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Incremental pluton emplacement by magmatic crack-seal

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ABSTRACT: A growing body of evidence indicates that some, and perhaps most, plutons are highly composite. However, the geometrical forms of increments and the processes by which they are added are poorly known. Magmatic crack-seal probably is an important incremental assembly process, particularly in the upper crust where wall-rock fracture is important. Evidence for magmatic crack-seal is clearest where it is antitaxial, i.e., new fractures form at the contact between wall rock and a growing intrusion. Local deviation of antitaxial cracks into wall rocks isolates wall-rock bodies that therefore mark increment contacts. Wall rock isolated by this process remains *in situ* and thus is likely to preserve a ghost stratigraphy. Previously described plutons are identified, and interpreted to have grown by antitaxial magmatic crack-seal. In contrast, it remains unclear what observable geological record may remain in plutons formed by syntaxial crack-seal, in which new cracks form in the middle of the growing pluton. Several plutons are identified that preserve possible indirect evidence for growth by syntaxial crack seal, but conclusive identification of a direct record of the process remains elusive. However, plutons with sharp discordant contacts but few xenoliths may have been emplaced incrementally by syntaxial magmatic crack-seal.

KEY WORDS: granite, incremental growth, intrusive mechanism

Granitic plutons have long been recognised to form a major component of the continental crust. However, the processes by which they grow are controversial and the estimated rates of processes that govern their formation, such as generation and ascent of magma and wall-rock deformation, range over several orders of magnitude (e.g., Miller *et al.* 1988; Paterson & Tobisch 1992; Petford *et al.* 2000; Gerbi *et al.* 2004). Limits to our understanding of the plutonic record restrict geologists' ability to take advantage of that record to understand the workings of magmatic systems and to incorporate pluton emplacement and other plutonic processes into tectonic syntheses. For example, although not all plutonic systems underlie volcanic vents, upper-crustal plutons are the most direct geological record of the magmatic plumbing systems beneath volcanic centres. A lack of consensus about how to interpret the plutonic record hinders the synthesis of volcanic and plutonic observations into an integrated understanding of magmatic systems.

A model for the origin of plutons is emerging that has great promise for reconciling and merging diverse research results into an integrated framework for understanding plutonic processes, rates, and developmental histories (Fig. 1). The central conceptual feature of the model is that, although plutons are by definition large accumulations of intrusive igneous rock, they need not form, and perhaps only rarely do form, by crystallisation of large accumulations of magma (e.g., Cruden & McCaffrey 2001; Glazner *et al.* 2004; Annen *et al.* 2006). Rather, plutons may grow in increments that are substantially smaller than the ultimate dimensions of the pluton, and such increments may be added episodically at rates several orders of magnitude faster than the long-term average growth rate. This implies that the active magma body at any point in time may be small compared to the pluton that contains it, and a pluton may even be entirely solid at times during its growth. Such a pluton may take millions of years to grow, such that different parts of what is mapped as a single continuous body differ substantially in age (e.g., Coleman *et al.* 2004; Condon *et al.* 2004; Matzel *et al.* 2005, 2006; Cruden *et al.* 2005; Walker *et al.* 2005).

The idea that plutons may be composite and constructed in increments is not particularly new (e.g., Pitcher 1979; Petford 1996). However, the increment dimensions envisioned by earlier authors generally have been comparable to entire small plutons (i.e., 'stocks' with outcrop dimensions of around 100 km^2). However, it appears that increment dimensions may be much smaller than this, and even small plutons (e.g., the McDoogle pluton and the Alta stock discussed below) may be highly composite.

1. Crack-seal model

A critical concern regarding incremental pluton growth is the recognition in natural examples of growth increments and their dimensions and spatial forms. These features in turn must reflect physicochemical processes that operate both during and

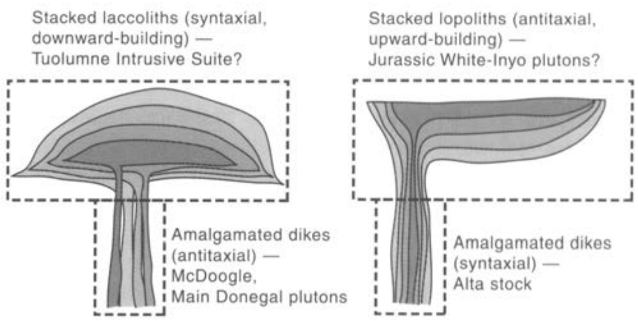

Figure 1 Possible growth modes of incrementally constructed plutons, with possible natural examples that are discussed in the text. It is hypothesised that amalgamated-dyke plutons commonly represent feeders of laccolithic and lopolithic plutons. However, the combinations shown of syntaxial versus antitaxial growth, upward versus downward growth, laccolith versus lopolith, and feeder centred versus off-centre were chosen arbitrarily. It is not intended to imply that any such links between particular pluton types are typical, and it is anticipated that all possible combinations of such variations will be found in nature. It is also anticipated that mixtures of growth modes, e.g., both syntaxial and antitaxial growth, will be found in nature.

in between the addition of growth increments. Many plutons are emplaced into the upper crust where fracturing of wall rock is a major mechanical process. Ductile flow of wall rocks during pluton emplacement probably is progressively more important as depth increases, although brittle fracture may occur at any depth if the strain rate is sufficiently high. In any case, many large batholiths grew in the upper 15 km of the crust (e.g., Hamilton & Myers 1967; Ague & Brimhall 1988; Leake & Cobbing 1993; Pitcher 1993, Ch. 14; Jowhar 2001) where fracture-based emplacement mechanisms clearly are important. This assertion is strongly supported by the predominance in many batholiths of sharp, discordant intrusive contacts.

Discordant contacts have commonly been interpreted to reflect emplacement by stoping (e.g., Cobbing 1999; Yoshinobu *et al.* 2003). However, an alternative fracture-based intrusive mechanism that produces similar contacts is the opening of cracks to form dykes, sills, and/or laccolithic bodies *sensu lato* (including lopoliths, saddle reefs, etc.). Tabular plutons clearly could grow by crack opening but, at least in principle, plutons with more complex shapes might form by amalgamation of sheet-like intrusions emplaced in varying orientations.

Pluton growth by injection of magma into dilatant cracks eliminates serious problems that are encountered if a significant volume of wall rock is inferred to have been removed by stoping (Glazner & Bartley 2006). Xenoliths are common but very sparse in most plutons, even on well-exposed pluton floors. Geochemical data rarely indicate that large-volume stoping has been obscured by assimilation. If the volume of stoped blocks is a significant fraction of the volume of the pluton, as is required for significant ascent by stoping, much of the magma present must end up trapped in pore spaces among stoped blocks. This would produce voluminous intrusive breccias that are rarely, if ever, observed in nature. Fragmentation consistently produces particle size distributions with a fractal scaling exponent near 2·5, regardless of the fragmentation mechanism. Small stoped blocks therefore should be vastly more abundant than large blocks. The assertion that xenoliths are scarce in ostensibly stoped plutons because stoping is highly efficient if only large blocks are stoped (e.g., Marsh 1982) thus conflicts with well-established observations of fragmentation.

Because wall rocks remain *in situ*, pluton emplacement by crack dilation requires net dilation around the emplacement site, e.g., crustal extension to accommodate dykes and surface uplift to accommodate sills and laccoliths. Thus, for this mechanism to be viable for the growth of plutons, wall-rock displacement rates must be compatible with pluton growth rates (Tikoff & Teyssier 1992). Paterson & Fowler (1993) and Yoshinobu *et al.* (1998) argued that wall-rock displacement rates by tectonic extension are too slow to permit dyke-like plutons to grow by this mechanism. However, the long-term average growth rate of a composite sheet-like pluton may be slow, depending on the time between the addition of increments (Cruden & McCaffrey 2001).

Plutons formed by crack opening grow at their sites of emplacement: magma ascends to the emplacement level along conduits such as dykes and, once formed, the pluton does not ascend farther. Pluton emplacement by opening and filling of cracks thus is particularly compatible with slow pluton growth by small increments, and this is required if tectonic dilation is the dominant space-making mechanism during emplacement of a pluton.

Incremental growth of a pluton by crack opening would closely resemble incremental growth of quartz veins by crack-seal (Fig. 2; Ramsay 1980a), a cyclical process of tensile crack opening, sealing of cracks by precipitation of quartz from water drawn into the cracks, and then opening of new cracks. Crack-seal permits the growth of thick quartz veins without opening a crack with a large aperture. The aqueous pore fluid in a rock need not be completely removed before the solid framework again fractures to admit another growth increment to a quartz vein. Similarly, addition of a growth increment to a crack-seal pluton requires only the reestablishment of a continuous solid framework capable of tensile fracture, not complete solidification of pore melt remaining from previous increments.

