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Longevity of Geothermal Resources and Incremental Pluton Emplacement

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ABSTRACT

Thermal modeling of geothermal resource areas often reveals that multiple episodes of intrusion are required to adequately explain heat flow data and account for the fact that large volumes of liquid magma are not geophysically imaged under the areas. These observations are consistent with new evidence that even apparently homogeneous plutons are assembled incrementally over millions of years. Although incremental assembly broadly applies to pluton growth, the idea may be particularly relevant to releasing bend regions where structural models already predict the likelihood of incremental intrusion. Cooling histories of incrementally assembled plutons in the Sierra Nevada batholith confirm that they remained hot much longer than would comparable volumes of magma emplaced in a single episode of intrusion. Thus the incremental assembly of plutons likely accounts for the longevity of some geothermal systems.

Introduction

Modeling the heat flow in geothermal resource areas is complicated by many factors including uncertainty in initial and boundary conditions, and the composition size, shape, depth and intrusive history of magma bodies (Wohletz *et al.*, 1999). Drilling and geophysical imaging yield insight into the compositions and dimensions of intrusions below geothermal areas. Intrusive volumes and histories of magma systems are extrapolated from volumes of associated volcanic rocks and their isotopic ages (Dalrymple *et al.*, 1999) and assumptions about the proportion of magma erupted from the magma chamber (Smith and Shaw, 1975; Smith *et al.*, 1978). Thermal modeling of geothermal areas based on such data and assumptions often results in two observations: 1) emplacement of a single batch of magma does not yield a good fit to observed heat flow (*e.g.*, Stimac *et al.*, 1997; Dalrymple *et al.*, 1999), and 2) emplacement of large batches of magma predicts that significant volumes liquid magma should remain under the resource areas, yet they are not observed in geophysical data (Wohletz *et al.*, 1999).

Problems with the existing geothermal models can be at least partially resolved by considering multiple episodes of magmatism (Stimac *et al.*, 1997; Dalrymple *et al.*, 1999; Wohletz *et al.*, 1999). Maintaining high heat flow through multiple magmatic events is consistent with the observation that eruptions occur episodically throughout the history of most volcanic regions. However, until recently the plutonic view of magma systems has focused on large, rapidly emplaced magma bodies with high (>50%) proportions of liquid present, capable of processes such as mixing, fractionating, stoping and diapiric rise (*e.g.*, Bateman, 1992; Miller and Paterson, 1999).

The view of plutons and pluton emplacement processes has taken a turn recently to emplacement and assembly of plutons *via* dikes and sheets (Clemens and Mawer, 1992; Wiebe and Collins, 1998; Petford *et al.*, 2000). In particular, dike assembly in regions of active extension has been explored because it provides a partial solution of the so-called "room" problem of pluton emplacement (Hutton, 1988). Given reasonable geologic displacement rates, pluton emplacement driven by wall-rock dilation and magma buoyancy is possible (Petford *et al.*, 2000 - but see Paterson and Fowler [1993] for a dissenting view) and makes testable predictions regarding the structure, geochronology and thermal evolution of plutons assembled in this manner (Hanson and Glazner, 1995). Incremental pluton assembly may be of particular importance for geothermal resources because resource areas can be localized in extensional settings within more complicated deformation regimes (Glazner *et al.*, 1994; Unruh, *et al.*, 2002), and thus incremental emplacement may significantly impact the longevity of these geothermal resources.

Here we outline recently compiled evidence that requires incremental pluton assembly, examine the cooling history of several plutons, and discuss the implications for the longevity of geothermal resources.

Incremental Pluton Assembly The Idea and Implications

Glazner *et al.* (2004) outline the geophysical, field and geochronologic evidence in favor of incremental pluton assembly. In sum, these authors argue that the lack of geophysical evidence for large magma bodies with greater than a few percent liquid, even under active arc volcanoes (Iyer, 1984; Lees *et al.*, 1992; Zandt *et al.*, 2003) and geothermal resource areas (Sanders, 1993; Miller and Smith, 1999), demonstrates that 1) such bodies must be short-lived features, and 2) many plutons may be amalgamated from much smaller batches of magma. In support of this, they cite field evidence that shows plutons often preserve evidence for incremental assembly including preservation of internal sheeting (Wiebe, 1993; Mahan *et al.*, 2003; Taylor, 2004). Additionally, U-Pb zircon geochronology of the Mesozoic Tuolumne Intrusive Suite, California, demonstrates that it was assembled over at least 10 m.y., and that an individual "homogeneous" pluton (the ~200 km^2 Half Dome Granodiorite) within the suite was assembled over at least 4 m.y (Coleman *et al.*, 2004). Two-dimensional thermal modeling demonstrates that the Half Dome pluton must have been incrementally assembled because a magma chamber of that size would have solidified in fewer than one million years if emplaced as a single batch of magma (Glazner *et al.*, 2004).

