoir 15′ quadrangle shows the leucocratic portions of the kilometer-scale cycles as aplite intrusions. However, felsic layered Half Dome Granodiorite is distinguished from aplite dikes by sparse but prominent euhedral hornblende crystals that range up to 2 cm in length and by complex and diffuse contact relations with more typical Half Dome Granodiorite.

Tabular bodies of dark-gray porphyritic hornblende diorite up to tens of meters in length appear sporadically within modally layered granodiorite bodies (Fig. 3D; Perlroth, 2002; Coleman et al., 2005). Layering in the adjacent granodiorite is consistently concordant with contacts of the diorite bodies. The diorite bodies consist of ~1 cm hornblende and plagioclase phenocrysts in a fine-grained phaneritic matrix and, following Perlroth (2002), are interpreted to be disrupted dikes. Most of the mafic enclaves in the unlayered granodiorite lithologically resemble the hornblende diorite dikes, and commingling of dioritic magma with the unlayered granodiorite probably produced the abundant enclaves. However, in the study area, the disrupted hornblende diorite dikes are found exclusively inside layered granodiorite bodies that intruded the unlayered granodiorite, and therefore enclaves in the unlayered granodiorite are older than the dikes.

Field Relations

Mapped bodies of modally layered granodiorite are broadly tabular, have sharp contacts with surrounding unlayered granodiorite, and vary in thickness from less than one meter to more than 20 m. The layered bodies have geometrical features typical of crack systems such as branches, jogs, relays, and T-intersections (Fig. 2), and we therefore interpret the layered bodies to be dikes that intruded the unlayered granodiorite. Note that use of the term "dike" here only refers to injection of magma into a dilating crack and carries no connotation regarding orientation. Low-angle branches (Fig. 4A) commonly rejoin along strike, resulting in the enclosure of lenses of unlayered granodiorite (e.g., Fig. 2B, 282525, 4189825). High-angle dike intersections define mosaics of angular blocks that fit together in jigsaw-puzzle fashion (e.g., Fig. 2A, 282650, 4190140). Contacts of layered dikes sharply truncate markers in adjacent rock such as mafic enclaves, aplite dikes, and other layered dikes and the modal layering in those dikes (Figs. 4B and 4C). Markers can commonly be matched across a dike, in some cases with lateral separation (Fig. 2A, 282645, 4190155; Fig. 4C). Lateral separations are generally dextral across NW-striking dikes and sinistral across NE-striking dikes.

Most thin (10–30 cm) layered dikes contain a single mafic-felsic gradational cycle. Dikes thicker than one meter invariably contain several cycles (Fig. 3C). Field relations exemplified by the dikes labeled "1" and "2" in Figure 2A support the inference that each cyclic layer represents a distinct intrusive increment. The easternmost layer in dike 1 branches northward away from the rest of the dike at (282608, 4190082). This layer crosscuts the NE-striking dike at the top of the map at (282609, 4190136), whereas the NE-striking dike crosscuts all other layers in dike 1. Therefore the easternmost layer is younger than the