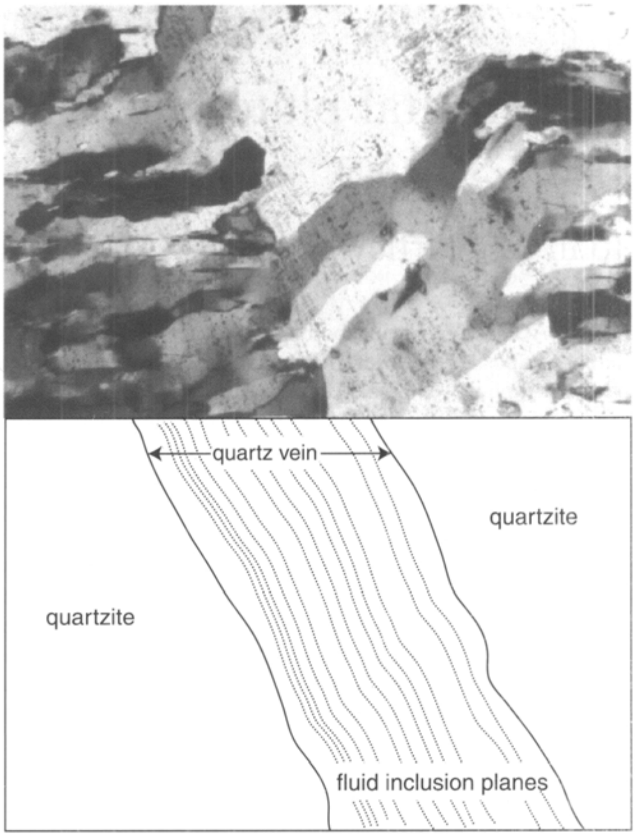

Figure 2 Photomicrograph (crossed polars; view is ~2 × 3 mm) and line drawing of crack-seal quartz veins. Fluid inclusion planes mark locations of cracks during incremental opening.

Cracking events are commonly recorded in quartz veins as planes of fluid inclusions that represent cracks healed by quartz precipitation (Fig. 2). Quartz crystals that fill the veins, however, commonly are much larger than the spacing of the inclusion planes such that each individual crystal spans many fluid-inclusion planes. Either the quartz crystals grew incrementally over many cracking events, or later recrystallisation eliminated quartz grain boundaries formed during incremental crack opening without displacing the fluid inclusions. In either case, without the fluid-inclusion planes, the operation of crack-seal would be difficult to demonstrate in the example in Figure 2, and the large number of discrete cracking events that produced the vein would be obscure. In the absence of suitable markers, crack-seal surfaces in plutons may be equally obscure.

2. Types of internal plutonic contacts

A principal objection to the concept of incremental pluton growth is that many plutons lack clearly defined internal contacts. However, contacts within superficially homogeneous

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plutons may be far more common than is generally acknowledged, because recrystallisation and other late-stage processes may obscure or obliterate them. Studies of layered mafic intrusions have repeatedly shown that late-stage recrystallisation can significantly modify grain boundaries and textures in coarse-grained plutonic rocks (e.g., McBirney & Hunter 1995; Boudreau & McBirney 1997). Even classical adcumulate texture, regardless of how it is produced, requires significant recrystallisation in order to expel interstitial liquid from pore spaces (Wager & Brown 1968; Walker *et al.* 1988). If such recrystallisation processes are widespread in relatively small, dry, and rapidly cooled mafic bodies such as the Skaergaard intrusion, then they should also operate in the larger, more hydrous, and more slowly cooled granodioritic plutons discussed in the present paper. Further, in plutons emplaced in tectonically active settings, shear-driven percolation of pore melt (Petford & Koenders 2003; Didericksen & Bartley 2003) may further obscure internal intrusive contacts.

Contacts of plutonic rocks vary greatly in clarity. Contacts against cooler wall rocks are generally sharp and unambiguous. Contacts formed when two magmas of contrasting composition occupy the same conduit are also usually clear and relatively sharp. Contacts between magmas of similar composition but contrasting texture (Fig. 3a) are less obvious and may be too subtle to find in the field. Finally, contacts between different injections of intermediate or silicic magma of the same composition and texture will generally be invisible in the field in the absence of other markers (e.g., Fig. 3b) because such magmas commonly do not form chilled margins even against cooler wall rocks (see section on McDoogle pluton, below). Late-stage recrystallisation can further obliterate evidence of injection boundaries.

The common failure to appreciate subtle internal contacts in plutons may result from an *a priori* assumption that plutons crystallise from large bodies of highly molten magma. Internal variations in plutons have commonly been assumed, rather than demonstrated, to reflect local phenomena within a large (kilometre-scale) largely molten system. In their first several seasons of field work in the Tuolumne Intrusive Suite, the present authors failed to see, or ignored, significant internal variability within mapped plutons. Geochronological data (Coleman *et al.* 2004) forced them to reexamine the plutons and they found abundant evidence for internal contacts, aided by magnetic susceptibility mapping that helped them to train their eyes to see such contacts (Coleman *et al.* 2005).

2.1. Pluton–xenolith contacts

Intrusions in which xenoliths mark sheet boundaries (Fig. 3c) may offer the clearest evidence in favour of pluton formation by repeated injection of magma. The Main Donegal and McDoogle plutons, discussed below, exemplify this style of pluton growth. Contacts between igneous rock and xenoliths are generally clearly defined, and mark the boundaries of individual magma pulses. If the xenoliths were isolated from one another by repeated magma injections, then opposite sides of a xenolith mark the boundaries of different magma pulses. However, along strike beyond the end of the xenolith, little evidence may remain for distinct pulses.

2.2. Internal contacts between magmas of contrasting composition

Internal contacts between intrusive increments of contrasting composition may offer the best opportunity for insight into the shape of individual increments added to growing plutons. These contacts, unlike contacts between rock types that vary only in texture, are unlikely to be obscured by late recrystallisation, although initially sharp contacts may be obscured by magma mingling and mixing (e.g., Flinders & Clemens 1996). Blake *et al.* (1965) suggested that such contacts may be well preserved as a result of the difference in solidus temperature of the magmas, which can result in quenching of the higher-temperature mafic magma. Such contacts are well documented in a variety of tectonic settings (Blake *et al.* 1965; Frost & Mahood 1987; Wiebe 1993; Coleman *et al.* 1995; Metcalf *et al.* 1995; Sisson *et al.* 1996; Wiebe *et al.* 2002).

A recurring theme in each of the cited examples is sheet intrusion of mafic and felsic rocks, commonly in subhorizontal orientations. Like pluton–xenolith contacts, these offer clear evidence for incremental addition of magma. However, such examples are limited in both occurrence and extent, and they are commonly interpreted to reflect addition of mafic sheets to a much larger silicic magma chamber (Wiebe 1993, 1994; Snyder & Tait 1995, 1998) and thus only to indicate the forms of mafic additions. The shape(s) and dimensions of the coeval body or bodies of felsic melt are less certain.

2.3. Internal contacts between rocks with contrasting texture

Composite mafic dykes unambiguously record magmatic crack-seal as a series of internal chilled margins within a dyke (Fig. 3d). However, chilled margins are rare in granitic rocks, probably owing to the smaller temperature contrast between granitic magma and their wall rocks, and to slower cooling that permits sub-solidus textural modification. Without chilled margins, recognition of crack-seal in the growth of a granitic pluton may be as difficult, as would be recognition of crack-seal in the quartz vein in Figure 2 without the fluid inclusions.

Internal contacts in granitic plutons may be marked where one intrusion truncates features in a similar intrusion (Fig. 3b), or where wall-rock screens locally ornament the contacts (Mahan *et al.* 2003; Fig. 3c). Internal contacts indicated by abrupt changes in texture or petrography are also recognisable (Fig. 3a; Coleman *et al.* 2005). Although locally obvious, many such contacts are gradational, or they change along strike from sharp to gradational or invisible (e.g., Bateman 1992; Coleman *et al.* 2005). Contacts between rock types of uniform composition but contrasting texture may be interpreted as floors and walls of magma chambers. However, the present authors doubt this interpretation because such features commonly become cryptic along strike.

At least two processes may account for cryptic contacts in granitic plutons. First, thermal pulses introduced by intrusive increments will cause isotherms to fluctuate and thus the melt fraction in a surrounding crystal-liquid mush to fluctuate (Bartley *et al.* 2004). The resulting recrystallisation may obscure or entirely erase textural evidence of contacts between intrusive increments. If adjacent increments are closely similar in composition, contacts between them may be rendered virtually invisible. Second, thermal models indicate that slow incremental growth can maintain much of a pluton at temperatures corresponding to the amphibolite facies of metamorphism, or higher, for extended periods (Fig. 4; Hanson & Glazner 1995; Gray 2003; Bartley *et al.* 2004). Prolonged annealing at such temperatures will promote subsolidus textural modification that is likely to further obscure primary intrusive contacts between increments. Thus, except where they are sharp, truncate features in adjacent rocks, or are ornamented by wall-rock screens, contacts mapped on the basis of texture may reveal more about the thermal history of a pluton than about the size and geometry of magma batches that contributed to its construction.

