VOLUMINOUS STOPING IN THE MITCHELL PEAK GRANODIORITE, SIERRA NEVADA BATHOLITH, CALIFORNIA, USA

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Abstract

The Mitchell Peak Granodiorite, Sierra Nevada, California, has an outcrop exposure of nearly 50% stoped blocks in its youngest intrusive phase and an estimated 20% exposure of stoped blocks throughout the entire pluton. In this pluton, stoping thus is an important process. It is an excellent locale to study the effect of stoping on the evolution of magmatic systems. Preliminary work in the Mitchell Peak area has shown a complex pattern of stoping at pluton margins, with abundant evidence for mechanical disintegration of the granodiorite blocks. Preserved blocks range in size from hundreds of meters across down to K-feldspar xenocrysts. Many stoped blocks have a sharp contact with the surrounding pluton; rare examples have a diffuse, partially melted contact. Abundant xenocrysts derived from the stoped blocks provide evidence of contamination. In addition, a variety of magmatic features concentrated along the margin of stoped blocks, such as swarms of microgranitoid enclaves, schlieren layering, aplite intrusive bodies and orbicular granodiorite, suggests that these are areas of repeated injection or pulsing of magma. We speculate that repeated injection of magma plays an important role in the mechanical and chemical breakdown of host-rock margins and of stoped blocks. Stoping may play an important role in the thermal, mechanical, and chemical contamination of magmas in arcs, and deserves further attention.

Keywords: magmatic stoping, pluton emplacement, contamination, Sierra Nevada batholith, California.

Sommaire

A l'affleurement, la granodiorite de Mitchell Peak, dans la chaîne des Sierra Nevada, en Californie, montre une surface faite de presque 50% de blocs effondrés représentatifs du faciès précoce, et ailleurs dans le pluton, d'environ 20% de blocs effondrés. Dans ce pluton, l'effondrement de blocs semble un processus important. Il s'agit donc d'un endroit exceptionnel pour étudier les effets de tels affaissements dans l'évolution de systèmes magmatiques. Les travaux préliminaires portant sur la région de Mitchell Peak ont démontré un schéma complexe d'effondrements le long des bordures du pluton, avec évidence abondante témoignant de la désagrégation mécanique des blocs de granodiorite. Les blocs conservés vont de centaines de mètres à la taille d'un xénocristal de feldspath potassique. Plusieurs blocs effondrés font preuve d'un contact franc avec le pluton qui les englobe; de rares exemples présentent le cas d'un contact flou, signe d'une fusion partielle. L'abondance de xénocristaux dérivés de blocs effondrés témoignent d'une contamination importante. De plus, une variété de phénomènes magmatiques concentrés le long de la bordure des blocs effondrés, par exemple des essais d'enclaves microgranitiques, un rubannement en schlieren, des masses intrusives d'aplite et une texture orbiculaire de la granodiorite, fait penser qu'il s'agit d'injections répétées ou d'une pulsation de magma. A notre avis, l'injection répétée de magma jouerait un rôle important dans la destruction mécanique et chimique des bordures des blocs de roche encaissante et des blocs effondrés de la paroi. Ces effondrements pourraient bien jouer un rôle important dans la contamination thermique, mécanique et chimique des magmas typiques d'archs, et méritent ainsi une attention accrue.

(Mots-clés: effondrement magmatique, mise en place d’un pluton, contamination, batholite de Sierra Nevada, Californie.

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INTRODUCTION

Magmatic stoping, a process whereby host-rock surrounding an intrusive body is incorporated into it, has been recognized for well over a century (e.g., Goodchild 1892, Daly 1903). The term “stoping”, derived from mining activities, was adapted to describe observations made in plutons by Daly (1903). Stoping involves the dislodgement of pieces of host rock (referred to here as blocks) by magma, and subsidence (or ascent) of included blocks due to the difference in density between the block and the enclosing magma. Magma can “mine” its way upward and sideways by this process. Large volumes of stoped blocks are rarely preserved in plutons, which makes it difficult to assess: (1) processes that lead to the formation of stoped blocks at pluton margins, (2) the mechanical and chemical disintegration of stoped blocks once in the magma chamber, (3) other emplacement-related processes active at pluton margins (e.g., ductile flow, faulting) prior to stoping, and (4) the true volumetric significance of both stoping and other material-transfer processes active during emplacement.

Work in the Mitchell Intrusive Suite (MIS), Sierra Nevada, California, specifically in the fine- and coarse-grained facies of the Mitchell Peak Granodiorite (MPG), suggests that in this area, stoping played a major role, at least during the final stages of emplacement. Not only are pluton margins stepped and irregular (e.g., Fowler & Paterson 1997), but stoped blocks of the coarse-grained facies of the MPG found throughout the youngest phase, the fine-grained facies of the MPG, account for approximately 20% of the surface area exposed, based on mapping by Moore & Sisson (1987). Our detailed mapping along the pluton margin reveals that local abundances of blocks exceed 50%! This area is an atypical example, where large volumes of stoped blocks are preserved, allowing for a detailed examination of their evolution. Mapping has shown a complex spatial arrangement of stoped blocks and excellent evidence for mechanical disintegration of blocks. The blocks range in size from hundreds of meters across down to K-feldspar xenocrysts. Block contacts with the surrounding pluton are sharp, with only one example of a more diffuse, partially melted contact observed. Therefore, the MIS provides an excellent field laboratory for the study of the evolution of stoped blocks and the effect that stoping has on magmatic systems. We present in detail the field and petrographic evidence that supports the conclusion that in the MIS, stoping is an important process, and that once stoped blocks become incorporated into a magma chamber, they break down mechanically, which may lead to thermal and chemical contamination of the system.