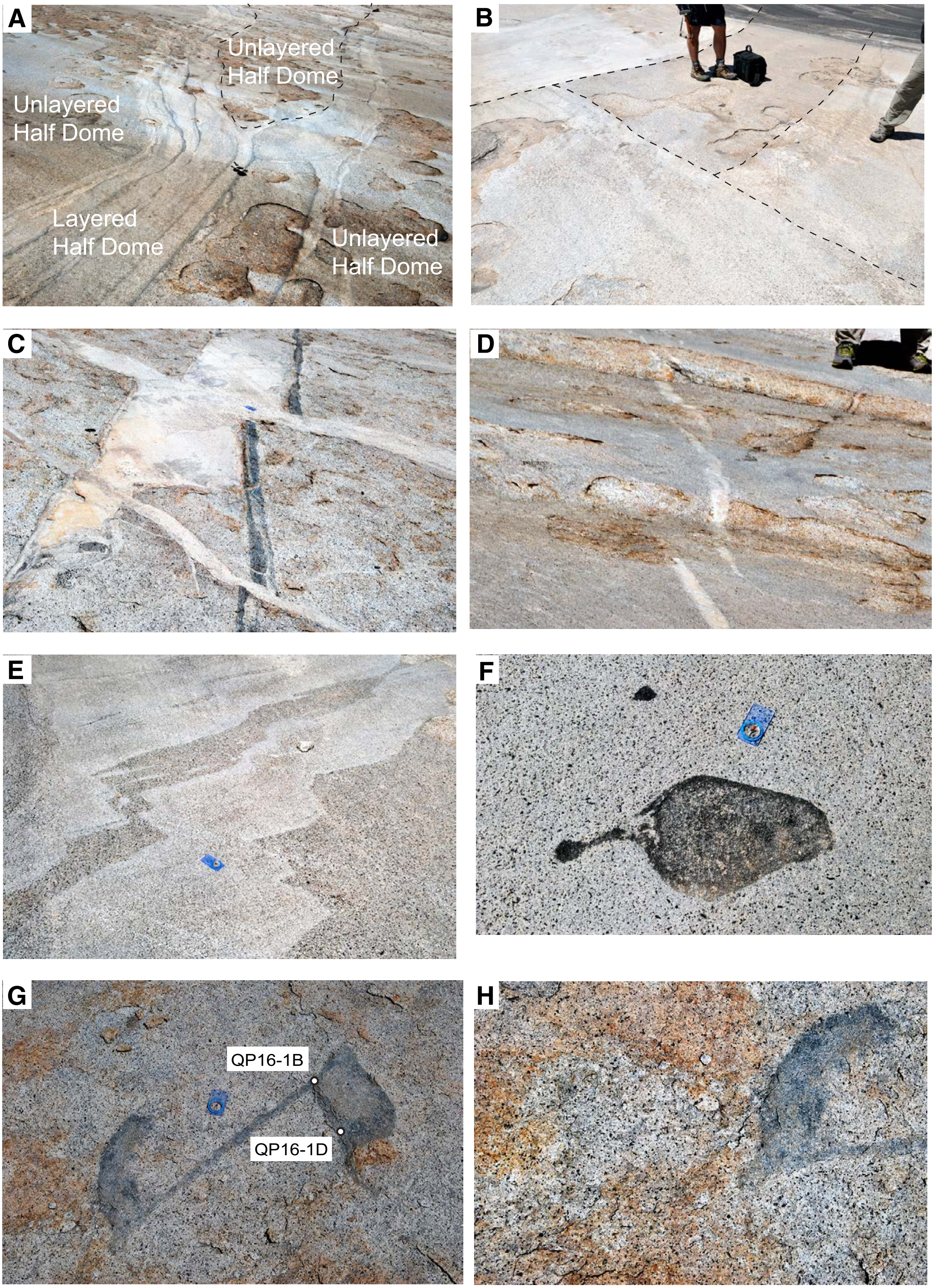

Figure 4. Structural features in the study area; dashed lines have been added to some photographs to mark faint contacts. (A) Branching layered dike isolates a screen of unlayered Half Dome Granodiorite. (B) Crosscutting relations define three ages of modally layered dikes. (C) NE-striking, modally layered dike that contains a dark porphyry layer is dextrally offset across NW-striking, more leucocratic layered dikes; (D) NE-striking, sinistral en echelon array of aplite dikes (also see Fig. 2B, 282580, 41899105); (E) discrete shear zones sinistrally offset layers in modally layered dike; (F) mafic enclave in unlayered Half Dome granodiorite forms a sigma clast that indicates sinistral shear across a NE-striking shear plane; (G) the Eighth Note, a mafic enclave in unlayered Half Dome Granodiorite offset by 60 cm of sinistral shear across a 2-cm-thick shear zone. (H) Close-up view of the SW end of the Eighth Note, illustrating the absence of mesoscopic textural evidence in the granodiorite for the shear zone that offsets the mafic enclave.

rest of dike 1. The westernmost layer at the northern end of dike 2 (282620, 4190113) crosscuts the NE-striking dike at (282616, 4190143), but dike 2 otherwise is crosscut by the NE-striking dike. Southward, the trace of the westernmost layer crosscuts several other layers to a southern termination in the center of dike 2, further confirming that this layer is younger than the rest of dike 2.

Crosscutting relations on the map indicate at least four ages of layered granodiorite and thus at least five ages of Half Dome Granodiorite including the unlayered granodiorite. However, because each thick dike contains numerous mafic-felsic cycles and each mafic-felsic cycle appears to represent a distinct intrusive event, dozens of intrusive events appear to be recorded in the map area.

Aplite dikes are moderately abundant and both crosscut and are crosscut by dikes of layered granodiorite. Therefore, multiple ages of aplite dikes also are exposed in the study area, and their intrusion overlapped in time with the layered granodiorite dikes. Some aplite dikes were intruded as en echelon arrays that indicate a sense of shear during their intrusion (Fig. 4E). The pattern of shear senses indicated by en echelon aplite dikes match those indicated by markers offset across layered dikes, i.e., NE-striking arrays record sinistral shear (Fig. 4E), and NW-striking arrays record dextral shear.

Three-dimensional exposures that permit measurement of structural orientations are sparse on the smooth glacially polished exposures, but, wherever measurable, contacts of both layered dikes and aplite dikes dip moderately to steeply westward (28°–72°, average 50°; Fig. 2). The consistent westward gradational decrease of color index within modal layers (Figs. 3B and 3C) thus can be interpreted to be an upward decrease.

Some layered dikes contain tabular to somewhat irregular bodies of hornblende-plagioclase porphyry that are mingled with the more felsic host ("Holstein" dikes). Holstein dikes do not appear to have been emplaced at a particular stage during growth of the pluton but rather are components of most of the dike emplacement phases defined by crosscutting relations.

Most of the layered dikes have nearly straight contacts that are consistent with the other evidence for a fracture-opening origin (Figs. 2 and 4). However, both the contacts and the internal layering of many north- to NNW-striking dikes are wavy (e.g., Fig. 2A, 282630, 4190090; Figs. 3C and 5A). Modal layering and the dike contacts generally bend concordantly. We interpret these dikes to have been folded. The diffuse NE-striking foliation in the unlayered granodiorite is oriented approximately parallel to the axial plane of the folds and may have formed coevally with the folds.

Although less obvious than in the modally layered dikes, the unlayered Half Dome Granodiorite also preserves evidence of internal contacts (Fig. 6). Coleman et al. (2005) noted sharp contacts in the granodiorite that were generally not traceable for more than a few tens of meters, and several such contacts are found in the study area.

Mafic enclaves and layering in the granodiorite are locally deformed by thin shear zones (Figs. 4E–4G and 5B). The shear zones commonly have the same pattern of shear senses as offsets across dikes and en echelon gash arrays, i.e., NE-striking shear zones produce sinistral offsets, and NW-striking shear zones produce dextral offsets. The shear zones do not contain a foliated rock fabric, even in instances of extreme strain concentration (e.g., Fig. 4G), and instead contain rock with the same hypidiomorphic granular texture that characterizes their surroundings. Consequently, the shear zones completely disappear where they project into unlayered granodiorite (Fig. 4H).

For example, the shear zone in Figure 4G is 2 cm thick and offsets a mafic enclave by 60 cm to produce a feature that we refer to as the Eighth Note. The geometry of the Eighth Note indicates a shear strain γ of 30 in the plane of the outcrop, which in turn corresponds to an axial ratio of the finite strain ellipse in the outcrop plane of 900, i.e., an extremely large finite strain. This is only a minimum for the actual finite strain magnitude. Owing to the two-dimensional exposure and the lack of mesoscopic deformation fabrics, the geometric relation of the outcrop surface to the principal strain axes in three dimensions is unknown. If the plane that contains maximum and minimum elongation directions is oblique to the outcrop plane—which seems likely—then the ratio of the maximum to minimum strains is even larger.