The composition and texture of an igneous rock reflect the particular 'recipe' by which it formed. In a highly composite

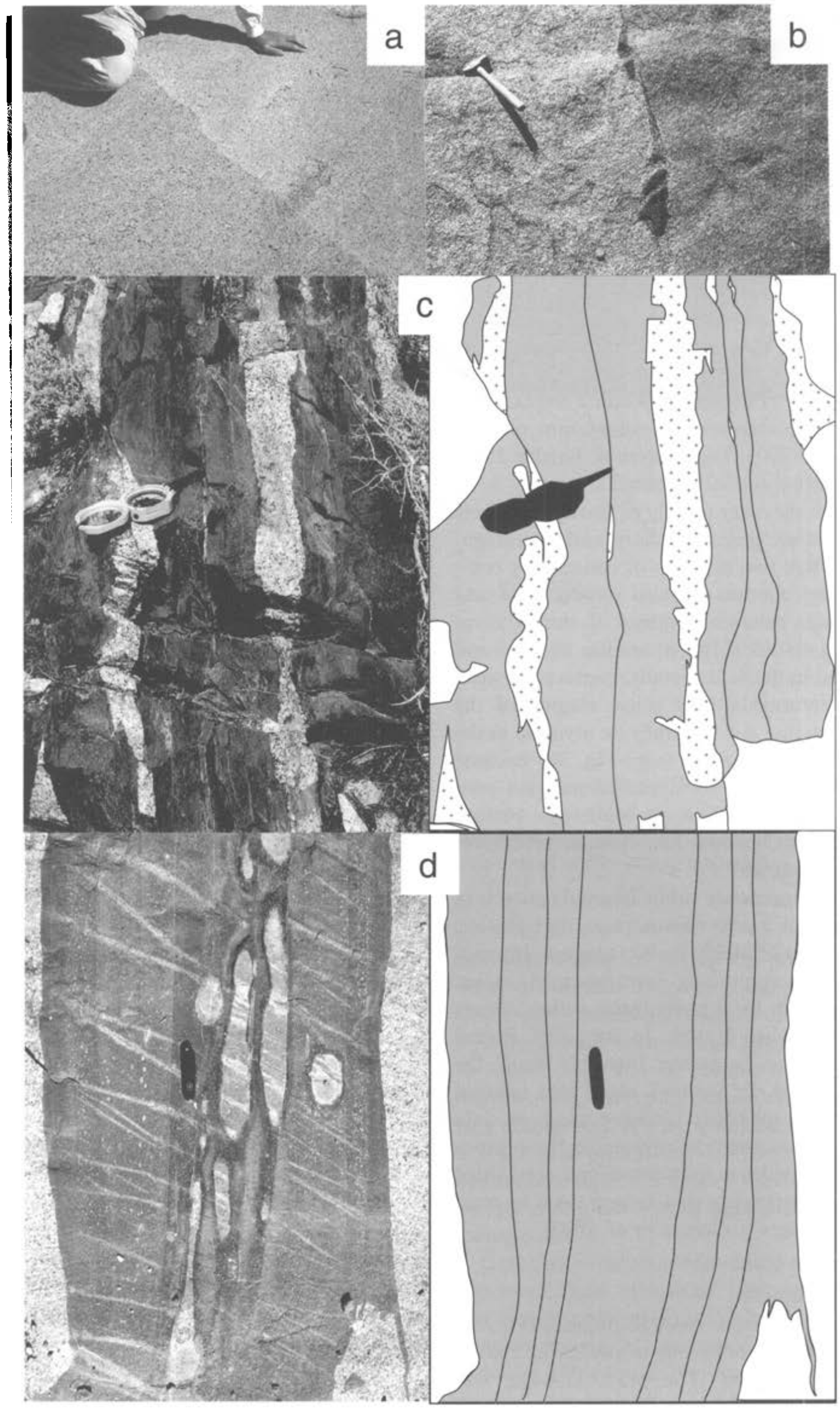

Figure 3 Examples of internal contacts in igneous intrusions: (a) Subtle internal contact within Half Dome Granodiorite, Tuolumne Intrusive Suite; (b) Truncation of magmatic foliation and mafic enclaves at internal contact within Lamarck Granodiorite, Sierra Nevada batholith; (c) Photograph and line drawing of composite mafic dyke with contacts marked by wall-rock screens, Independence dyke swarm, Sierra Nevada; (d) Photograph and line drawing of composite mafic dyke, Independence dyke swarm, Sierra Nevada. Ovoid light patches reflect post-emplacement alteration.

pluton, a lithologically defined unit need not correspond to a particular magma body, but rather to a degree of uniformity in the petrological recipe (e.g., the poorly known petrological conditions that account for growth of the distinctive, large, euhedral hornblende grains that distinguish the Half Dome Granodiorite). A lithological unit in a composite pluton thus is conceptually equivalent to a facies in a sedimentary sequence. Because similar geological settings yield similar plutonic rocks across both space and time, it is self-evident that a series of incremental additions to a pluton could be petrographically indistinguishable and would be mapped as a single unit, and this inference is confirmed by geochronology (e.g., Coleman *et al.* 2004). Lithological contacts in a highly composite pluton thus may be diachronous for the same reasons that lithologic contacts in a sedimentary sequence commonly are diachronous. Therefore, lithological contacts within plutons may, but need not, correspond to contacts of incremental additions.

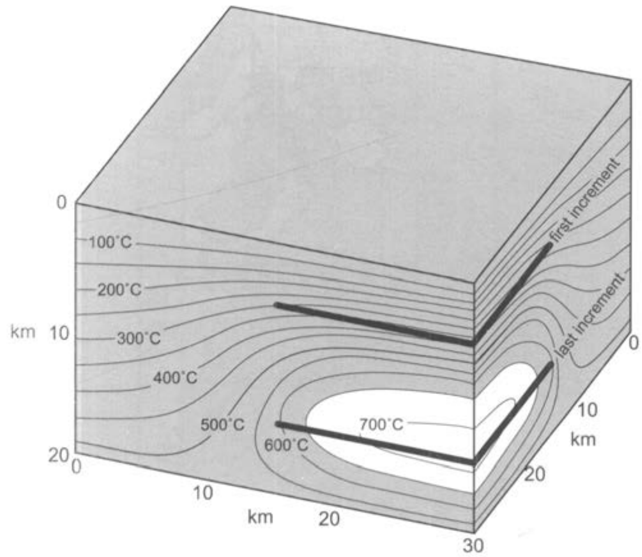

Figure 4 Results of 3-D thermal model generated using Heat 3-D by Ken Wohletz (Wohletz & Heiken 1992). Model shows thermal structure after building a pluton incrementally by intruding twenty 0·5 km-thick horizontal sheets successively from the top down. This model ran for three million years with an initial geothermal gradient of 25°C/km, resulting in a pluton 5 km below the surface, with final dimensions of 10 km (thick) and 30 × 30 km (wide). Figure is cut through the centre of the pluton. The size, shape and position of the first and last increments (intruded 3 million years apart and bounding the final pluton volume) are shown. The white area is the volume of pluton and wall rock above 650°C, the solidus T used in the model, ~140 ka after intrusion of the last increment. The volume above the solidus T reflects neither the size nor shape of the increments added to build the volume.

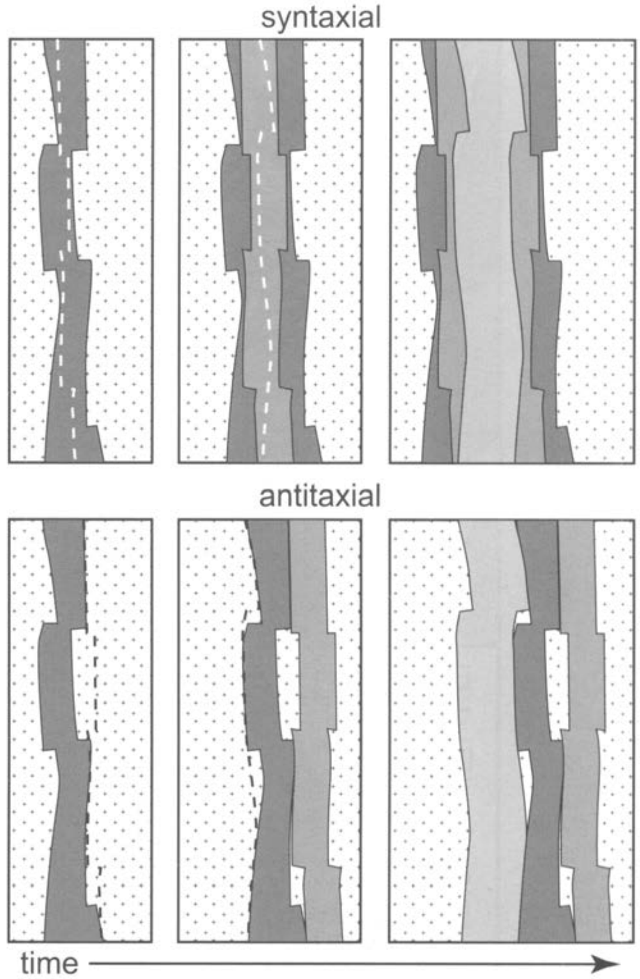

Figure 5 Syntaxial and antitaxial growth of crack-seal intrusions; gray shades correspond to dykes, '+' pattern to wall rock. *In situ* isolation of wall-rock fragments is likely during antitaxial growth but impossible during syntaxial growth (compare with Fig. 3c, d).