BACKGROUND INFORMATION

The apparent scarcity of stoped blocks in plutons has led many investigators to conclude that stoping is not an important process during emplacement of plutons (e.g., Tikoff et al. 1999, Bachl et al. 2001, Bartley et al. 2001, Glazner & Bartley 2005). However, preservation of stoped blocks in plutons is predictably unlikely, since the rate at which blocks sink, hours to days, according to Paterson & Okaya (1999), is much greater than the rate at which magmas crystallize, $10^3$ to $10^6$ years according to Paterson & Tobisch (1992). Therefore, only blocks formed near solidus conditions are likely to be trapped within a chamber (Paterson & Okaya 1999). In fact, many plutons show at least minor to moderate evidence for stoping, which should be a favored material-transfer process where large thermal gradients exist at magma – host-rock boundaries (Daly 1903, Grout 1937, Marsh 1982, Furlong & Myers 1985, Cobbing 1999, Pignotta et al. 2001, Pinotti et al. 2002).

Evidence supporting or refuting stoping should not simply include the presence or absence of stoped blocks in a pluton. More importantly, discordant relationships between the host rock and pluton, lack of evidence for other material-transfer processes (e.g., ductile flow, faults) and lack of a high strain or a metamorphic aureole strongly suggest that stoping plays a role, at least during the late stages of pluton emplacement. Numerous examples show host-rock stratigraphic markers and structures truncated at highly irregular (stepped) margins of plutons, with little to no evidence of other material-transfer processes preserved in the host rock (e.g., Paterson et al. 1996, Yoshinobu et al. 2003). We find it difficult to account for these discordant relationships and the lack of higher strain or metamorphic aureoles without some degree of stoping, and suggest that stoping must play an important role during emplacement of at least some plutons.

GEological SETTING

The study area lies within the southern Sierra Nevada batholith, in Sequoia – Kings Canyon National Park. The Mitchell Intrusive Suite is exposed between the older Sequoia Intrusive Suite to the west and the younger Whitney Intrusive Suite to the east (Moore & Sisson 1987). Barometry for this portion of the Sierra Nevada batholith, using the aluminum-in-hornblende technique, suggests emplacement depths of ~2–3 kbar for these intrusive suites (Ague & Brimhall 1988). The MIS consists of the Granodiorite of Castle Creek (98 ± 2 Ma, U–Pb, Bushy-Spera 1983), and the coarse- and fine-grained facies of the Mitchell Peak Granodiorite (91 Ma; Chen & Moore 1982). Sisson & Moore (1984) and Moore & Sisson (1987) have shown that the older Granite of Lodgepole (>115 Ma; Chen & Moore 1982) was intruded by younger granodiorite plutons of the MIS (Fig. 1). Spectacular three-dimensional outcrops across alpine cirque basins expose the roof of the MIS and stoped blocks of the Granite of Lodgepole, both at and hundreds of meters below this roof. Intrusive contacts, along the roofs and walls of these well-exposed plutons,
have been formed along discordant brittle fractures that truncate all structures in the older Granite of Lodgepole, and are not sheared or coincident with regional faults. Several stoped blocks a few hundred meters below this roof show magmatic fabrics that wrap around stoped blocks, that are broken apart along fractures intruded by magma (Fowler & Paterson 1997).
Similarly, the youngest intrusive phase in the MIS, the fine-grained facies of the MPG, is dated at 91 Ma (Kmf, Fig. 1); it intrudes the slightly older, coarse-grained facies of the MPG (Kmc), and hosts a suite of stoped blocks of the older phase (Moore & Sisson 1987, Sisson 1992). The coarse-grained facies of the MPG is a coarse-grained, biotite–hornblende granodiorite containing megacrysts of K-feldspar up to 4 cm in length (Moore & Sisson 1987, Sisson 1992). Microgranitoid enclaves in this phase are rare, and this unit is lighter in color than the younger unit. The younger, finer-grained phase is a biotite–hornblende granodiorite with plagioclase phenocrysts and K-feldspar occurring only as groundmass minerals (Moore & Sisson 1987). This younger phase is slightly darker in color and contains many microgranitoid enclaves, typically 6–18/m² (Sisson 1992).

The stoped blocks of coarse-grained MPG have a large range in size and are located at variable distances from contacts with the fine-grained phase. Both the margins and stoped blocks are superbly exposed, and offer excellent three-dimensional control. Field studies from this area confirm that the formation of Mode-I (opening mode) fractures played a major role in the mechanical erosion of this pluton’s margins. Fractures and dikes are pervasive at the contacts and in individual stoped blocks. Networks of fractures have been observed along the pluton – host-rock boundaries, suggesting a complex evolution of the magma – host-rock margin. Aplite, minor pegmatite and evidence for multiple pulses of fine-grained MPG magma are found in fracture networks and along block margins, even in blocks located in the interior of the pluton away from contacts.