Incremental pluton assembly has the first-order effect of prolonging the thermal anomaly associated with emplacement of a given volume of magma. Hanson and Glazner (1995) concluded that incremental assembly increases the duration of contact metamorphism in wall rocks. Stimac *et al.* (1997) note that both the timing and size of the thermal anomaly at the surface is affected by incremental intrusion and is, in part, controlled by the geometry of the successive magma batches. Consequently, incremental intrusion provides testable hypotheses regarding the thermal history of intrusions and geothermal resources. To some extent, the hypothesis that surface heat flow will be impacted is already supported by the observation that incremental intrusion models fit the heat flow data in some areas better than single intrusion models.

Thermochronology of Sierran Plutons

Cooling histories of Mesozoic plutons exposed in the Sierra Nevada batholith of California can be examined for evidence of incremental assembly. The Tuolumne Intrusive Suite is a concentrically zoned intrusion, typical of arc batholiths, that was emplaced between ~95 and 85 Ma (Figure 1; Coleman *et al.*, 2004). Zircon U-Pb geochronology of the Tuolumne requires incremental assembly of the suite as a whole, and of individual plutons with in it. Although the shapes and orientations of individual magma pulses are not always apparent, abundant evidence for (presently) steeply dipping sheets is preserved along the margins of the Tuolumne (Taylor, 2004). However, existing data permit the possibility that the sheets are tilted from shallower dips. The Lamarck and Goodale plutons are exposed south of the Tuolumne (Figure 1). The Lamarck is mapped as a single body within the Mono Pass Intrusive Suite that in many ways resembles the Tuolumne suite. Existing U-Pb data for these intrusions are limited to a single sample of each dated at ~92 Ma (Coleman *et al.*, 1995) and, consequently, it is not yet possible to determine if they were incrementally assembled.

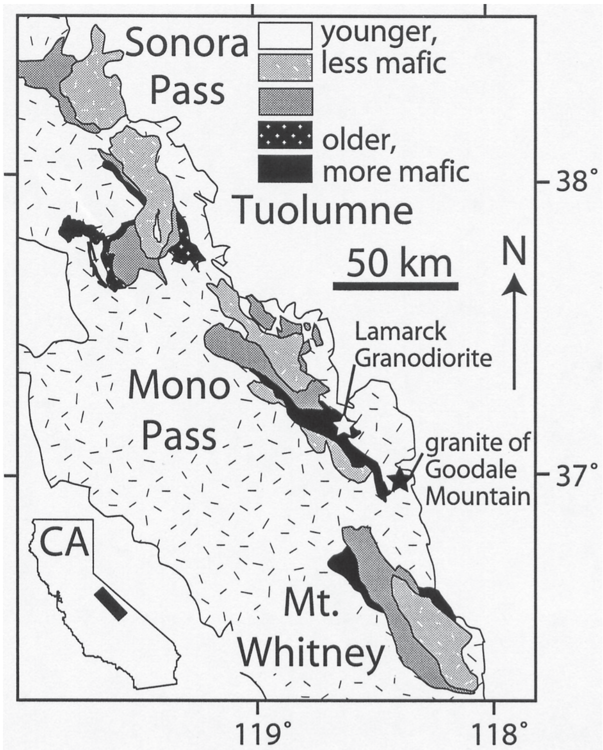

Figure 1. Cretaceous intrusive suites of the central Sierra Nevada batholith. Existing data demonstrate incremental emplacement of the Tuolumne Intrusive Suite over at least 10 m.y. (Coleman *et al.*, 2004) and similar histories are likely for the other suites. For the Tuolumne, the succession of intrusions from oldest (most mafic) to youngest (most felsic) indicated by the patterns is 1) Sentinel Granodiorite, 2) tonalite of Glen Aulin and Kuna Crest Granodiorite (although the last two units have different names they are mapped as western and eastern bodies, respectively, of the same pluton -- they have indistinguishable ages [Coleman *et al.*, 2004] and are shown with the same pattern), 3) Half Dome Granodiorite, 4) Cathedral Peak Granodiorite, and 5) Johnson Granite Porphyry. Approximate locations of samples from the Lamarck Granodiorite (of the Mono Pass Intrusive Suite; open star) and the granite of Goodale Mountain (solid star) are also indicated.