An important consequence of incremental assembly over a protracted time period is that the shape and dimensions of the part of a pluton that contains melt at a given time may differ greatly from the shapes and dimensions of growth increments (Fig. 4). This is because some parts of growth increments will solidify more quickly than others, whereas parts of previously added increments may be partially remelted when later increments are added. An incrementally growing pluton therefore should contain two different types of internal contacts: emplacement contacts between incremental additions of different ages, and solidification fronts that separate solid plutonic rock from partially molten material. Generally, these contacts will be mutually discordant, even if all emplacement contacts are parallel.

3. Syntaxial versus antitaxial crack-seal in plutons

Wall-rock inclusions can mark crack-seal planes, both in quartz veins and in granitic intrusions, if the crack-seal process is antitaxial (Fig. 5). A crack at the margin of an intrusion that does not follow the contact precisely will result in pieces of rock split away from the wall and isolated from the wall as the new crack fills with magma (compare Fig. 3c). Such pieces of wall rock are surrounded by the intrusion, but were never engulfed or suspended in magma. In contrast, when crack-seal is syntaxial, wall-rock inclusions will only form early in the process of assembly, and will be isolated at the margins of the pluton. Any wall-rock inclusions formed after initial growth will be inclusions of the host pluton itself, and thus cannot provide a means by which the products of crack-seal might be recognised. The following section summarises some examples of intrusions that formed, or may have formed, by antitaxial or syntaxial crack-seal.

3.1. Independence dyke swarm, Sierra Nevada

Glacially polished exposures of the Late Jurassic Independence dyke swarm in eastern California (Moore & Hopson 1961; Carl & Glazner 2002; Glazner *et al.* 2008) provide clear examples of both antitaxial and syntaxial dyke growth. Most of the dykes are composite and consist of several parallel sheets of mafic intrusive rock (Fig. 3c, d). Thin sheets of granodiorite wall rocks are commonly found within dykes at sheet contacts that are otherwise defined by grain-size variations. Sheets of granodiorite wall rock within the dykes record antitaxial growth (Fig. 3c), and multiple sheets of similar rock in the same dyke with one-sided chilling and without wall-rock inclusions represent syntaxial growth (Fig. 3d). Based on field relations that resemble those in Figure 3 and on geochronological evidence for protracted incremental assembly, it is argued that this intrusive style scales up to large plutons.

3.2. McDoogle and adjacent plutons, Sierra Nevada

The McDoogle pluton is a steep-walled NW-striking tabular pluton, at least 12 km in length by ~2 km in width (Fig. 6a; Moore 1963), that was emplaced near the eastern margin of the Sierra Nevada batholith. U–Pb zircon and titanite data indicate that the McDoogle pluton was emplaced at 94–95 Ma, but beginning perhaps as early as 98 Ma (Mahan *et al.* 2003). Mahan *et al.* (2003) interpreted the McDoogle pluton to be an incrementally assembled sheeted complex that was intruded into a steeply dipping, reverse-sense shear zone during the

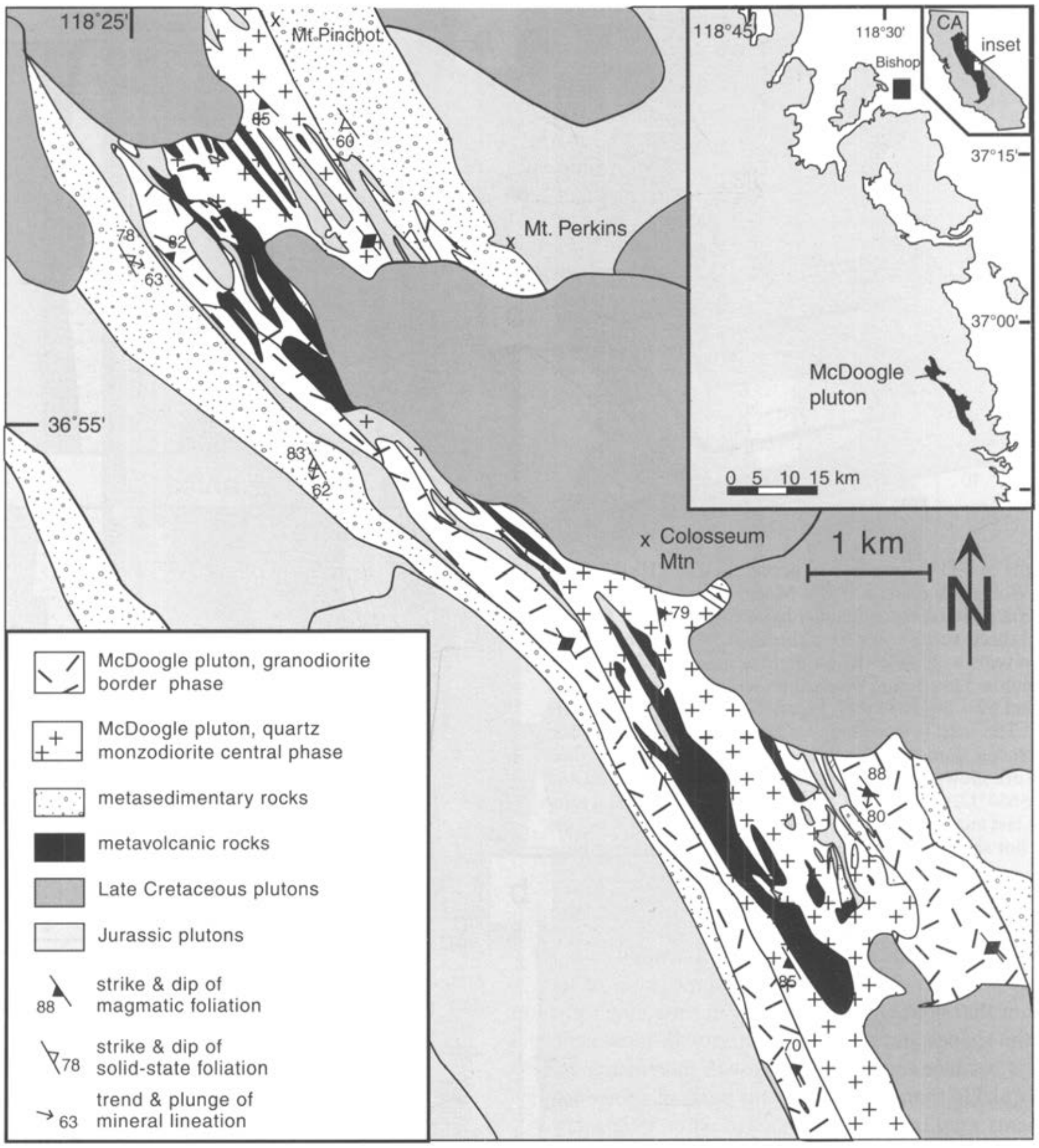

Figure 6 (A) Geologic map of the McDoogle pluton, Sierra Nevada, USA (simplified after Mahan *et al.* 2003); (B) Geologic map of central Mt Pinchot 15′ Quadrangle, Sierra Nevada, USA (simplified after Moore 1963).

latest stages of shear. The following summarises key observations from that study and implications for the crack-seal model.

Field evidence indicates that the abundant wall-rock bodies enclosed in the McDoogle pluton remained *in situ* during intrusion. The inclusions are tabular and aligned parallel to the length of the pluton. They range from several metres to 2 km in length and compose ~30% of the mapped area of the pluton. Approaching the northern end of the pluton, the map pattern grades from screens of wall rock enclosed in the pluton to dykes of the pluton injected into wall rocks. Foliation and lineation in the wall-rock screens (regardless of size, location, shape, or rock type) are concordant with their orientations in wall rocks outside of the pluton. Solid-state deformation is rare in the pluton and, where an intrusive contact locally is not parallel to the wall-rock foliation, the intrusive contact truncates the foliation. Rock units in the screens collectively form a pattern that agrees with the arrangement of wall rocks outside of the pluton, thus forming a ghost stratigraphy. These observations combine to indicate that rocks in the screens remained *in situ* during intrusion of the pluton and thus, even though some screens now are entirely enclosed by the McDoogle pluton, wall-rock bodies were never engulfed in a dominantly liquid magma chamber. Rather, the screens were isolated by sequential injection of numerous dykes that were amalgamated to form the pluton. Incorporation of wall-rock screens thus is interpreted here to record antitaxial crack-seal.