There is one mesoscopic textural difference between the shear zone and the unsheared enclave in the Eighth Note, however. Plagioclase phenocrysts that are present in the weakly deformed enclave are absent from the shear zone. Such phenocrysts are ubiquitous in Half Dome enclaves, and their absence from the shear zone therefore appears to be a product of the shearing.

Features found along strike from the Eighth Note support the cryptic persistence of the shear zone through visibly undeformed granodiorite (Fig. 5B). An enclave ~2.5 m to the northeast has a sinistral "tail" that is aligned with the Eighth Note shear zone. Approximately 6 m to the southwest, a thin aplite dike array makes a 60 cm sinistral jog, i.e., the same sense and distance as the Eighth Note shear zone. It appears very unlikely that coincidence could account for this alignment of three features that indicate shear of the same sense and orientation, two of them also indicating the same offset.

Microstructure

The lack of preserved deformation microstructures in the shear zone in Figure 4H is confirmed by SEM imaging of samples collected from the deformed enclave (Fig. 7). The backscattered electron images confirm that (1) there is no meaningful difference in microstructure inside versus outside of the shear zone, and (2) the imaged microstructures provide no suggestion of the mylonitic texture that might be expected to result from extreme concentration of finite strain.

DISCUSSION

Geometric forms and crosscutting relations of the layered granodiorite bodies favor the interpretation that the bodies are dikes that intruded the unlayered granodiorite that surrounds them. Pronounced modal layering is

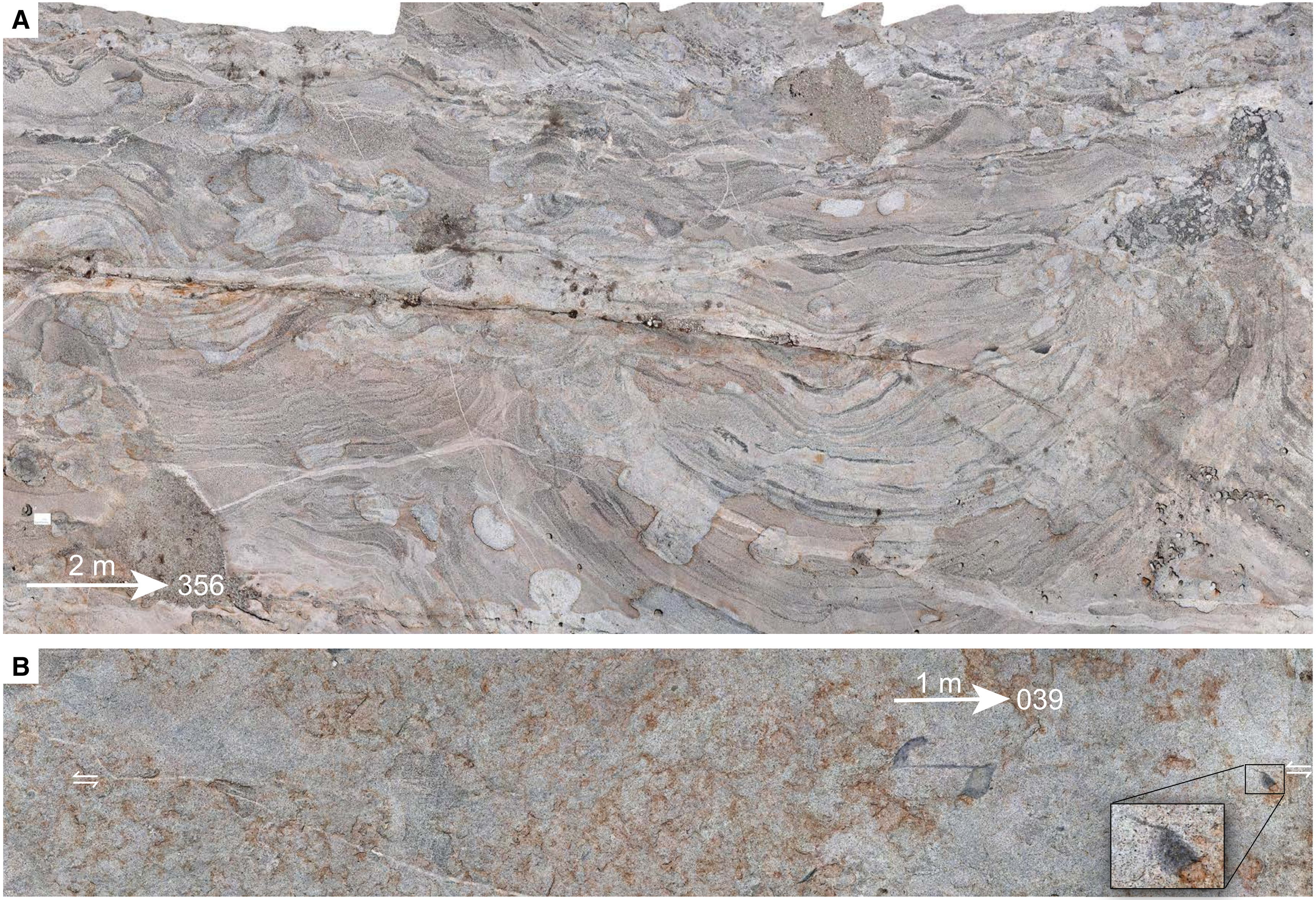

Figure 5. Orthophoto mosaics of outcrops in the study area. Full-size zoomable images are available at the following sites: (A) (26,800 pixels wide): http://www.gigapan.com/gigapans/e4514a4a938b7fdccec5b14b1cb56105. (B) (16,500 pixels wide): http://www.gigapan.com/gigapans/3c7726bf04079a777c1f01a06d9a19c2. (A) Folding of layered dikes of Half Dome Granodiorite. Less strongly folded dikes crosscut more tightly folded dikes, indicating that folding and dike intrusion overlapped in time. (B) The Eighth Note and other features seen in the outcrop along strike of the shear zone. An enclave several meters to the northeast has a sinistral "tail" that is aligned with the shear zone that crosscuts the Eighth Note. Along the southwestward projection of the shear zone, an aplite vein makes a 60 cm sinistral step, i.e., the same magnitude and sense as offset of the Eighth Note. Also see Figures 4F–4H and accompanying text.

found only within granodiorite dikes that sharply truncate features in their walls. Regardless of the process that produced the layering, the modal layering formed inside meter-scale dikes rather than at the bottom or sides of a large magma chamber.