CHARACTERISTICS OF STOPED BLOCKS IN THE MIS

Overview

The fine-grained facies of the MPG (Kmf) contains abundant blocks of the older, coarse-grained facies (Kmc) throughout the entire southern half of the pluton (Fig. 1). In addition, many exposures of aplite blocks and rare xenoliths of metasedimentary and metavolcanic rocks are observed throughout the fine-grained facies. In some domains within this southern portion, the pluton is choked with blocks of the older facies, as indicated by examination of the original geological map of Moore & Sisson (1987) (Fig. 1). Calculations from this map yield estimates for the exposed surface-area of stoped blocks of approximately 20%. Detailed mapping in the MIS reveals that locally, stoped blocks account for more than 50% of the exposed surface-area. For

Fig. 2. Detailed map of the Hidden Lakes area in the MIS (initial mapping at 1:5000 scale). Units are the same as in Figure 1, except for the addition of the marginal facies of the fine-grained facies of the MPG (denoted Kmm in the map legend). See text for additional description of this unit. Note that magmatic foliations shown on map are a subset of measurements for clarity.
example, the exposure shown in the map in Figure 2 is 56% stoned blocks.

Blocks throughout the fine-grained MPG, and in particular in the area chosen for detailed study (Fig. 2), range in size from hundreds of meters down to individual xenocrysts (Figs. 3b–d). An analysis of the distribution of block sizes is presented in Figure 3a. The largest blocks in the area are on the order of 100,000 m², with an average size of 13,000 m². These calculations do not take into account any blocks smaller than approximately 15 x 15 m, since features of this size and smaller could not be represented on the map accurately. Many blocks are observed in this 15 x 15 m size range, which is intermediate between map-scale blocks and xenocrysts. These blocks are found throughout the map area, in particular in domains denoted in Figure 2 by the “blocky” pattern. In many areas, these smaller fragments were derived from other larger blocks or from blocks that completely disaggregated. There is a rough trend of decreasing numbers of blocks as size increases from the large peak at 2000 m². Also, the inset plot shows the distribution of block sizes only for blocks that are smaller than 2000 m² (i.e., the first bin in the larger histogram). These smaller blocks also show a trend of decreasing numbers of blocks as size increases within this range.

The shapes of blocks vary greatly. Angular shapes are most common, many blocks being triangular, whereas very few blocks are circular or roundish in map section (see Fig. 3d for a rare exception). The shapes of individual blocks are complex for the most part, which leads to the intricate map-pattern (Fig. 2). Corners or protrusions from blocks are commonly broken off and separated from larger blocks. This mechanical “rounding” of blocks is seen at the map to meter scale, and many of the corners and protrusions are separated from the main block only by a dike or vein. Furthermore, many blocks can be fitted back together, much like pieces of a jigsaw puzzle, though commonly complex block-geometries do not match up with neigh-
boring blocks. These observations suggest that there has been differential movement between many of the blocks in this area.

**Dikes within blocks**

Dikes are common features within the Kmc blocks in the area of the detailed map (Fig. 2). Different compositions of dikes observed include: fine-grained MPG, aplite and pegmatite. The fine-grained MPG composition in the area of the detailed map is highly variable within the domain of preserved blocks (the eastern portion of Fig. 2), compared with the typical composition observed outside this domain. Slightly more mafic compositions, abundant microgranitoid enclaves and swarms of enclaves, schlieren layering, and xenocrysts characterize the fine-grained MPG within this domain of preserved blocks. Thus, we consider it a marginal facies of the fine-grained MPG (Kmm). The dikes that intrude blocks within the Kmm domain have compositions and features similar to those found in the surrounding granodiorite (Fig. 4). They vary in width from centimeters to meters, and most commonly cut entirely through blocks. However, numerous Kmm dikes do not fully cut through blocks and taper down from their origin at a block margin to a dike tip (Figs. 4a–b). The radius

![Fig. 4](image-url)

**Fig. 4.** a) Dike of Kmm cutting Kmc block with small to no aplite margin. b) Dike of Kmm cutting Kmc block with a wide and irregular aplite margin. c) Aplite margin of larger composite dike with aplite xenolith removed by intrusion of Kmm. d) Close-up of block margin with dike of Kmm intruded along pre-existing aplite dike in block of Kmc. This dike only intruded ~2 m into the aplite dike, which continues for ~20 m.
of the tip of granodiorite dikes ranges from a meter scale that can be mapped (Fig. 2) down to a centimeter scale (Paterson & Miller 1998a). Rarely, granodiorite dikes do not connect to the host pluton (in the plane of the mapping) and are wholly contained within a block (e.g., two dikes within a western block in Fig. 2). Aplite is another commonly observed composition of dikes within blocks. These dikes are typically not very wide (a few cm to tens of cm) and very fine layering, similar to schlieren layering, locally occurs within the aplite. This layering is wispy and typically margin-parallel. Pegmatite dikes are observed, but are rare in the area of the detailed map.

Timing relationships between dikes that break up blocks are consistent across the area of the detailed map. Aplite dikes within blocks are commonly intruded along their length by marginal-facies fine-grained MPG (Figs. 4b, d). Many of these granodiorite dikes have an aplite margin and small pieces of the original aplite dike incorporated in them (Fig. 4c). Not all granodiorite dikes that intrude aplite dikes continue along the full length of the original aplite dike, thereby breaking a block apart; some terminate (freeze) part way along the dike.

Magmatic fabric patterns within blocks

Foliations and lineations measured in the field in the coarse-grained facies of the MPG (Fig. 5) are magmatic, on the basis of field and microstructural criteria [Fig. 6a; see Paterson et al. (1998) for a discussion of criteria used to determine the magmatic nature of fabrics]. Magmatic fabrics (i.e., foliations and lineations) in the blocks are defined by the preferred alignment of minerals (feldspars, biotite, and hornblende) and rarely by alignment of elongate microgranitoid enclaves. The only subsolidus fabrics noted in the area are associated with late regional brittle faulting of uncertain age.