A key feature of the McDoogle pluton is that even thin (<10 cm) dykes, whether injected into the wall rocks or into thinner wall-rock screens, are as coarse-grained as the remainder of the pluton and lack chilled margins. If chilled margins did not form against wall rocks, then they would certainly not have formed if similar dykes intruded granodiorite that was only slightly older. Therefore, the McDoogle pluton could have been amalgamated from numerous dykes without preserving textural evidence of internal contacts. If successive dykes were closely similar in composition, the contacts would be difficult or impossible to distinguish.

The McDoogle pluton is lithologically layered parallel to its margins, and this layering may at least partly reflect dyke assembly. A roughly 1-km thick central body of mafic quartz monzodiorite is flanked on both sides by more leucocratic granodiorite. The marginal granodiorite bodies are relatively uniform, but the central quartz monzodiorite is weakly to strongly internally layered at scales ranging from metres to tens of metres. Contacts between lithological layers at all scales

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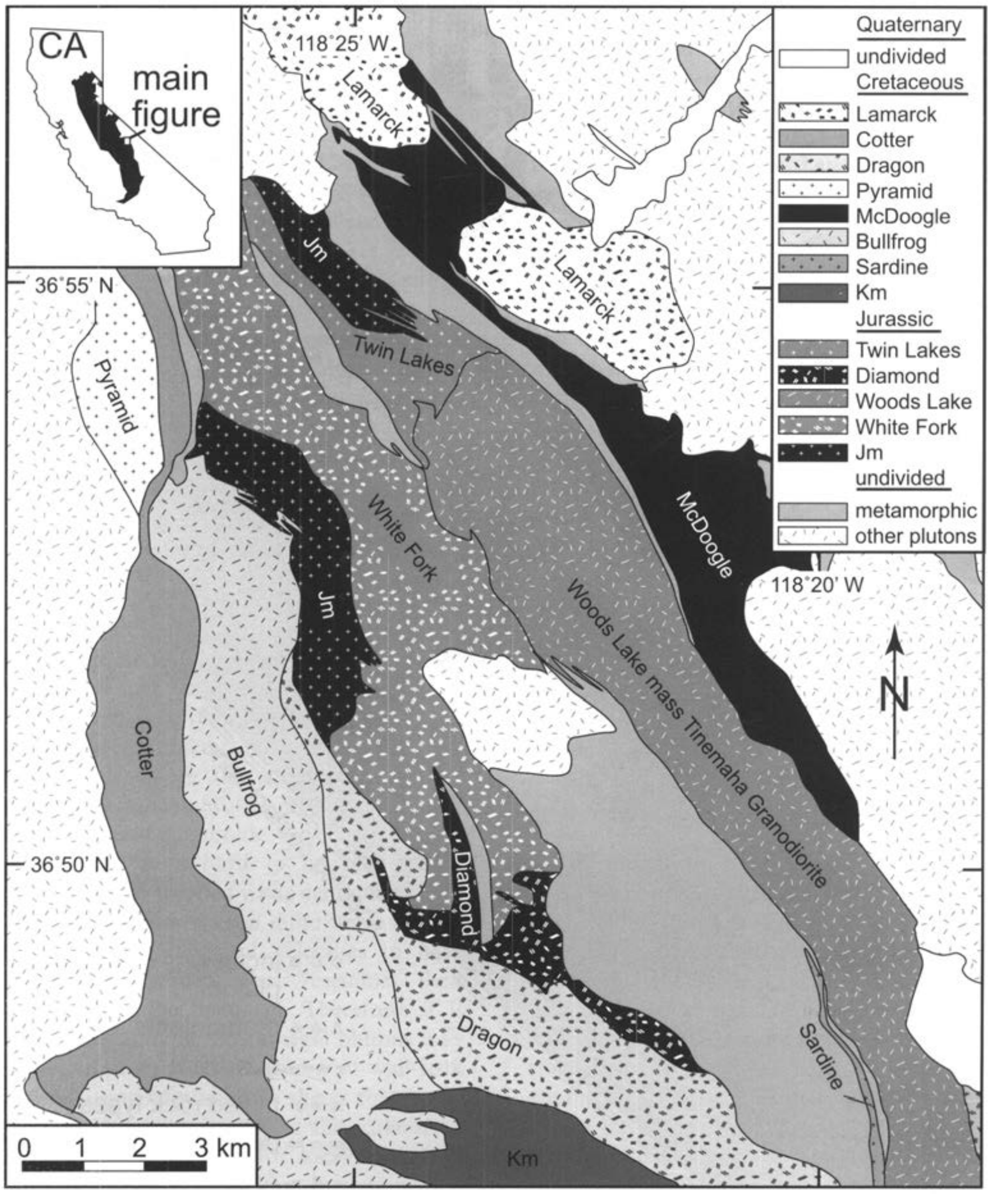

Figure 6 *Continued.*

are indistinct in outcrop. The lack of sharp contacts between lithological varieties suggests that secondary textural modification may have been important in accounting for the absence of sharp internal contacts.

The McDoogle pluton is one of several plutons that combine to form a larger sheeted intrusive complex that ranges in age over at least 73 Myr (165 Ma to 92 Ma; Fig. 6b). Among the plutons, only the McDoogle contains abundant wall-rock screens, but thin screens of wall rock are common between all of the plutons. Because each pluton is a steep-walled, tabular body orientated parallel to the others, it seems likely that all were emplaced by similar processes. Thus, wall-rock screens may be absent from the other plutons because only the McDoogle pluton was emplaced by antitaxial crack-seal. If the other plutons were emplaced by syntaxial crack-seal, they could be similarly composite, but would lack lithological markers to distinguish internal contacts (Fig. 5). The structural geology of the wall rocks can account for this difference. The McDoogle pluton was intruded concordantly into highly foliated rocks of a mylonite zone (Mahan *et al.* 2003). Owing to intense foliation, the fracture resistance of wall rocks parallel to the foliation was probably less than that of previously emplaced granitic dykes. This would favour antitaxial cracking and inclusion of abundant wall-rock screens.

3.3. Donegal plutons

The diverse granitic plutons of Donegal have long served as paradigms of pluton emplacement styles, and the brief discussion in the present paper is based primarily on the landmark study by Pitcher & Berger (1972). In considering potential application of the crack-seal model, the present authors focus on the Main Donegal, Thorr, and Fanad plutons which are reported to contain a ghost stratigraphy of wall-rock inclusions (Fig. 7).

Although much larger (>45 km long and up to 12 km across), the Main Donegal pluton markedly resembles the McDoogle pluton. The pluton is a steep-walled, tabular body that contains a pervasive magmatic fabric orientated subparallel both to its walls and to a pervasive solid-state fabric in the wall rocks. Geometrical and chronological relations led Pitcher and Berger to interpret intrusion of the Main Donegal pluton as late synkinematic with respect to wall-rock tectonic deformation. The pluton is lithologically heterogeneous and layered subparallel to its margins. The most pervasive layering