Crosscutting relations of the thicker dikes indicate that they are composite and grew incrementally over a longer duration than the emplacement time of a single-cycle layered dike. Because cooling of felsic dikes in this size range takes no more than a few years (e.g., Webber et al., 1999), the intricate intrusive relations per se do not require a duration comparable to the millions of years over which U-Pb geochronology indicates that the Half Dome Granodiorite was assembled (Coleman et al., 2004; Memeti et al., 2011). However, it seems clear that the myriad diking events were part of this protracted growth process.

Synintrusive Deformation

An assortment of structures record synintrusive deformation, including the NE-SW preferred mineral orientation that is present in the unlayered granodiorite but absent from the layered dikes; lateral offsets of markers across dikes and shear zones; en echelon stepping of dikes; and varying degrees of folding of broadly N-striking dikes and of layers in those dikes. All of the observed structures are consistent with bulk strain that produced N-S shortening and E-W extension (Fig. 2A, inset). Emplacement of the dikes themselves also accommodated broadly E-W dilation that conforms to this strain pattern. Some dikes that produced lateral offset are crosscut by younger dikes, and some strongly folded layered dikes are crosscut by similarly oriented but less folded layered dikes (Fig. 5A). In combination, these observations indicate that the deformation was synchronous with growth of the pluton by dike intrusion. Deformation appears to have played a significant role in opening space for magmatic increments added to this part of the pluton.

Perhaps the most striking evidence for deformation is the shearing of mafic enclaves (e.g., Figs. 4F–4H and 5B). Several other similarly sheared enclaves were found in the area of Figure 2. Where rendered visible by deformation of the mafic enclave in Figure 4G, the shear zone has sharp, planar boundaries, and outside of the shear zone, there appears to be minimal strain.

Such abrupt and intense strain localization is unlikely to be achievable in a melt-rich system. Strain softening—i.e., a material decreases in strength as strain accumulates in it—is a prerequisite to strain localization. The equivalent term in fluid materials is thixotropy, which has been experimentally demon-

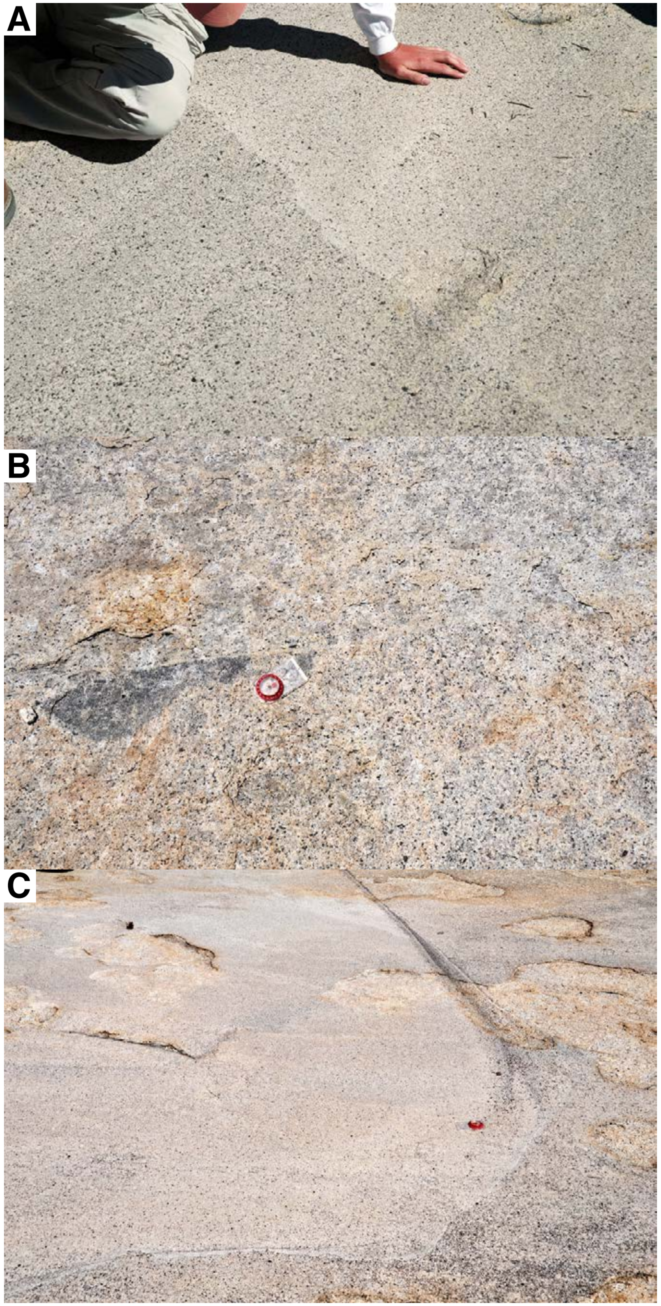

Figure 6. Features in the unlayered Half Dome Granodiorite that indicate that it is a composite intrusion that has undergone substantial near-solidus textural modification. (A) Contact between two phases of the Half Dome Granodiorite distinguished by differences in color index. This contact is distinct for only ~10 m. (B) NNE-striking contact revealed by truncation of a mafic enclave and a very slight change in color index. (C) Sinuous internal contact between unlayered Half Dome with differing color indices and locally marked by a mafic modal layer. This contact becomes impossible to trace where gradational changes in color index eliminate the visible color contrast.