Within the blocks of coarse-grained MPG, the intensity of mineral fabrics is commonly weak [see Miller & Paterson (2001) for a discussion of qualitative intensity of fabric] and at many outcrops, mineral fabrics were not observed (Fig. 2). The average orientation of the mineral foliation in the blocks is 113°/71° (right-hand rule). However, there is a large amount of scatter in the data (Fig. 5). Similarly, the orientations of mineral lineations are typically moderately to steeply plunging, but not consistent throughout the map area. The proportion of enclaves within the coarse-grained facies is less than in the fine-grained facies, and typically, they show a lack of preferred orientation (Fig. 6b). Fabric orientations are inconsistent, both between blocks at the map scale and within individual blocks (Fig. 2). Thus on the basis of these fabric data and on field observations throughout the MIS, the coarse-grained MPG is characterized as being a relatively homogeneous and isotropic unit.

Foliation within the blocks is normally truncated by block margins, and not deflected along them (Figs. 6b, d). Margin-parallel mineral-defined foliation is rare, and typically limited to a few tens of cm to no more than a few m from the block margin. Patterns of continuous deflection from internal to margin-parallel orientations have not been observed. It is unclear whether this pattern reflects a realignment of the internal foliation along the margin(s) or whether the pattern is fortuitous, considering the weak nature and inconsistency of the foliation within the blocks, coupled with complex geometries of these blocks.

Characteristics of Block Margins of the Stopped Blocks

Overview

The margins of blocks in the fine-grained MPG vary in shape, orientation and style. Observations of block margins come primarily from the area of the detailed map, where nearly all contacts have been walked in

![Fig. 5. Structural data plotted in lower hemisphere, equal-area stereonets; poles to foliation and lineation separated and color coded to the three major rock-units found in Figure 2.](image-url)
their entirety. The only contacts that have not been walked out completely are on steep to vertical cliffs in the central domain of the map area.

Most block margins are angular stepped contacts, the steps being centimeters to tens of meters long. Several steps may occur along the contact of a single block (Fig. 7a). However, they do not necessarily step in the same direction (e.g., not all are left-stepping along a single contact). Similarly, there is no consistent or typical size of the steps along individual margins or throughout the area of the detailed map. Dikes or veins of fine-grained MPG or aplite are commonly injected into the block at the inside corners of steps. Commonly, fragments broken from the stepped margin are found close to their origin. Corners of blocks are also typically angular (Fig. 7b). Even for the largest blocks in the area, block corners are sharp, with high angles between margins. Along both dike and block margins, xenocrysts of K-feldspar in the initial stages of removal from larger blocks are also observed.

Figure 2 shows that orientations (both strike and dip) of block margins are highly variable. Throughout the area of the detailed map, contact dips vary considerably, and a single contact may change from shallowly dipping to steeply dipping along its length, and even change direction of dip (Fig. 7c). The complex variation in orientation along a single margin of a block is generally mimicked by a nearby margin, suggesting that those margins were once together.

*Styles of block margins*

Several styles of block margins are observed in the map area: (1) sharp contacts between blocks and fine-grained MPG (Figs. 8a–c), (2) sharp contacts between block and surrounding pluton, but with an aplitic layer along the block margin (Figs. 3, 8d–e), and (3) diffuse or gradational block margins (Fig. 8f). Sharp contacts dominate, with very few examples of gradational margins (i.e., two examples) that indicate partial melting of the block.

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**Fig. 6.** a) Photomicrograph in cross-polarized light of typical Kmc lithology; note lack of subsolidus deformation. b) Contact between Kmc block and Kmm; foliation in Kmc is discordant to margin and foliation in Kmm is parallel to margin (red dashed lines added for clarity). c) Rare example of heterogeneity within a block of Kmc; the orbicular structure seen in the photo is widespread in the MIS (Moore & Sisson 1987); photo looking up a vertical face. d) Kmc block with foliation subparallel to foliation in Kmm.
Blocks with sharp contacts but with no aplite do exhibit variability in style. Blocks are commonly found in direct contact with typical fine-grained MPG. However, many also have schlieren layering along them, formed by concentrations of mafic minerals and enclaves, typical of the marginal facies of the fine-grained MPG (Fig. 8, see below for description). Sharp contacts in some instances are bordered by aplite. These aplite rinds are margin-parallel, and some contain a very fine, wispy layering similar to schlieren layering, but at a much finer scale. Both the contacts between block and aplite and between host pluton and aplite are sharp (Figs. 8d, e). A single margin of a block typically has a consistent style along its length, but some do change from one style to another (i.e., sharp contact turns into a sharp contact with aplite, or features within the marginal facies of the MPG change, e.g., ± schlieren layering, enclaves, etc.). The change in style of a margin is typically accompanied by a change in orientation, but not exclusively.

Diffuse contacts are rare. In fact, only two examples of diffuse contacts that suggest partial melting or recrystallization of a block were observed. Both examples are small (< 5 m) blocks of what appears to have been coarse-grained MPG, but are much coarser grained, with predominantly plagioclase and K-feldspar megacrysts and large crystals of biotite and hornblende. The blocks themselves appear as “ghost” or residual blocks with little resemblance to the typical coarse-grained phase.