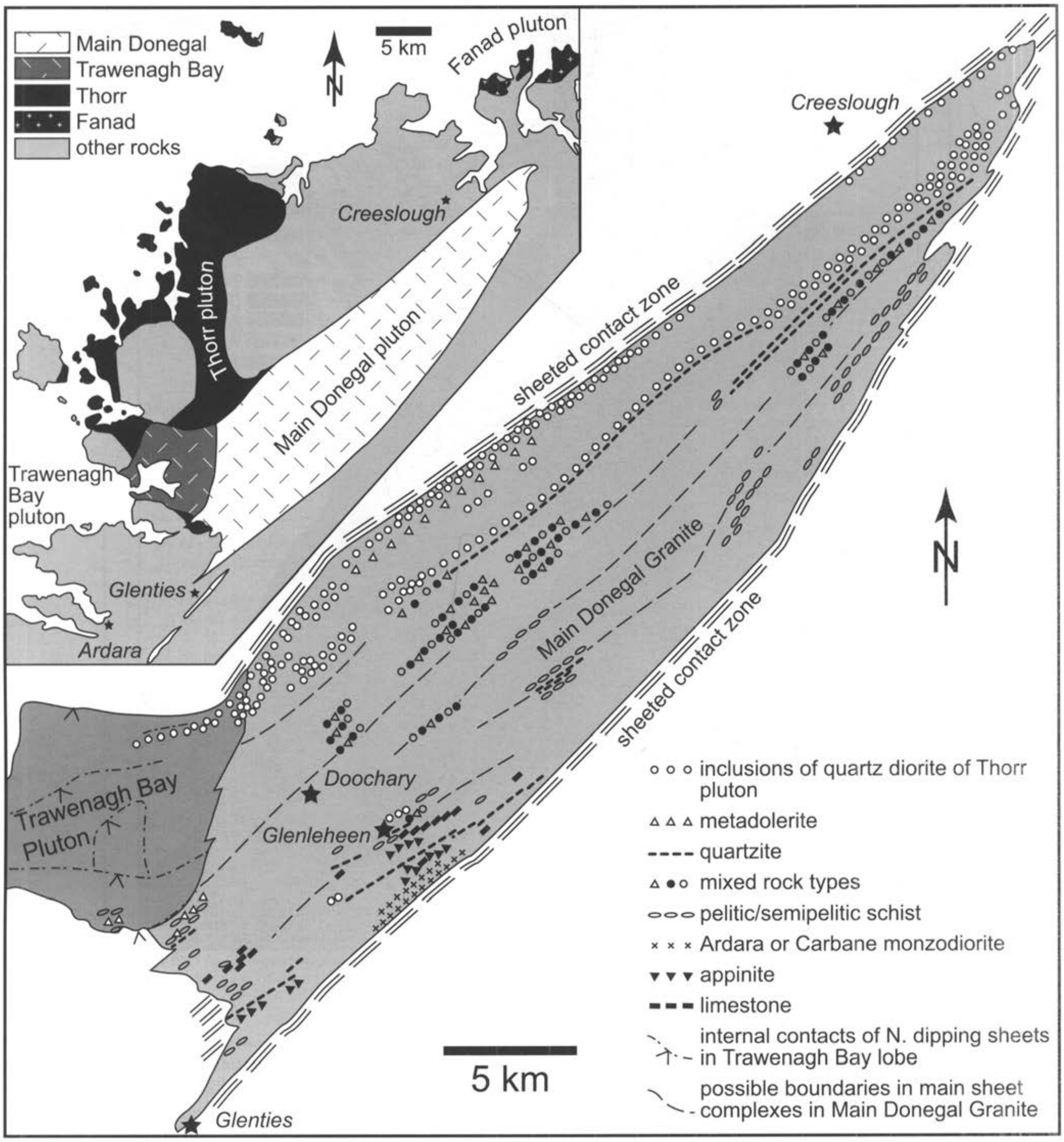

Figure 7 Geologic map of Main Donegal granite; inset shows location relative to Thorr and Fanad plutons (simplified after Pitcher & Berger 1972; Pitcher & Hutton 2003).

('regular-banding') is characterised by diffuse rather than sharp contacts, including the contacts of 'cross bands' which are compositional layers that geometrically resemble dykes and cut across earlier regular-banding (Pitcher & Berger 1972; Fig. 6c). Lithologically diverse dykes with sharp contacts compose a significant fraction of the pluton, and field relations indicate that dyke intrusion began early and persisted throughout growth of the pluton. Last and perhaps most important, wall-rock inclusions are common throughout the pluton and define a ghost stratigraphy.

Although Pitcher & Berger (1972) expressed uncertainty about the precise emplacement mechanism, the preferred interpretation was that the Main Donegal pluton formed by coalescence of concordant intrusive sheets. Paterson *et al.* (1994) likened this process to crack-seal, but apparently chose not to pursue the concept further. More recent U–Pb geochronology supports interpretation of the pluton as amalgamated from multiple sheets and demonstrates that sheets accumulated over at least 7 Myr (Condon *et al.* 2004). The present interpretation of the McDoogle pluton resembles this interpretation, but with a significant difference. Pitcher & Hutton (2003) mapped a relatively small number of sheets (eight to ten), each of which is comparable in dimensions to the entire McDoogle pluton. However, the number of wall-rock screens crossed in a traverse across an antitaxial crack-seal pluton (~10 in the case of the McDoogle pluton) provides only a minimum bound on the number of intrusive sheets, because there are likely to be additional cryptic contacts that are unmarked by wall-rock screens. Note that, in both the Main Donegal and McDoogle plutons (Figs 6a, 7), sheet boundaries are commonly not marked by wall-rock screens along their full lengths. Thus, there could easily be many more sheets present than are defined by wall-rock screens. The difference is important, because the mechanical requirements are very different for making space for kilometre-scale magmatic sheets as compared to the metre-scale sheets that the present authors envision in the McDoogle.

Pitcher & Berger (1972) did not extend their interpretation of the Main Donegal Pluton to the Thorr and Fanad plutons, in spite of their observation that each also contains a ghost stratigraphy of wall-rock inclusions. They interpreted the inclusions in Thorr and Fanad to reflect stoping, although they did not necessarily regard this as the primary ascent mechanism, and acknowledged that preservation of a ghost stratigraphy during stoping raises difficulties regarding the timing of incorporation of the inclusions and the physical state of the magma at the time of their incorporation. Even putting aside general reasons to doubt the efficacy of stoping (e.g., Glazner & Bartley 2006), Pitcher and Berger did not address a particular difficulty for stoping in a pluton with a ghost stratigraphy, and that is the huge range of settling rates suggested by the observed size range of wall-rock inclusions. The inclusions in the Thorr pluton range over more than four orders of magnitude in size, from several centimetres to 1600 m. Because settling rate generally depends on the square of fragment dimension, this size range implies Stokes settling rates that differ by roughly eight orders of magnitude. Given such a huge range of settling velocities, it is hard to imagine that a 1600 m-long inclusion could be trapped while centimetre-sized inclusions could sink at all, and it is even more unreasonable for inclusions settling at this range of velocities to have remained in a spatial arrangement that resembles their arrangement in the walls of the intrusion. Therefore, it is suggested that ghost stratigraphy in the Donegal plutons may record a single process, that is, *in situ* isolation of wall-rock bodies by sequential intrusion of numerous sheets that amalgamate to form plutons. However, stoping at the scale of an individual intrusive sheet may account for local mixing of wall-rock types and the considerable variation in bedding and foliation orientations in wall-rock inclusions.

3.4. Tuolumne Intrusive Suite

The Late Cretaceous Tuolumne Intrusive Suite (TIS) is a well-known example of a concentrically zoned plutonic complex (Bateman & Chappell 1979; Bateman 1992) with the relatively mafic granodiorites of the Kuna Crest-Glen Aulin units at its margins and the leucocratic, megacrystic Cathedral Peak Granodiorite in the middle. In between is the Half Dome Granodiorite, which is generally intermediate between the other two units in both composition and texture, but varies sufficiently to overlap the units on both sides (Gray 2003). Recent U–Pb zircon geochronology indicates that the Tuolumne Intrusive Suite was intruded over 8 to 10 Myr, and that the Half Dome and the Cathedral Peak granodiorites each grew progressively inward over durations of 3 to 4 Myr (Coleman *et al.* 2004; Matzel *et al.* 2005).

Field evidence regarding emplacement processes from the marginal Glen Aulin granodiorite broadly resembles that from the McDoogle pluton (Glazner *et al.* 2004). Although older plutonic rocks form the walls of much of the Tuolumne Intrusive Suite, metasedimentary rocks form the wall in the May Lake area. Glen Aulin granodiorite in that area contains abundant xenoliths of the metasedimentary rocks. Like the McDoogle pluton, the Glen Aulin granodiorite is lithologically layered and the xenoliths that it contains are not orientated randomly (Taylor 2004; Glazner *et al.* 2004). In small isolated xenoliths and in wall rocks adjacent to the Tuolumne Intrusive Suite, field measurements define the same girdle of poles to foliation and the same point maximum of lineation measurements. It is therefore inferred, as in the McDoogle pluton, that the xenoliths were isolated *in situ* by sequential intrusion of dykes or sheets that now may be expressed as prominent metre-scale lithological layering.

Xenoliths are absent and lithologic layering is rare in the much more voluminous Half Dome and Cathedral Peak granodiorites. The long emplacement durations of these units and the consistent pattern of inward growth suggest that the change may record a transition from early antitaxial growth to syntaxial growth through most of the history of the complex. The transition may have occurred because expansion of the plutonic complex isolated friable wall-rock bodies from the magma source. Alternatively, the transition may reflect thermal maturation and establishment of a persistent magma body in which cracking was not an important process. Such a thermal history is predicted by thermal models of dyke emplacement in a dilational zone (Sleep 1975; Hanson & Glazner 1995).

3.5. Alta stock, Utah

Vogel *et al.* (1997, 2001) proposed that tectonic dilation was a major space-making mechanism for Cenozoic intrusions of the Wasatch Range, including the Alta stock. Properties of the Alta stock that favour this model include: (1) subparallel, steeply dipping walls; (2) spatial association with dike swarms orientated parallel to it; (3) regional evidence that the Wasatch plutonic suite was emplaced during crustal extension (Constenius 1996); and (4) field and petrographical evidence from the stock that favours synkinematic emplacement (Didericksen & Bartley 2003). The tectonic dilation rate at the time of emplacement of the Alta stock is unknown, but long-term rates of local tectonic dilation – i.e., at the scale of a single intrusion – greater than 1–2 mm/yr are unusual during continental extension. Space for the ~2 km wide Alta stock would have been made by this mechanism over ~1 Myr, a duration far too long to sustain a magma chamber in a small, shallow (<5 km depth; John 1989) intrusion like the Alta stock (e.g., Hanson & Glazner 1995). Therefore, if tectonic dilation was an important space-making mechanism, the Alta stock likely must be highly composite.