Like the U-Pb data, Ar-Ar thermochronologic data for the Tuolumne Intrusive Suite (Kistler and Fleck, 1994) show a regular age progression from oldest to youngest from the margins inward (Table 1; Figure 2a). However, the hornblende ^{40}Ar/^{39}Ar date for each intrusive unit is significantly younger (4-6 Ma) than the U-Pb date for the same rock. Biotite Ar-Ar dates are predictably younger than hornblende dates for the same samples. Some of the discrepancy between zircon and hornblende dates could result from real variations in the ages of the samples dated by the different techniques because U-Pb and Ar-Ar dating were not performed on the exact same samples. We think it is unlikely that this explains all of the variation for several reasons: 1) the outer tonalites (Glen Aulin and Kuna Crest) are relatively thin sheets with overlapping U-Pb ages (Coleman et al., 2004) and, consequently there is no evidence to suggest that intrusion of this unit spanned 5

Ma; 2) the rocks show spatially regular changes in crystallization age (described above) and, therefore, distinctions such as the "inner" and "outer" Half dome should avoid mixing older U-Pb samples with substantially younger Ar-Ar samples; 3) the age pattern is very regular, with U-Pb dates for all samples older than corresponding Ar-Ar dates. It seems very unlikely that all of the samples would show such a systematic pattern if it resulted from sampling. Therefore, we conclude that the convex-up cooling histories are representative of the thermal evolution of the magma system.

The cooling histories of both the Lamarck and Goodale plutons contrast with that of the Tuolumne suite (Table 1; Figure 2b). These plutons both show rapid cooling from zircon to hornblende closure followed by slow cooling to biotite closure, resulting in concave up (rather than convex up) cooling paths.

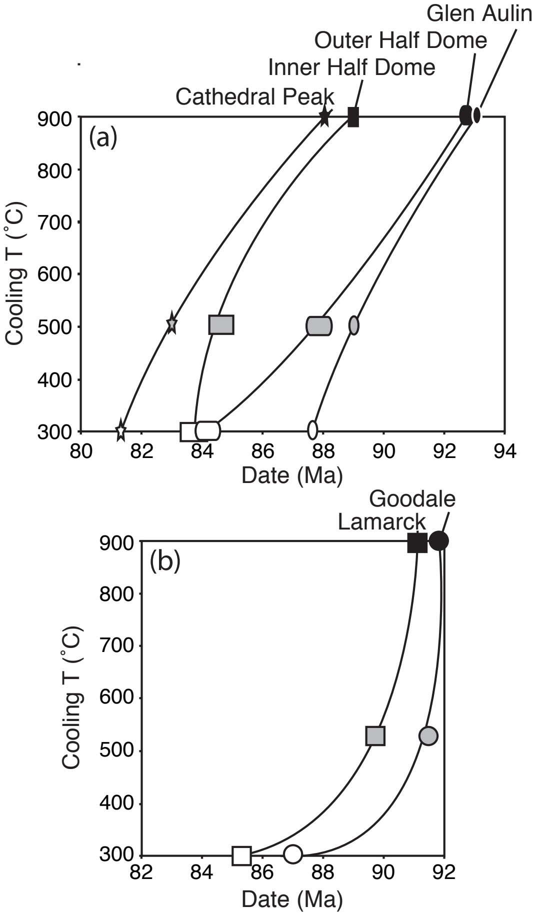

Figure 2. Cooling histories of plutonic rocks from the Tuolumne Intrusive Suite (a) and the Lamarck and Goodale plutons (b). Data sources are cited in Table 1. Rock units in the Tuolumne as described in Figure 1. In both figures, U-Pb zircon dates are black symbols (closure temperature ~900°C; Cherniak and Watson, 2001), ^{40}Ar/^{39}Ar hornblende dates are gray symbols (closure temperature ~525°C; Spear, 1995) and ^{40}Ar/^{39}Ar biotite dates open symbols (closure temperature ~300°C; Spear, 1995). Samples from the Tuolumne show consistent convex up cooling paths whereas those from the Lamarck and Goodale are concave up. The difference may be related to the documented incremental intrusive history of the Tuolumne.