**Characteristics of the Fine-Grained Mitchell Peak Granodiorite**

**Overview**

The fine-grained MPG in the area of the detailed map has been divided into two domains (Fig. 2). The domain in the western portion is fine-grained MPG, whereas the eastern domain, named here the marginal...
facies (Fig. 9a), contains abundant blocks of the coarse-grained facies and is distinguished compositionally and texturally from the fine-grained facies. These differences include: an increase in mafic mineral content, increased amounts of enclaves and swarms of enclaves, abundant schlieren layering, magma tubes and increased occurrence of xenocrystic K-feldspar (Figs. 9b–d). Ample evidence throughout the MIS supports local pulsing of magma around blocks, in particular those found in the area of the detailed map, in the fine-
grained facies of the MPG. This includes the presence of enclave swarms throughout the fine-grained facies (Fig. 9), abundant schlieren layering (Figs. 8c, 9c, 10c), magma tubes (Weinberg et al. 2001; Fig. 9b), and numerous occurrences of orbicular granitoids, which have been interpreted to form partly as a result of superheating during magmatic fluxing (Moore & Lockwood 1973, Moore & Sisson 1987, Vernon 1985; Fig. 6c). In addition, patterns of the magmatic fabric are more complex in the marginal facies than in the rest of the fine-grained MPG.

Xenocrysts of megacrystic K-feldspar are observed throughout the fine-grained MPG in the area of the detailed map and in other domains where stoped blocks are common (Figs. 2, 11). Concentrations of K-feldspar xenocrysts greatly increase within this domain, and are not necessarily concentrated along block margins, but occur throughout the marginal phase.

Magmatic fabric patterns in the fine-grained Mitchell Peak Granodiorite

Magmatic fabrics are defined by both mineral alignment (foliations and lineations) and alignments of elongate microgranitoid enclaves. The two fabric elements are almost exclusively parallel throughout the map area. Fabric intensity is highly variable, particularly within the marginal facies of the MPG, where block abundance is highest, with more intense fabrics generally noted closer to blocks. Outside this domain, fabric intensities are generally weak, but more intense fabrics exist locally throughout the fine-grained facies of the MPG.

In the fine-grained facies in the west and elsewhere throughout the MPG, magmatic foliations are typically steep, with a general trend of NW–SE (Fig. 5). However, within the domain of high abundance of
blocks, foliation and lineation orientations are highly variable. They also show both concordant and discordant relationships to block margins, foliation trends striking into block margins at angles from a few degrees to 90°. These discordant foliations strike right up to the block margin, typically with little or no deflection, even centimeters from the margin (Fig. 10a). In addition, several examples were observed where single enclaves are truncated at a block margin (Fig. 10b). Locally, at block margins, foliation trends change from oblique to margin-parallel (Fig. 10c). Only rarely do magmatic foliations wrap around blocks, either in vertical or horizontal sections (Fig. 10d). The variable patterns of the fabric and the different relationships between fabrics and blocks suggest a complex rheologic and fabric-formation history in this portion of the magma chamber.

**Discussion**

**Evidence that xenoliths are stoped blocks**

Before further consideration of the consequences of stoping in the MPG and the broader implications of stoping for magmatic systems in general, it is important to address whether the xenoliths preserved within the fine-grained phase are displaced stoped blocks or in situ rafts (i.e., blocks that have not been displaced at all). For example, previous work in the MIS on host-rock blocks by Fowler & Paterson (1997) has been questioned by others, who suggested that the blocks may still be attached to roof exposures (Hutton et al. 1999).

The general issue of the importance of stoping has been raised elsewhere, and it has been suggested that stoped blocks are more likely to represent isolated bodies of wallrock found between successive intrusive bodies, rather than fragments of wallrock that were engulfed by...
magma and transported (Glazner et al. 2004, Glazner & Bartley 2005).

Evidence throughout the MPG suggests that the xenoliths are indeed stopped blocks, as shown by the following examples.

1. At numerous localities, blocks can be fitted back together, much like pieces of a puzzle, if rotated into the proper orientation. Conversely, many blocks in close proximity have dissimilar margins that could not possibly be fitted together without some type of translation. Furthermore, margin complexity between adjacent blocks (e.g., orientation, nature of stepping, presence or absence of aplastic margins) precludes separation only by dike injection, and requires some translation of the block(s).

2. The most common rock-type in the blocks throughout the southern portion of the fine-grained MPG is the coarse-grained facies. However, as previously mentioned and also noted by Moore & Sisson (1987), blocks of aplite occur throughout the southern portion of the fine-grained facies, including within the area of the detailed map, mixed in with blocks of the coarse-grained facies (Fig. 2). Furthermore, several small xenoliths of metasedimentary and metavolcanic rock are found in this domain in close proximity to blocks of aplite and coarse-grained facies. As no
substantial exposures of aplite or metamorphic host-rock exist along the contacts of the fine-grained facies, and yet these rock types are now juxtaposed within the pluton, they must have originated elsewhere and have been translated (sunk) to their present position in the fine-grained MPG.

(3) We interpret several different types of fabric patterns as suggesting block motion. Some patterns of

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**Fig. 12.** a) Summary diagram in plan view illustrating observed features within and around stope blocks in the fine-grained facies of the MPG. b) Cartoon diagram depicting processes and timing of events during generation of stope blocks along a cross-sectional view of a magma – host-rock interface.
fabric deflection around blocks suggest block sinking (Paterson & Miller 1998b). Fabrics within the fine-grained facies along lower (typically subhorizontal) surfaces of blocks are typically margin-parallel. Furthermore, these margins commonly have higher concentrations of mafic minerals, enclaves, and enclave swarms (Figs. 8a–c, 9c, 12a). We suggest that as blocks sink through a crystal-rich magma, mafic material accumulates along the lower margin and fabrics form parallel to this surface as it pushes through the magma, similar to a filter-pressing mechanism (Marsh 1987, Sawyer 1994).

