# Rethinking the emplacement and evolution of zoned plutons: Geochronologic evidence for incremental assembly of the Tuolumne Intrusive Suite, California

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## ABSTRACT

**New U-Pb geochronologic data indicate that the Tuolumne Intrusive Suite, California, was assembled over a period of at least 10 m.y. between 95 and 85 Ma, and that the Half Dome Granodiorite intruded over a period approaching 4 m.y. Simple thermal considerations preclude the possibility that a magma chamber the size of the Half Dome pluton could have existed as a liquid at shallow crustal depths for that long. Rather, field evidence for sheeting along the margins of the suite, the range of ages, and the regular decrease of ages toward the center of the suite and within individual plutons suggest incremental assembly. Geochronologic evidence for incremental assembly is consistent with the failure of geophysical methods to detect large magma chambers with more than ~20% melt, even in active volcanic areas. Because it is unlikely that the individual plutons composing the Tuolumne ever coexisted as liquid-rich magmas, the chemical evolution of the suite cannot be the result of simple fractionation and/or mixing between exposed units, but instead must reflect processes occurring during magma generation.**

**Keywords:** plutons, magma chambers, U/Pb geochronology, Sierra Nevada batholith.

## INTRODUCTION

The nature of magma chambers is a central problem in geology. The questions of how long magma chambers live and how plutons are constructed are clearly intertwined, because the fill rate of a magma chamber cannot be separated from space-making processes (e.g., Paterson and Tobisch, 1992). A diapir would rise slowly and displace wall rocks by ductile processes (e.g., Miller et al., 1988). In contrast, magma can rise many orders of magnitude faster in dikes, fast enough that large plutons could be filled on time scales of $10^1$–$10^4$ yr (Clemens and Mawer, 1992; Petford, 1996). But to do so requires displacing a host-rock volume equal to the pluton in the same time, leading to the suggestion that many plutons might be made by slower, incremental addition of magma to a growing body via dike intrusion, perhaps over a period of ~1 m.y. (Petford, 1996).

If plutons are emplaced as large molten bodies, then thermal studies indicate that they should cool below the closure temperatures of zircon (U-Pb) and hornblende (K-Ar) within a few hundred thousand years (e.g., Harrison and Clarke, 1979). Thus, the supersolidus lifetime of a pluton, and the lifetime of a volcanic system derived from it, should be on the order of a few hundred thousand years.

In contrast to the ‘‘single-blob’’ model, there is a growing body of data indicating that some major plutonic systems accumulated in small batches and were never fully molten at any given time. For example, Wiebe and Collins (1998) described the progressive assembly of plutons by intrusion of stacked sheets of mafic magma below a long-lived felsic magma chamber. Similarly, McNulty et al. (1996) and Mahan et al. (2003) argued for emplacement of plutons in the central Sierra Nevada batholith of California as a series of dikes. Geochronologic data suggesting protracted emplacement of plutonic systems (possibly over as long as 8 m.y.) were presented by McNulty et al. (1996) and Brown and McClelland (2000).

The question of whether plutons cooled from large magma chambers or accumulated incrementally is fundamental to both petrology and structural geology because it bears on how the crust is assembled, how fabric relationships in and around plutons should be interpreted, how magma is generated, and how magma systems evolve chemically. Here we present data from the Tuolumne Intrusive Suite in California demonstrating that emplacement of the suite occurred incrementally over at least 10 m.y. Consequently, models for diapiric intrusion, fractional crystallization, and magma mixing in the Tuolumne Intrusive Suite and other zoned plutonic suites should be reconsidered.

## GEOLOGIC SETTING

The 1200 $km^2$ Tuolumne Intrusive Suite is one of several large-volume zoned intrusive suites emplaced in the Sierra Nevada in the Late Cretaceous (Fig. 1). These suites all have mafic granodioritic outer phases that grade progressively inward to granodioritic or granitic cores (Bateman, 1992), and were intruded at pressures of 1–3 kbar (Ague and Brimhall, 1988).

From rim to core, the Tuolumne Intrusive Suite includes the granodiorite of Kuna Crest and the tonalite of Glen Aulin (assumed to represent the eastern and western parts of the same intrusion; Bateman and Chappell, 1979), the Half Dome Granodiorite, the Cathedral Peak Granodiorite, and the Johnson Granite Porphyry (Fig. 1). Kistler and Fleck (1994) also considered the Sentinel Granodiorite on the west side of the suite to be part of the Tuolumne. Rocks of the Tuolumne Intrusive Suite are commonly interpreted to be cogenetic. Both fractional crystallization of exposed units (Frey et al., 1978; Bateman and Chappell, 1979) and mixing between them (Reid et al., 1983; Kistler et al., 1986) have been invoked to explain the chemical evolution of the suite.