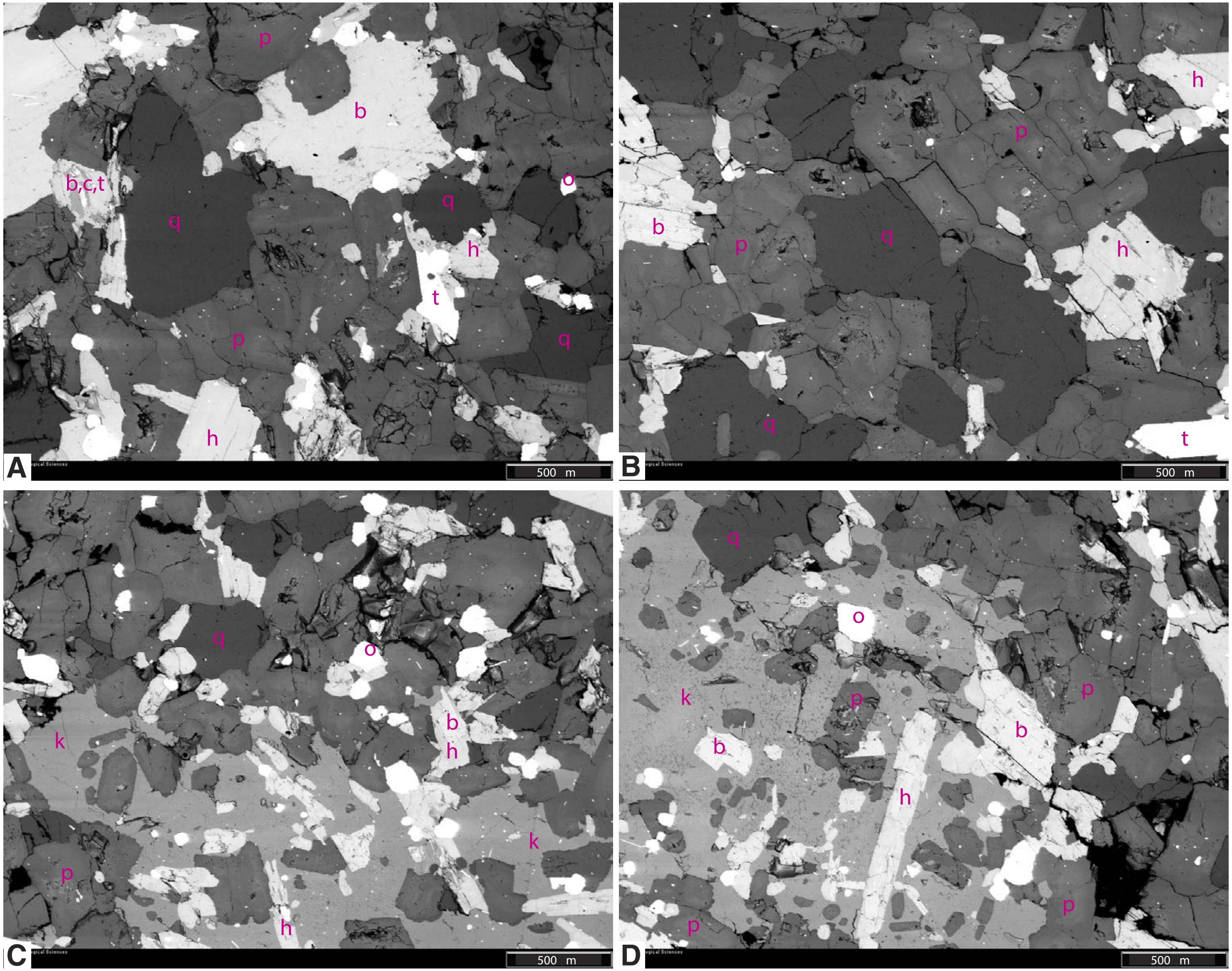

Figure 7. Backscattered electron micrographs of samples collected from the Eighth Note enclave shown in Figures 4G and 4H. (A and C) QP16-1B (inside of the shear zone); (B and D) QP16-1D (outside of the shear zone). b—biotite; c—chlorite; h—hornblende; k—K-feldspar; o—Fe(-Ti) oxide; p—plagioclase; q—quartz; t—titanite.

strated in crystal-bearing magmas (e.g., Ishibashi and Sato, 2007). Thixotropy becomes pronounced with increasing crystal content because shear strain causes segregation of melt-rich and crystal-rich domains after which strain is focused in the weaker melt-rich domains.

Observed characteristics of the Eighth Note are inconsistent with this strain-softening mechanism. The melt in partially molten granodiorite is significantly more siliceous than the coexisting crystalline fraction. Strain concentration by melt segregation therefore should produce shear zones that are distinctly more leucocratic than their surroundings. Such shear zones are observed in the Half Dome (e.g., Fig. 4F), but no such compositional contrast is observed at the Eighth Note.

Therefore, we infer that shearing of the Eighth Note occurred when both the enclave and its granodiorite host were sufficiently solidified to contain a continuous solid framework that had to be deformed for bulk flow to take place. Strain concentration probably was achieved by strain-softening mechanisms similar to those that operate in solid rock (e.g., White et al., 1980). This inference is corroborated by the absence of plagioclase phenocrysts in the shear zone in Figure 4H, which we interpret to reflect grain-size reduction (i.e., mylonitization) in the shear zone.

The field relations shown in Figures 4 and 5 indicate that the zones of highly focused shear strain are visible only where they intersect suitable markers. This observation has two significant implications.

First, there could be many more comparable shear zones present in the host granodiorite that did not intersect such a marker, and, at least at present, we have no way of knowing where such shear zones are or how many there might be. Burgess and Miller (2008) described similar structures ("magmatic faults") from the adjacent Cathedral Peak Granodiorite and drew a similar conclusion. Second, if a rock fabric formed in the shear zone, it now has been thoroughly obscured. Burgess and Miller (2008) inferred the lack of a fabric to reflect deformation of a partially molten mush, but we discount this alternative in view of the extreme strain concentration observed. We therefore interpret the absence of a fabric to reflect thorough recrystallization after the shear zone formed. This inference is consistent with independent evidence from mineral chemistry and rock textures for extensive near-solidus to subsolidus recrystallization (e.g., Johnson and Glazner, 2010). We conclude that the unlayered granodiorite has been much more strongly deformed than is evident from its texture. The only suggestion of strain during the overprinting recrystallization is the weak preferred orientation of hornblende grains. The implication is that local deformation waned while the Half Dome pluton was still warm such that the final texture reflects recrystallization under nearly static conditions.