(4) We interpret the truncated enclaves within the fine-grained facies along block margins to reflect truncation by block sinking (Fig. 10b). We can think of no mechanism by which enclave truncation would occur if these blocks are in situ rafts.

(5) Abundant three-dimensional exposures of blocks that are completely enclosed by the fine-grained facies are observed. This lack of connectivity between blocks, in concert with points 1, 2 and 3, suggest that these are in fact stopted blocks and not rafts of host rock that were engulfed by magma.

The above observations hold throughout the southern portion of the fine-grained facies of the MPG. However, the eastern margin of Figure 2 is near the contact with a substantial body of coarse-grained MPG (Fig. 1), and some xenoliths mapped along this eastern margin may indeed be rafts, i.e., xenoliths that have not undergone any translation or rotation. However, stopted blocks are observed even along this margin, some of which are mappable and many others of which are too small to be represented, and thus are denoted by the stippled pattern in Figure 2. Many of the blocks must have been translated (i.e., they sank through the magma) to their present position.

**Block formation and disintegration**

The disintegration of blocks may be assisted by fracturing, by both mechanical and thermal mechanisms. If macroscopic cracks develop or exist in host-rock blocks, these flaws probably will be utilized by magma, volatiles and local stress-fields to further break apart the blocks (e.g., Fig. 12). The formation and propagation of opening-mode (or Mode I) fractures require that the tensile strength of rock be exceeded (Pollard & Segal 1987, Rubin 1995). Devolatilization of blocks in a magma chamber may lead to excess fluid pressures that may lead to fracturing and incipient disintegration of blocks. Also, far-field stresses may be transmitted to the blocks through a crystal-rich magma (i.e., > 75% crystals) which would permit fracture formation.

Several types of mechanisms of thermal stress cracking have also been proposed by Clarke et al. (1998), namely: (a) thermal gradient cracking, (b) thermal expansion mismatch, and (c) thermal anisotropy cracking. The relatively homogeneous and isotropic nature of the coarse-grained MPG may have allowed thermal stress gradients to form cracks within the blocks. Thermal expansion mismatch between individual crystals in the blocks may also play a role in developing microcracks, as discussed below.

Thermal stresses have long been considered to play an important role in both the formation of stopted blocks along the margin of a magma chamber and in the disintegration of blocks, once incorporated into the chamber (Daly 1903, Marsh 1982, Furlong & Myers 1985, Clarke et al. 1998). These authors have shown, through thermal modeling, that thermal stresses can greatly exceed the tensile strength of rock. Furthermore, experimental studies on granite samples heated from moderate to high temperatures (i.e., 300 to 620°C) at moderate rates (< 2°C/min) have led to the conclusion that cracks developed as a result of thermal stresses (Fredrich & Wong 1986, Wang et al. 1989). When more rapid heating of materials occurs and larger thermal gradients exist, for example when a block is immersed in a magma at a different temperature, a thermal shock is likely to occur. Under these conditions, materials may fail dynamically, i.e., shatter rather than just permit a crack to form and propagate (Gatewood 1957). The presence of a volatile phase or phases, in concert with thermal cracking, may also be responsible for rapid breakdown or explosive disintegration of stopted blocks (Clarke et al. 1998).

The presence of K-feldspar xenocrysts from the coarse-grained MPG throughout the marginal facies of the fine-grained MPG suggests that mineral-scale fracturing occurs possibly by cracking due to thermal expansion mismatch. Thermal expansion mismatch can occur between minerals with different coefficients of thermal expansion, and microcracks can form along mineral boundaries (Wang et al. 1989). We suggest that cracking along grain boundaries leads to the “shedding” of individual K-feldspar xenocrysts from block margins. Where thermal shock occurs, dynamic disintegration of blocks is possible. In addition to xenocryst formation, the coalescence of microcracks at the mineral scale induced by thermal expansion mismatch could lead to macroscopic cracks that either break off larger fragments of a block or facilitate diking.

Dikes played a major role in the formation and disintegration of blocks in the MIS (Figs. 4, 12). Hundreds to thousands of granodiorite and aplite dikes (i.e., fractures filled and propagated by magma) occur within and between stopted blocks in the MPG (e.g., Rubin 1993, 1995, McLeod & Tait 1999). Dikes are preserved at a variety of stages of formation, from initial injection, i.e., where dikes do not completely cut blocks, to through-going dikes separating fragments of blocks. Aplite dikes later intruded by granodiorite along their length indicate that re-intrusion along cracks is important for both the formation and breakdown of stopted blocks (Fig. 12b). Rubin (1993) suggested that aplitic margins along granodiorite dikes in the MPG may be a consequence.
of volatile loss during the intrusion of granodioritic magma, as exsolved volatiles at the propagating dike-tip would thermally quench the granodioritic magma. On the basis of our field observations, we suggest that re-intrusion of granodioritic magma along dikes of aplite is the dominant mechanism that results in granodiorite dikes with aplite margins. We also interpret aplite rinds along block margins that are now surrounded by fine-grained granodiorite as a record of an earlier episode of diking that successfully broke apart blocks, the aplite becoming attached to the block (e.g., Fig. 12a), rather than reflecting crystallization along the block margin.

Not all granodiorite between blocks in the area of the detailed map is present in dikes. We infer that much of the granodiorite between blocks was trapped between blocks as they sank, rotated and settled. A block margin possibly was once a dike wall, during incipient breakup of a block, but since many adjacent margins of blocks do not match, granodiorite between these margins may not be dikes.