Wilson (1961) divided the Alta granodiorite into a central leucocratic porphyritic phase and a more mafic equigranular border phase. A sharp contact between the intrusive phases can locally be mapped but differences between the phases commonly are subtle and gradational such that the contact can be impossible to distinguish reliably in outcrop or hand sample. The published geological map (Baker *et al.* 1966) therefore depends heavily on Wilson's petrographic studies, and the outcrop pattern was poorly defined in the western part of the stock where Wilson collected few samples and the texture tends to be intermediate in character.

Recent magnetic susceptibility mapping (Fig. 8) helps to clarify the field relations. Bulk magnetic susceptibility of the Alta granodiorite correlates well with colour index and, in the eastern part of the stock where the porphyritic–nonporphyritic contact is best defined, lower susceptibility ($<28 \times 10^{-3}$ SI units) corresponds closely to the central porphyritic phase. The central low-susceptibility body continues westward as an E–W striking dyke-like body that is several hundred metres thick. The border phase is much more heterogeneous than the central phase and ranges in composition from quartz diorite to relatively leucocratic granodiorite (Vogel *et al.* 2001). The variations commonly take the form of lithologic layering on a

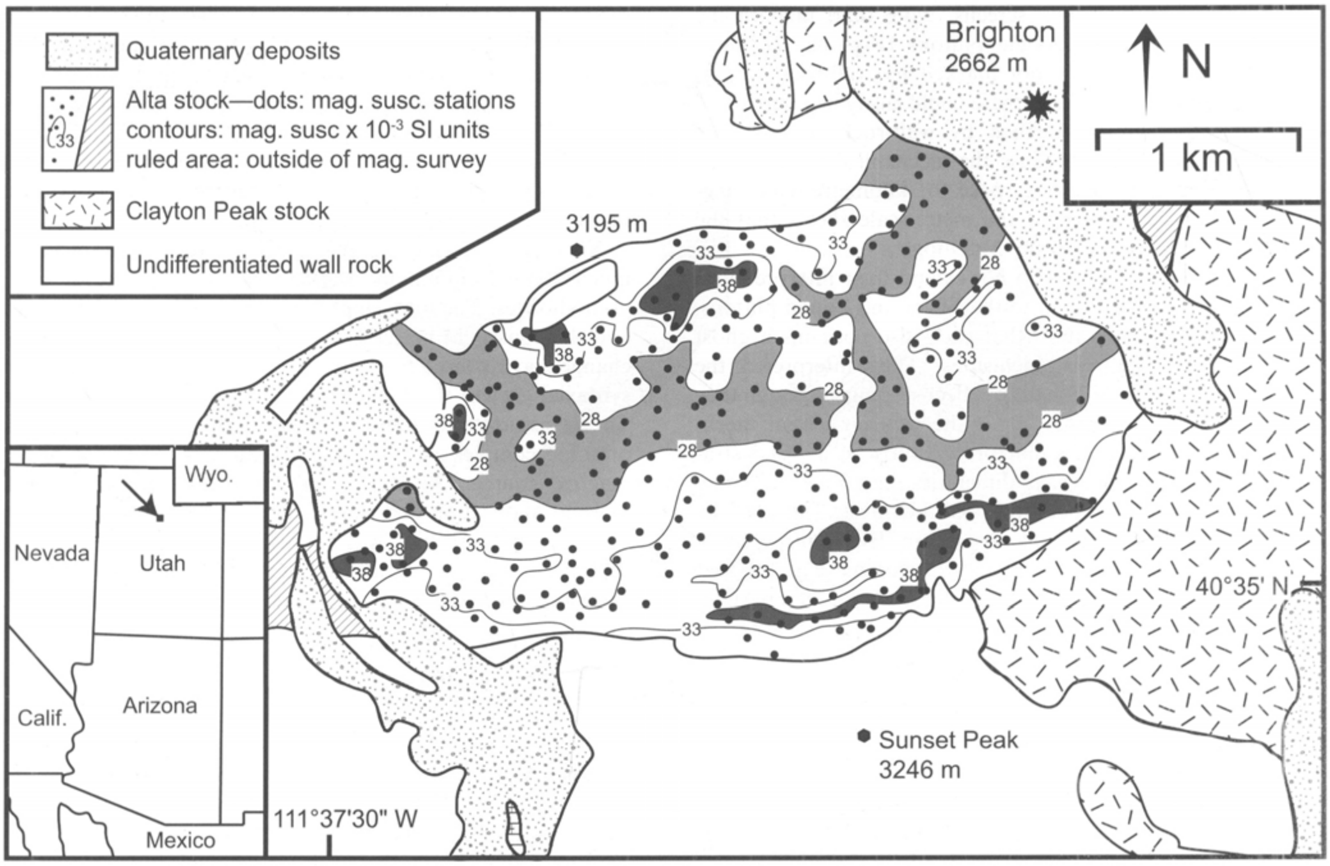

Figure 8 Simplified geologic map of the part of the Alta stock, modified after Baker *et al.* (1966) and Crittenden (1965). Magnetic susceptibility measurements are averages of 6–12 measurements on fresh, planar outcrop surface made using a ZH Instruments SM-30 hand-held susceptibility meter. Susceptibility contours were hand-traced from colour-gradient map constructed using inverse-distance-weighted interpolation.

scale of metres to tens of metres in a manner similar to the McDoogle pluton and the margins of the Tuolumne Intrusive Suite in the Sierra Nevada. However, the Alta stock does not contain wall-rock screens. This observation may mean that the Alta stock grew by syntaxial rather than antitaxial magmatic crack-seal. This hypothesis is consistent with the observation that, whereas the McDoogle pluton intruded concordantly into highly foliated wall rocks, the steep intrusive contacts of the Alta stock and related dykes are orientated roughly perpendicular to wall-rock structures.

3.6. Jurassic intrusions, White-Inyo Mountains, California

The Sage Hen Flat, Marble Canyon and Eureka Valley-Joshua Flat-Beer Creek (EJB) plutons of the White-Inyo Mountains, eastern California (Fig. 9), were all emplaced into the same sequence of Cambrian to late Proterozoic strata during Middle to Late Jurassic time (for a summary of the geological settings and geochronology of the plutons, see Morgan *et al.* 2000). It would be reasonable to expect that similar processes account for emplacement of all three plutons, yet the field relations of the Sage Hen Flat pluton differ drastically from the other two plutons.

The contact aureoles of the Marble Canyon and EJB plutons underwent intense emplacement-related ductile deformation in response to downward and perhaps outward translation and tilting of the (meta-)sedimentary wall rocks, owing to sinking of the pluton after solidification (Glazner & Miller 1997) and/or to lopolithic floor subsidence and ballooning during emplacement (Morgan *et al.* 2000). In contrast, ductile strain is practically absent adjacent to the Sage Hen Flat pluton (Bilodeau & Nelson 1993). Therefore, previous authors have concluded that this pluton was emplaced by entirely different processes from the larger plutons to the SE. Sharp truncation of wall rocks at the intrusive contact, the absence of contact-parallel foliation within the wall rocks, and the lack of deflection of older structures and formation contacts as the pluton is approached, have all been interpreted to indicate emplacement by piecemeal stoping (Bilodeau & Nelson 1993; Morgan *et al.* 2000). However, Glazner & Bartley (2006) argue that such features are equally explicable by opening of a gently dipping crack system to form a lopolith (*s.l.*), and further argue that stoping was unlikely to be a significant process, most specifically because xenoliths are virtually absent from the pluton and bulk-chemical data exclude significant wall-rock assimilation.

All three plutons may have been emplaced by a single mechanism, however, and differences among them may be explained by the level within the intrusive system of present surface exposures. Incremental emplacement of all three intrusions as subhorizontally sheeted lopoliths (Fig. 9d) not only accounts for observed differences between the plutons in the field, but further accommodates all of the observations and arguments made in advocating other explanations of their emplacement histories and contact relations.