The broader significance of the synemplacement deformation depends on whether the driving force was generated locally by the magmatic system or reflects far-field stress. Both the geometric pattern of dike injection and the overall strain pattern favor deformation by far-field tectonic stress. Delaney et al. (1986) demonstrated that, when crack opening is driven by magma overpressure, dikes are emplaced in random orientations. The dikes instead have a strong preferred orientation that indicates control by the regional stress field, which, during emplacement of most of the dikes, was oriented with a NNW-trending maximum horizontal compressive stress.

This stress-field orientation and the overall strain pattern are consistent with the plate-tectonic setting and regional tectonic history of the Sierra Nevada during Half Dome Granodiorite emplacement (ca. 93–89 Ma; Coleman et al., 2004; Memeti et al., 2011). Although the evidence is inconclusive as to whether the Kula or the Farallon plate was subducted at this time under the western margin of North America, both plates moved northward relative to North America and thus underwent dextral-oblique subduction (Engebretson et al., 1985). Coupling across the plate boundary would result in a maximum horizontal stress oriented counterclockwise from perpendicular to the NW-trending plate boundary. This orientation clearly is compatible with the geometric pattern of the dikes. Partitioning of the lateral component of plate motion into the arc is seen at many convergent margins (e.g., Fitch, 1972; Jarrard, 1986), and dextral strike slip within the Late Cretaceous Sierran arc probably reflects such partitioning (e.g., Lahren and Schweickert, 1989; Kistler, 1993; Saleeby and Busby, 1993; Tobisch et al., 1995; Tikoff and de Saint Blanquat, 1997). The observed pattern of north-south shortening and east-west dilation recorded in the study area is consistent with this regional tectonic context.

Recrystallization

The pervasive recrystallization that overprinted and obscured deformation in the Half Dome Granodiorite is inferred to result from residence at elevated temperatures (~400 °C) for millions of years during the protracted incremental assembly of the TIS (Coleman et al., 2004, 2012). Thermal modeling of large, incrementally constructed plutons (e.g., Annen et al., 2006; Davis et al., 2012) indicates that magmatic increments initially cool rapidly to near-solidus or subsolidus temperatures but then remain at conditions in the greenschist to lower-amphibolite facies for millions of years. Pervasive recrystallization not only accounts for the cryptic nature of the shear zone that deformed the Eighth Note and for observed low-temperature phase compositions, but it also likely explains the general obscurity of internal contacts. Because many, if not all, large plutons are now recognized to be incrementally assembled, it is likely that subsolidus recrystallization is a general feature of large plutons.

If far-field stresses drove synemplacement deformation, why did late-stage recrystallization take place under static conditions? The most likely reason is strain localization in response to far-field stress shifted to the Cathedral Peak Granodiorite, which began to grow as the Half Dome Granodiorite underwent final consolidation.

Origin of Modal Layering in the Dikes

The precise origin of layering in the granodiorite remains unclear. However, the fact that the layered rocks are confined to dikes that are 1–10 m thick clearly rules out crystal settling in a large magma chamber. Nonetheless, the fact that the dikes uniformly dip to the west (Fig. 2) and denser mafic minerals are persistently concentrated on the east sides of layers suggests that gravity played a role in the origin of the layering.

Clarke and Clarke (1998) proposed that unidirectional, decimeter-scale modal layering in granodiorite in Nova Scotia resulted from extremely efficient settling of small biotite crystals in thin dikes. There are several reasons that this explanation is untenable for modal layering in the Tenaya Lake area. The mechanism should scale up with dike thickness because thicker dikes have longer thermal lifetimes; yet modal differentiation is most strongly developed in dm- to cm-scale dikes, both in the Tenaya Lake area and in other granitic plutons (e.g., Wilshire, 1969; Foley and Glazner, 2009). Further, in this hypothesis, the source of the dike magma is an immediately surrounding crystal mush. Because the local mush must be sufficiently crystallized to fracture, pore melt extracted from it would be highly filtered and thus crystal-poor, and it would have a minimum-melt granite composition. The upper parts of the layers have precisely such a composition, but the lower parts are rich in ferromagnesian components that would not be present in such a late-stage magmatic liquid. Therefore, whereas extraction of late-stage pore melt into fractures almost certainly accounts for aplite and pegmatite dikes (also see Glazner et al., 2008), it is inconsistent with the characteristics of the layered dikes.

Flow sorting in the dikes via the Bagnold effect, as proposed by Bateman (1992), is also excluded because the Bagnold effect should produce symmetric layering with fine-grained materials on the sides and coarse in the middle, whereas the observed layering is compositionally asymmetric (mafic on the east, grading to felsic on the west) and shows little grain-size variation (although grain sizes probably have been modified by recrystallization, as noted earlier). Žák et al. (2009) suggested that a combination of flow and gravitational sorting could account for the asymmetry by concentrating clots and glomerocrysts only along the base-flowing margin. Essentially, this hypothesis is a modification of the crystal settling hypothesis with the added complication that dense crystals on the upper side of a dike would need to settle through the slurry of coarser crystals being moved to the center. This is improbable for the reasons cited above.

The meter-scale compositional variations in the layered dikes mimic the compositional variations that define the kilometer-scale cycles in the Half Dome pluton (Fig 1B; Coleman et al., 2012). This suggests that both might reflect similar processes operating over a range of length scales. As noted above, the asymmetry of the layering suggests that gravity played a role in producing the layering. However, rather than crystal settling in a melt-rich magma chamber or dike, we interpret the main process that formed the kilometer-scale cycles was upward transport of pore melt through cracks and other pore spaces in a largely static crystal mush (Coleman et al., 2012). Inside an individual layered dike, perhaps leucogranitic pore melt percolated upward over a length scale of 0.1–1 m, thus passively concentrating early-crystallizing components in a static residue on the lower side of the dike.