The lack of evidence for partial melting of blocks suggests that this breakdown was mechanical rather than involving a melting process. In geochemical modeling, contamination of magmas by assimilation of host-rock material is typically regarded as being accomplished via melting (DePaolo 1981, Spera & Bohrson 2001, 2002). However, we suggest that for the MPG, and potentially in other systems, mechanical contamination by block disintegration may play a role in the evolution of the magmatic system. This aspect requires further petrological and geochemical investigation.

**Block settling and magma pulsing**

After the formation of stope blocks at a magma—host-rock boundary (i.e., roof or wall), and as detached blocks are actively breaking apart or disintegrating, they may be settling through the magma. Whether a stope block sinks in a magma depends primarily on the density contrast between the block and surrounding magma, the size of the block and the viscosity of the magma (Sparks et al. 1977, McLeod & Sparks 1998, Paterson & Miller 1998b, Paterson & Okaya 1999). Calculations using appropriate densities for coarse-grained MPG (~2.5 g/cm²; Sisson 1992), fine-grained MPG magma (~200–10² Pa s) [see Paterson et al. (2004) and references therein] and an average size of block of 100 m yield a range of sinking rates from meters to hundreds of meters per year. Regardless of the actual rates of block settling, it is clear from observations in the area of the detailed map and discussions above that many of the blocks did settle (sink) somewhat.

Magma must fill the region vacated by the settled block. We infer that local magma pulsing, forming schlieren layering and accumulations of enclaves along the margins of blocks (lower, upper and sides), occurred as blocks sank and rotated in the magma chamber and magma flowed upward to fill in behind the block (Fig. 12). The input of “fresh” magma into an active chamber, in addition to local pulsing of magma around blocks, transfers heat and volatiles in the system (e.g., Moore & Lockwood 1973), and may contribute to further sinking or settling and block disintegration, by assisting in dike formation and thermal cracking.

**Preservation of blocks**

The question of why the MIS preserves such an abundance of stope blocks remains enigmatic. Factors that influence whether a stope block is preserved in a pluton include: the geometry of the body of magma, the rate of block disintegration, and the conditions of block settling that are influenced by the rheology of the magma (i.e., its effective viscosity and yield strength). The preservation of large volumes of stope blocks and xenoliths in plutos is rare. This should be the situation if blocks settle and disintegrate, as discussed above. Thus, the strongest evidence for stopping is not the presence of blocks, but rather the sharp, stepped margins of the pluton that commonly truncate host-rock structures (Paterson et al. 1996, Yoshinobu et al. 2003), combined with a lack of evidence for other processes of material transfer at the pluton – host-rock margin (e.g., ductile deformation, faulting).

In the fine-grained MPG, we envision three possible ways to preserve blocks at the current level of exposure: (1) the exposed area is the pluton floor or an “elephant graveyard” (e.g., Clarke et al. 1998), (2) the exposure is near a pluton roof, or (3) the exposure is in close proximity to an internal rheological boundary (i.e., floor of a magma chamber). Moore & Sisson (1987) suggested that the geometry of the fine-grained facies of the MPG was a thin tabular sheet floored by the coarse-grained facies, and that present levels of exposure are close to the pluton floor. This hypothesis is based on observations from Deadman Canyon (located in the east-central portion of Fig. 1 and on the very eastern edge of Fig. 2), where the fine-grained facies overlies the coarse-grained facies, and on some exposures of the coarse-grained facies at lower elevation. In another hypothesis, Fowler & Paterson (1997) proposed that the MIS plutons along the western margin of the suite preserve a portion of the chamber roof. The well-exposed, gently dipping roof is composed of older plutos, namely the Granite of Lodgepole; however, the roof contact could be just a subhorizontal step along the near-vertical contact (wall) of the MIS plutos (Fowler & Paterson 1997). Our field observations and map analysis suggest that the overall geometry of the fine-grained facies is not thin nor tabular. Detailed mapping along the western wall of Deadman Canyon (i.e., the easternmost portion of Fig. 2) shows that the body of coarse-grained facies from the map of Moore & Sisson (1987) (Fig. 1) is not intact. This area consists of coarse-grained facies...
broken up by injections of fine-grained facies and blocks of coarse-grained facies included with the fine-grained facies. Furthermore, map relationships and three-point calculations throughout the MIS suggest that the contacts between the fine-grained facies of the MPG and all other units, including nearly all contacts with the coarse-grained facies, are subvertical. These planar contacts cut right across substantial topographic relief (> 400 m) without deflection. Finally, exposures of coarse-grained MPG are not only present at lower elevations within the MIS, but are present at all the same topographic levels as the fine-grained facies. Given these constraints, it is equally plausible that numerous blocks of the coarse-grained MPG are preserved in the fine-grained facies because present levels of exposure are near the roof of the pluton, near the floor of the pluton, or alternatively near a rheological boundary within the pluton, i.e., a partially solidified floor of a magma chamber (Wiebe & Collins 1998), which stops blocks from sinking.