Table 1. U-Pb zircon and ^{40}Ar/^{39}Ar dates from plutons in the Sierra Nevada batholith.

map unit	concordant U-Pb zircon	^{40}Ar/^{39}Ar hornblende	^{40}Ar/^{39}Ar biotite
Tuolumne Intrusive Suite			
tonalite of Glen Aulin[1]	93.1	89.0	87.6
outer, equigranular Half Dome Granodiorite[1]	91.7	87.9	84.4
inner, porphyritic Half Dome Granodiorite[1]	88.8	85.1	83.9
Cathedral Peak Granodiorite[2]	88.1	83.0	81.0
other Sierran plutons			
Lamarck Granodiorite[3]	91.9	89.5	85.1
granite of Goodale Mountain[3]	92.6	91.2	87.0

[1] U-Pb from Coleman et al. (2004); ^{40}Ar/^{39}Ar from Kistler and Fleck (1994)
[2] U-Pb from Coleman and Glazner (1997); ^{40}Ar/^{39}Ar from Kistler and Fleck (1994)
[3] U-Pb from Coleman et al. (1995); ^{40}Ar/^{39}Ar from this study

Cooling of the Sierran Plutons

Existing thermal models demonstrate that incremental intrusion is capable of establishing and maintaining upper-crustal (<10 km) magma chambers in less than 100 ka at geologically reasonable spreading rates (Hanson and Glazner, 1995). These models also show that initial intrusions should cool more quickly, resulting in sheet-like intrusions at the margins, before small magma chambers may be sustained (Hanson and Glazner, 1995; Yoshinobu *et al.*, 1998). Fundamentally, late intrusions are emplaced into warmer wall rocks than early intrusions, thus prolonging conductive cooling. Simple models for successive dike intrusion thus predict relatively rapid cooling of the margins of a sheeted intrusion with more prolonged cooling histories for the centers of the intrusions.

It is appealing to use incremental intrusion to account for the thermochronologic data from the Sierran plutons, but, there are some inconsistencies. The thermal histories for the Lamarck and Goodale samples may reflect cooling along the margin of a more complicated intrusion; however, because we have only one sample of each of these plutons, there are not enough data to evaluate any spatial variations in the cooling histories. The more comprehensive data set from the Tuolumne allows better insight into the thermal history of an incrementally assembled pluton.

Marginal units of the Tuolumne Intrusive Suite show cooling histories similar to more interior units; therefore, the suite does not fit the prediction of rapidly cooled margins and a more slowly cooled core. The outer Half Dome unit does suggest rapid cooling, however (Figure 2a). Dalrymple *et al.* (1999) demonstrate that, if the episodic intrusive history of a pluton is more spatially complicated (random in their model 2), the local thermal history will become necessarily more complicated with areas of the pluton being reheated long after initial intrusion. This intrusive scenario could account for some of the variation in cooling histories for the Tuolumne, but does not adequately account for the all the data because (with the exception of the outer Half Dome sample) they show regular space/time patterns. Instead, an "orderly" assembly seems required.

A possible scenario for orderly intrusion that could account for the thermochronologic data for the Tuolumne may be found in the modeling of Stimac *et al.* (1997). These authors investigated the impact of incremental intrusion on surface geothermal gradients and found that, if intrusions were stacked from the top down, arrival of the greatest thermal pulse at the surface was significantly delayed (their Figure 15, "bottom stack"). The crudely concentric, inward-younging Tuolumne Intrusive Suite may record such a downward-stacking of laccolithic sheets, and thus heating of sheets from below by later intrusions could account for the delayed cooling of early intrusions. Mechanically, successive batches of magma may stall as they encounter partially molten rocks above them because a crack cannot be propagated through them. Testing this hypothesis requires fine-tuning of the Stimac *et al.* (1997) model to include more pulses of magma and emplacement over longer time intervals.

Conclusions

Incremental pluton assembly seems an inescapable conclusion for the construction of intrusive suites and batholiths, and may be particularly appropriate for construction of plutons in localized extensional environments favorable for the development of geothermal resources. The hypothesis is supported by a variety of geophysical, geological and modeling studies, and helps bring the record of magmatism preserved in plutonic rocks into line with the record preserved in volcanic rocks. Incremental assembly of plutons results directly in extending the longevity of geothermal resources. An important conclusion to draw from this is that plutons preserve a record of the heat flux into the crust over significant time periods. Because they are amenable to dating and provide more direct estimates of magma flux into the crust than extrapolation from the volcanic record, plutons should be better exploited when deciphering temperature-time histories in geothermal resource areas.

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