However, three observations indicate that there were significant differences between the map-scale and cm-scale differentiation processes. First, the larger-scale transport process did not erase the smaller-scale layering preserved in the dikes. Second, the bulk composition of the layered dikes is leucocratic granodiorite rather than minimum-melt granite. Therefore, the magma from which these dikes formed either must have been extracted from a mush with a relatively large melt fraction, or the extracted melt must have been able to entrain mafic crystals and therefore was not efficiently filtered during extraction and transport. Third, plexuses of dikes like those mapped in Figure 2 are ubiquitous in the upper parts of cycles, beginning at the transition from the mafic to the felsic parts, but are absent in the mafic lower parts.

An important question that cannot yet be answered conclusively is whether the dikes in the study area have been reoriented since their intrusion. The crude bulls-eye pattern of contacts in the TIS and in such zoned complexes in general; the consistent outward dips of the contacts; and inward decrease in intrusive age in the TIS and other similar complexes have collectively led us to suggest (e.g., Bartley et al., 2006, Fig. 1; Coleman et al., 2012) that older components of the zoned complexes have been reoriented by doming as younger and deeper increments were emplaced as laccoliths. If correct, this process would steepen all of the mapped contacts in the study area and imply lower initial dips. However, this reorientation is not necessary for the layering to reflect a gravitational process; gravity acts across a dike that dips 50°, although the effective gradient is not as great as across a horizontal dike.

We synthesize these observations into the following conceptual model (Fig. 8). Upward percolation of pore melt took place on the meter scale throughout the active magma system, but some of the melt collected into fracture conduits. Once in a fracture, the melt ascended two to three orders of magnitude farther than it could by percolation (Fig. 8). The deeper part of the system likely was hotter and thus more melt-rich than the shallower part, and therefore melt transported in fractures was more mafic than the local pore melt in the upper part of a cycle. Dike transport also would have permitted crystal entrainment that could contribute to the granodioritic (rather than leucogranitic) bulk compositions of layered dikes.

Leucocratic dikes occasionally are seen to intrude from one cycle into the next higher one (Coleman et al., 2012), indicating that fracture transport occasionally extended beyond the active zone of interconnected melt. However, the rarity of such dikes indicates that the transport of pore melt both by percolation and in fracture conduits was largely confined to rocks that contained melt.

The Role of Dike Intrusion in Assembly of the Half Dome Granodiorite

Within the map area, layered dikes comprise up to 40%–50% of the Half Dome Granodiorite. The most conservative view of this observation is that this proportion of dikes applies only to the felsic domains of the kilometer-scale lithologic cycles, which themselves compose 10%–20% of the pluton as a whole. This implies that layered dikes compose ~4%–10% of the Half Dome pluton.

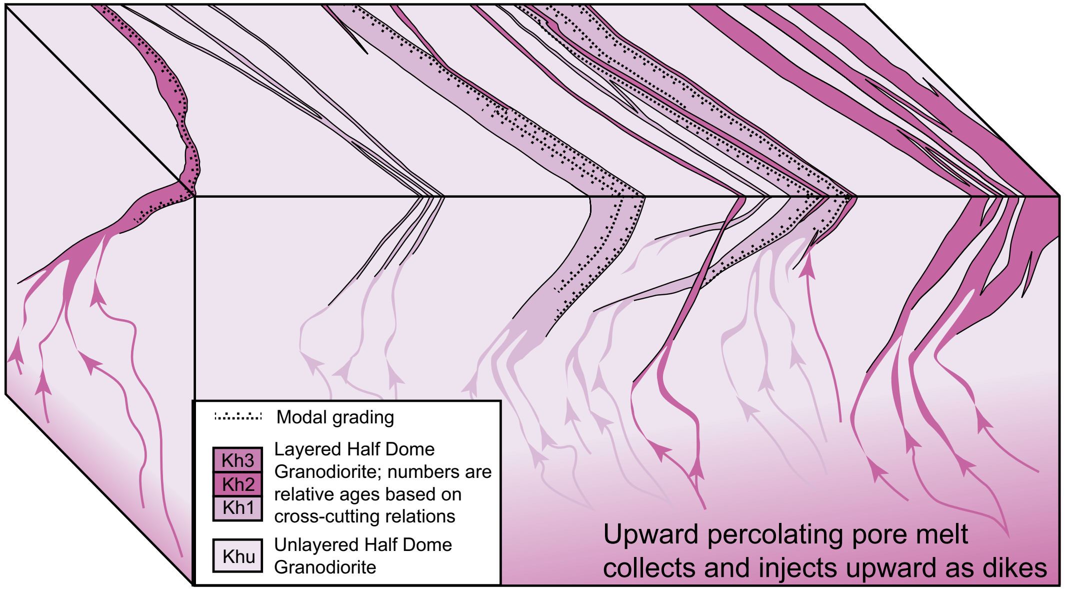

Figure 8. Conceptual model for the origin of the felsic domains of the map-scale lithologic cycles and for layering within the dikes in the felsic domains. Pore melt remaining in already-emplaced Half Dome Granodiorite percolates upward on a length scale of tens to hundreds of meters. A fraction of this melt collects in fractures and ascends to form dikes in the upper part of a cycle. Melt that undergoes fracture transport is less depleted in iron and magnesium than the leucogranite at the top of the cycle, as is required to form the mafic layers within the dikes, either owing to extraction from a deeper source that contains a higher melt fraction, entrainment of solids in the dike-transported magma, or both. Leucogranitic pore melt percolates upward through mush in crystallizing dikes to produce layering on a 0.1–1 m length scale.