Despite these geometrical uncertainties and the lack of strong evidence to support any of the above possibilities, the conditions required to trap blocks within a magma chamber are clear. Either a rheological boundary within the magma chamber had a high enough yield-strength to stop the blocks from sinking, i.e., floor of a magma chamber, or the fine-grained facies of the MPG had to have an overall yield-strength high enough to trap the blocks of the coarse-grained facies. Both of these possibilities would be aided by the small contrast in density between blocks and magma (e.g., Paterson & Miller 1998b, Sparks et al. 1977). A high yield-strength at the floor of a magma chamber close to the present levels of exposure at the time of block formation or sinking is possible. However, testing this hypothesis is difficult in the MIS. Evidence for present levels of exposure being near the pluton’s roof is compelling, owing to the angular nature of the blocks and the lack of evidence for partial melting. Longer residence-times in the magma would favor partial melting and further breakdown of the blocks (McLeod & Sparks 1998). In addition, Fowler & Paterson (1997) have shown that the western margin of the MIS preserves portions of its roof. Thus, our preferred hypothesis is that present levels of exposure are near the pluton roof, and that a high-yield-strength boundary existed not far below that roof, allowing blocks to be trapped.

**Implications for ascent and emplacement**

Stopping is an efficient mechanism for removing host-rock material from pluton margins as magma ascends and is emplaced in the crust, and thus can be an important material-transfer process (Buddington 1959, Marsh 1982, Furlong & Myers 1985, Paterson et al. 1996, Yoshinobu et al. 2003). The extensive preservation of host-rock xenoliths in the MIS is rare, and other examples of such “stopped block graveyards” in the literature are equally rare. We suggest that the norm should be plutons where stopped blocks are not observed, owing to the combination of: (1) rapid rates of sinking (Marsh 1982, Sparks et al. 1977, Paterson & Okaya 1999) and (2) thermal-mechanical disintegration of blocks (Clarke et al. 1998, this study).

The combination of thermal fracturing and of diking mechanically and thermally contaminated the fine-grained MPG, both locally and at the pluton scale. These processes may also be important in other magmatic systems where stopping has occurred and where evidence for contamination or assimilation is observed (DePaolo 1981, Ague & Brimhall 1988, Hildreth & Moorbath 1988, Miller & Glazner 1995). The degree of mechanical contamination is dependent on both the rate at which the magma ascends and the efficiency of breakdown of the blocks. As blocks are removed from magma – host-rock boundaries (i.e., roofs and walls) and fall through the chamber, continuous disintegration at a variety of scales may take place. Evidence of this mechanical contamination may only exist in plutons (or in volcanic rocks) as xenocrysts, like those observed in the MIS (Fig. 11; Gardner 1996). The mechanical disintegration of stopped blocks may prove to be much more efficient than melting or partial melting. The energy required to contaminate magmatic systems may be less than that required for melting, and thus merits further attention.

We are not advocating stopping as the only process of material transfer that operated during the ascent and emplacement of the MIS, nor as the only mechanism operating in other systems. We continue to find evidence for and favor the operation of multiple, temporally and spatially evolving processes of material transfer throughout the ascent and emplacement history of a magmatic system (Paterson et al. 1996).

**Conclusions**

The MIS is an example of a pluton that preserves abundant stopped blocks and allows for detailed examination of block formation and disintegration. With approximately 20% stopped blocks, locally exceeding 50%, exposed in a map section throughout the fine-grained MPG, it appears that stopping played a major role in the emplacement of the pluton as a process of material transfer, at least during the latest stages of emplacement. We believe that brittle processes dominated during the formation and disintegration of the stopped blocks. A complex interplay between diking and fracturing mechanisms (thermal and mechanical) is inferred to have facilitated both the formation of blocks along the pluton – host-rock interface and the subsequent disintegration of blocks once incorporated into the magma chamber. Furthermore, block sinking and the pulsing of magma and volatiles may have increased the effectiveness of processes operating to break the blocks apart. As a result, the blocks in the MIS have complex shapes, have
become mechanically “rounded”, and some have been broken down to individual xenocrysts. Domains with abundant blocks show evidence of pervasive contamination by xenocrysts. This breakdown and mechanical contamination continue through the latest stages of crystallization, where blocks have been trapped and little displacement can occur. This type of mechanical contamination of magmas should be energetically more favorable than chemical contamination. Via melting, and where complete disintegration of blocks down to xenocrysts size occurs, little to no macroscopic evidence within the pluton may remain. Thus, the inference that the lack of stoped blocks or xenoliths preserved within a pluton suggests that stoping did not occur should be carefully weighed. Other relationships from pluton-host rock contacts, including discordant margins and lack of ductile aureoles, are also evidence that stoping occurred. Combining this evidence with rapid rates of sinking and mechanical disintegration of blocks once in the chamber, the normal situation should be that stoped blocks are not preserved within a pluton. Furthermore, mechanical contamination should be considered and investigated where petrographic and geochemical studies of magmatic systems are being carried out. In large arc-related magmatic systems like the Sierra Nevada Batholith, stoping and mechanical disintegration of stoped blocks are effective means to recycle crustal material, including earlier intrusive bodies, that with similar compositions, may not be easily discernible in the field, petrographically or geochemically.

Acknowledgements

We thank Paul Lennox, Ron Vernon, Robert F. Martin and an anonymous reviewer for their constructive reviews of this manuscript. Thanks also to Bob Wiebe and Allen Glazner for an earlier review and helpful comments, and Tom Sisson for several discussions regarding the geology of Sequoia–Kings Canyon National Park. The staff and rangers at Sequoia–Kings Canyon National Park were quite helpful during our field work in the park, and we thank them for that. Support for this work was provided to GP by a Geological Society of America Student Research Grant and a Graduate Student Research Grant from the Department of Earth Sciences, University of Southern California.

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Received July 4, 2005, revised manuscript accepted July 15, 2006.