Based on the shallow outward dip of the southern contact, the uniformly leucocratic character of the intrusive rock, and the lack of deformation of the wall rock, all workers agree that the Sage Hen Flat pluton is exposed near its roof. Disagreement has focused on the process(es) by which wall rock was displaced away from that roof to make space for the pluton. As with the Chita pluton in the Andes (Yoshinobu *et al.* 2003), the field observations can be explained either by piecemeal stoping or cauldron subsidence. Glazner & Bartley (2006)

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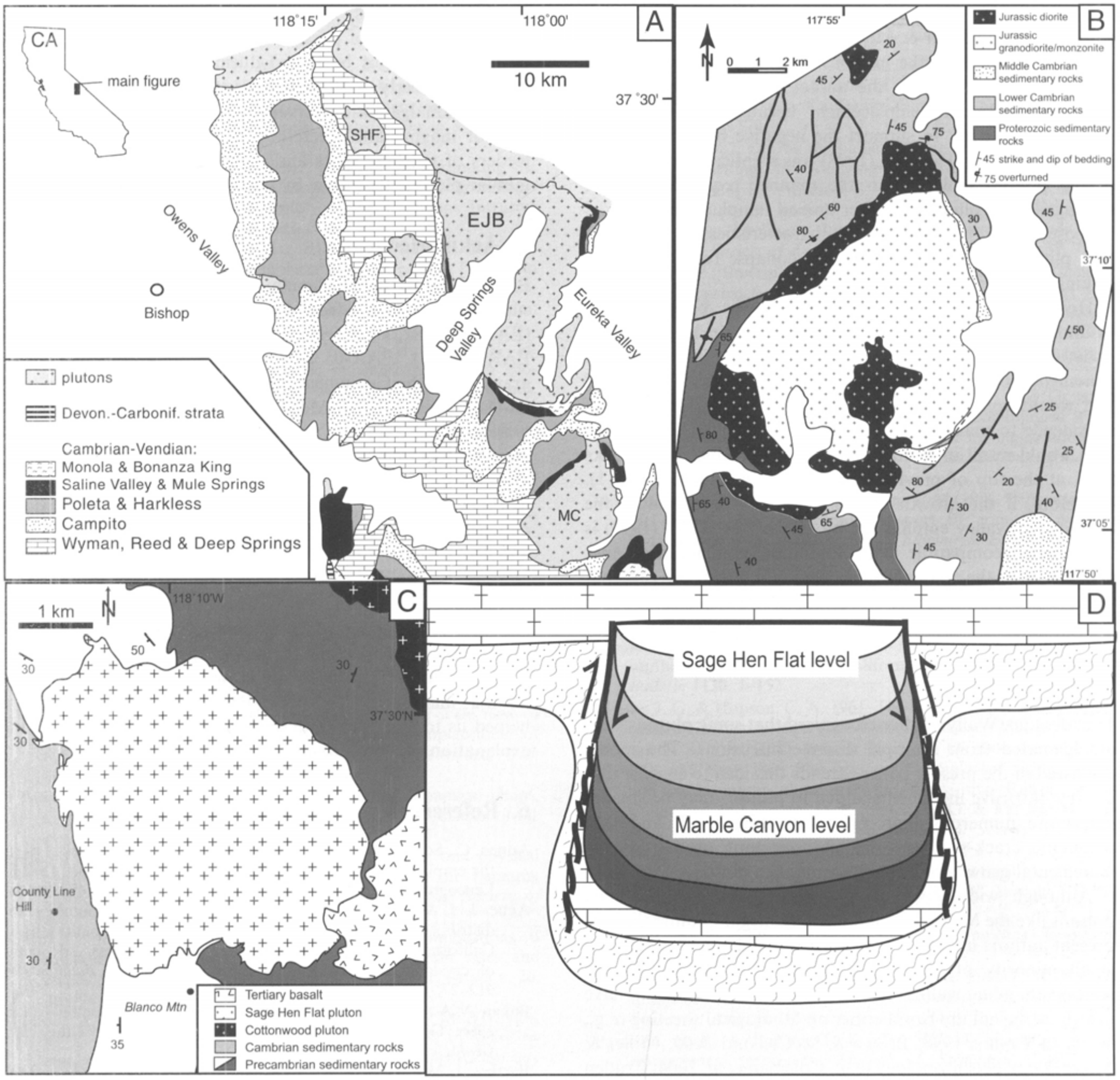

Figure 9 (A) geologic map of the White-Inyo Mountains, simplified from Morgan *et al.* (2000). SHF=Sage Hen Flat pluton; EJB=Eureka Valley–Joshua Flat–Beer Creek pluton; MC=Marble Canyon pluton: (B) geologic map of Marble Canyon pluton, simplified from Nelson (1971): (C) geologic map of Sage Hen Flat pluton, simplified from Bilodeau & Nelson (1993): (D) cartoon profile illustrating possible cauldron-subsidence/lopolith mechanism for generating all Jurassic plutons in the Inyo Mountains.

argue that cauldron subsidence is the preferred mechanism for generating this very common set of field relations because it does not entail the serious problems encountered with stoping of a large volume of wall rock. However, cauldron subsidence is kinematically equivalent to lopolith formation. If there is a meaningful difference between the two, cauldron subsidence implies subsidence of a rigid floor block by brittle faulting whereas a lopolith implies more distributed (ductile?) floor subsidence. A wealth of field data indicate that shallow faults become ductile shear zones as temperature increases with depth (e.g., Ramsay 1980b, Sibson 1982). Although the highly concentrated strain at the margins of the Marble Canyon and EJB plutons probably records a more complex strain path, pronounced downward deflection of strata adjacent to the pluton clearly indicates wall-rock subsidence beneath the pluton (Glazner & Miller 1997). Therefore, ductile strain in the structural aureoles of these two plutons reflects a pattern of wall-rock displacement similar to cauldron subsidence, perhaps modified by inflation of the intrusion to produce pronounced flattening strain (Morgan *et al.* 2000). Morgan *et al.* (2000) suggested that the roofs of these plutons were lifted at the same time, but there is no direct field evidence for this. Therefore, the most elegant explanation for emplacement of all three plutons is that they were emplaced by floor subsidence along a marginal displacement zone that is brittle in its shallow part and ductile at greater depth. The Sage Hen Flat pluton thus indicates the likely characteristics of the unpreserved roof zones of the Marble Canyon and EJB plutons, and unexposed parts of the Sage Hen Flat pluton with increasing depth may resemble the characteristics of the Marble Canyon and EJB plutons.

If these plutons, like other plutons described above, grew incrementally – a speculation for which there is as yet no direct evidence – this would also resolve controversy regarding

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whether the Marble Canyon and EJB plutons sank after emplacement. Glazner & Miller (1997) argued that, given the relative densities of the plutons and wall rocks and the temperatures achieved in the aureoles, such plutons would inevitably sink after emplacement because the wall rocks would be too weak to support the negative buoyancy of the plutons. However, Paterson (1998) was sceptical that the roofs of the plutons collapsed in the manner required above a sinking, solid pluton. If the unified emplacement model proposed here is correct, the characteristics of the Sage Hen pluton do not permit the roof collapse required by the sinking-pluton model.

However, the sinking-pluton model was based on the assumption that a pluton represents a single large magma body. If the pluton instead grew incrementally, then each increment would become negatively buoyant as it crystallised and would contribute to the driving force for further floor subsidence to make space for additional magma increments. This would result in antitaxial crack-seal in which new cracks form at the top of previously emplaced increments (Fig. 1). Therefore, if the growth of the lopolith is incremental, the negative buoyancy emphasised by Glazner & Miller (1997) is intrinsically compatible with lopolithic emplacement and, because only the floor subsides and not the roof, the roof collapse predicted by Paterson (1998) is not required.

4. Summary

Decades ago, Wally Pitcher recognised that some plutons were amalgamated from multiple discrete intrusions. The model discussed in the present paper extends this idea to suggest that discrete intrusive increments added to plutons may be smaller and more numerous than previously envisioned, and that magmatic crack-seal may be an important process during incremental growth of a highly composite pluton.

Although widespread in time and space, xenolith-filled plutons like the McDoogle and Main Donegal Granite that the present authors interpret to reflect antitaxial crack-seal form a small minority of plutons. However, plutons that do not contain abundant wall-rock screens nonetheless appear to have grown incrementally based either on lithological sheeting (e.g., Wiebe & Collins 1998; Brown & McClelland 2000; Miller & Miller 2002), geochronology (e.g., Coleman *et al.* 2004; Cruden *et al.* 2005), or both (e.g., Walker *et al.* 2005). Further, incremental emplacement by crack-seal accounts for field observations generally taken to indicate stoping without the difficulties of large-volume stoping (Glazner & Bartley 2006). Thus, discordant, xenolith-poor plutons may have grown by syntaxial magmatic crack-seal. The difference between antitaxial and syntaxial growth may be governed by the extent to which a pre-existing anisotropic mechanical weakness, such as wall-rock foliation, caused fracturing of wall rock is to be favoured over fracturing of previously emplaced intrusive increments. Whereas antitaxial growth produces an obvious record in the form of wall-rock inclusions that define a ghost stratigraphy, syntaxial growth may leave little or no record that is visible in the field. Means by which the internal structure of syntaxially constructed plutons may be directly observed remain a subject of on-going investigation.

It may be that most, if not all, plutons previously proposed to have been emplaced by stoping instead mainly grew by magmatic crack-seal. If this is correct, then magmatic crack-seal may be one of the dominant processes of pluton growth on the planet.

Fractures that conduct fluids, whether groundwater, hydrocarbons, hydrothermal solutions, or magma, must form interconnected networks. Figure 1 schematically illustrates two amongst a myriad of possible ways that different incremental pluton types might be linked during their growth. It seems particularly likely that tabular plutons with steep walls formed by dyke amalgamation served as conduits for vertical transport of magma and, therefore, such plutons may represent feeders of volcanic vents and/or of associated gently dipping tabular plutons that grew by vertical stacking of increments.

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