Similar dikes were mapped on the eastern side of the Tuolumne Intrusive Suite in the Mammoth Peaks area by Žák et al. (2009), who estimated that the dikes comprise <1% of the total volume of the entire Tuolumne Intrusive Suite. Like the Tenaya Lake area, dikes in the Mammoth Peaks area are modally layered, record multiple intrusive events, and cut more homogeneous Half Dome Granodiorite (Žák et al., 2009). Modal layering in both areas dips outward toward the margins of the intrusive suite and shows crosscutting relations that suggest younging toward the center of the suite. We therefore interpret the dikes in both regions to have formed by the same processes. However, the map area at Tenaya Lake is located near the inner contact of the Half Dome with the younger porphyritic facies of the Half Dome Granodiorite. Rocks in the study area formed in the second youngest of at least eight cycles (Fig. 1; Coleman et al., 2012) and therefore were intruded at ca. 90 Ma (Coleman et al., 2004). The Mammoth Peaks area studied by Žák et al. (2009) lies within the oldest and outermost cycle adjacent to the Kuna Crest Granodiorite, which Coleman et al. (2004) dated at 92.8 ± 0.1 Ma. Because layered dikes represent one mode by which the cycles formed (Fig. 8), this indicates that the dikes on Mammoth Peak are at least 2 m.y. older than the dikes at Tenaya Lake. This clearly is incompatible with the inference by Žák et al. (2009) that such dikes were intruded during late-stage thermal contraction of a rapidly assembled Kuna Crest and/or Half Dome pluton.

There is little obvious evidence for diking in the assembly of the unlayered Half Dome Granodiorite at either Tenaya Lake or Mammoth Peak, although internal contacts are locally evident (Figs. 2 and 5). Žák et al. (2009) therefore concluded that dike intrusion accounted for an insignificantly small fraction of pluton assembly. However, three lines of evidence challenge this interpretation: (1) the unlayered granodiorite preserves widespread if subtle field evidence for incremental assembly (Coleman et al., 2012); (2) mappable dikes are demonstrably diachronous and did not intrude in a single late episode related to cooling; and (3) stress during dike intrusion was not characterized by simple tension produced by thermal contraction.

Modal layering in the dikes and the fact that the modally layered dikes are hosted by a different rock type renders their anatomy readily visible. The rest of the pluton is more homogeneous, which, as is evident from Figure 6, renders internal contacts more difficult to locate and map. Composite dikes are commonly difficult to recognize where individual intrusions are texturally and compositionally similar (e.g., Mahan et al., 2003; Bartley et al., 2006). Field and microstructural evidence discussed above indicates that the textures of all units were severely modified by recrystallization after intrusion and deformation. The timing of this modification during the cyclic assembly of the composite pluton (early versus late fluid-rich recrystallization) also may have affected the formation of unlayered granodiorite versus modally layered granodiorite.

If dike intrusion occurred diachronously and was governed by regional deformation, then it is reasonable to hypothesize that the plutons as a whole were assembled by diking. The alternative would be an intrusive process in which two distinct modes of pluton assembly, intrusion of unlayered granodiorite and of modally layered dikes, alternated repeatedly during the growth of a pluton. In view of the subtlety of many internal plutonic contacts recognized in this study and in others (e.g., Mahan et al., 2003; Glazner and Bartley, 2008; Davis et al., 2012) and in view of the geochronologic evidence that the Half Dome pluton grew incrementally over millions of years, we favor the simpler interpretation that the dikes mapped in this study typify the anatomy of the pluton as a whole.

We thus propose that the Half Dome Granodiorite and likely the entire Tuolumne Intrusive Suite was assembled by dike intrusion as mapped in the Tenaya Lake area. The dikes in the modally layered rocks are evident because they intruded rocks that differ in composition and/or texture (the homogenous granodiorite) and because they themselves are inhomogeneous. Late-stage textural modification has obscured (but not completely erased) evidence for dike assembly of the unlayered granodiorite.

Finally, multiple lines of field evidence now confirm the inference, initially based on geochronology (Coleman et al., 2004), that the outer Half Dome Granodiorite crystallized long before the inner Half Dome Granodiorite was intruded and, therefore, that a magma chamber comparable in size to the mapped pluton never existed (cf. Paterson et al., 2016, Figs. 12 and 16). Each of the kilometer-scale compositional cycles mapped and characterized by Coleman et al. (2012) records a temporal cycle of incremental growth, internal differentiation by percolation of pore melt, and solidification, followed by initiation of a new cycle. This paper adds to that the internal complexity of the felsic domains of cycles, which record repeated tensile fracture and highly concentrated ductile shear during growth of the cycle. Both of these processes occur only in a competent matrix that supports significant elastic strain. Therefore, a significant portion of each cycle was largely solid even as the cycle grew. The volume of material capable of bulk viscous flow at any point in time was substantially smaller than the dimensions of one of the kilometer-scale cycles.

CONCLUSIONS

The Half Dome Granodiorite in the map area has an intricate internal structure that reflects incremental construction by dike intrusion as the body underwent bulk N-S shortening and E-W dilation. Meter-scale dikes of layered Half Dome Granodiorite intruded older unlayered granodiorite, and thus the layering reflects processes that operated in the dikes, not at the bottom or sides of a large magma chamber. The origin of the layering is uncertain, but field observations conflict with crystal settling and hydrodynamic sorting. We favor the hypothesis that the layering formed by upward percolation of leucogranitic melt through a largely static crystal framework.

Mapped crosscutting relations indicate at least four ages of layered granodiorite dikes, but all of the layered dikes thicker than one meter contain multiple dm- to m-scale mafic-to-felsic cycles. We interpret each mafic-felsic cycle to represent a separate dike intrusion event, as indicated by the presence of cycles in a multilayered dike that have opposite crosscutting relations with intersecting dikes. This in turn implies that dozens of dike intrusion events are recorded in the mapped area.

Layered granodiorite dikes comprise as much as 40%–50% of the mapped area. The mapped area appears to be representative of the leucocratic parts of the kilometer-scale compositional cycles found throughout the Half Dome pluton. Leucocratic cycle tops represent ~10%–20% of the whole pluton, and therefore dikes comprise at least ~4%–10% of the total volume of the pluton. However, given the subtlety of the contrasts mapped to define the dikes in the study area, it is possible that the anatomy of the study area is typical of the pluton as a whole, but that this anatomy is only readily visible in the felsic domains of the pluton where large local variations in composition render the anatomy visible.

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