## U-Pb GEOCHRONOLOGY

We present U-Pb data for 11 samples from the Tuolumne Intrusive Suite (Figs. 1 and 2; Table DR1[1]). Ages for samples that yielded a cluster of concordant points with data for individual points overlapping within uncertainty are presented as the weighted mean dates; also shown are the mean squares of the weighted deviates (MSWD) of the $^{206}Pb/^{238}U$ dates of the main cluster.

Samples of the Glen Aulin and Kuna Crest plutons yield indistinguishable ages of 93.1 ± 0.1 (Fig. 2A) and 93.5 ± 0.7 Ma (Fig. 2B), respectively. Ages for samples of the Half Dome Granodiorite vary across the pluton. Samples taken within a few meters of the contacts with the Kuna Crest and Glen Aulin plutons yield ages of 92.8 ± 0.1

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[1]GSA Data Repository item 2004071, Table DR1, U-Pb zircon data for rocks of Tuolumne Intrusive Suite, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

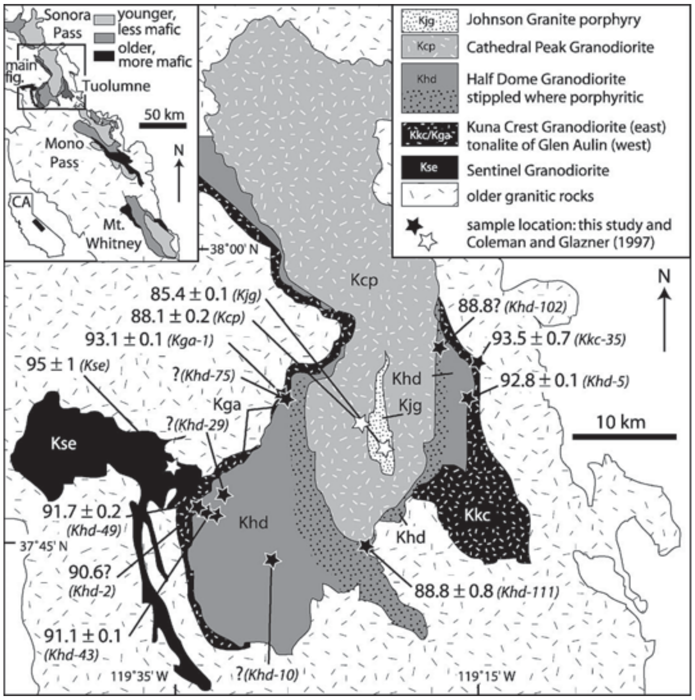


**Figure 1. Simplified geology of Tuolumne Intrusive Suite after Bateman (1992). Inset shows location of Tuolumne and other Sierra Crest zoned intrusive suites. Ages shown with errors are weighted means of clustered concordant data; geologic unit designation and sample number from Table DR1 (see footnote 1 in text) are in italics after age (samples from this study only). Queried dates are for samples with data that spread out along concordia and did not yield precise results. Samples with no date shown did not yield reliable ages. See text for discussion.**

Ma (eastern body; Fig. 2C) and 91.7 ± 0.2 Ma (western body; Fig. 2D). Samples collected on a transect eastward through the equigranular phase of the Half Dome Granodiorite (toward the contact with the Cathedral Peak Granodiorite) show progressively younger ages inward. A sample from the top of Half Dome (proper) yielded an age of 91.1 ± 0.1 Ma (Fig. 2E). Farther east, a sample of the porphyritic Half Dome adjacent to the contact with the Cathedral Peak Granodiorite yielded an age of 88.8 ± 0.8 Ma (Fig. 2F). Data for other samples (Figs. 2G–2K) show scatter along a significant increment of concordia with little or no overlap between points, but are included for completeness and discussion.

## DISCUSSION

### Interpretation of the Concordia Results

Concordia plots for samples from the Tuolumne Intrusive Suite are characterized by either clusters of concordant data with distinct outlier points, or a "smear" of data along an interval of concordia (e.g., cf. Figs. 2D and 2K). Scatter in the data, whether as outliers or a range of dates over an interval, must result from some combination of Pb loss and/or inheritance. Deciphering these possibilities is required for interpretation of the data and is significantly enhanced by air abrasion (Krogh, 1982) and analysis of single-grain and small zircon fractions (Connelly, 2001).

For any combination of crystallization ages, zircon inheritance, and Pb loss in the data for the Tuolumne, single-crystal analyses that yield clusters of results are likely to yield a crystallization age because (1) the composition of Tuolumne magmas favored rapid dissolution of inherited grains (Watson and Harrison, 1983) and thus precluded the possibility that all grains are inherited, (2) Pb loss in young, unmetamorphosed rocks should be low, and (3) it is unlikely that individual grains of variable size and U content that are air abraded prior to analysis will exhibit identical inheritance or Pb loss. Consequently, we interpret the dominant populations of data for samples in Figures 2A–2F to be crystallization ages; the outlier points for these samples we interpret to indicate inheritance for all but HD01-49 and KGA-1, which each have a single analysis characterized by Pb loss. Some additional source of scatter may be present in samples HD01-49 and HD01-35 resulting in MSWDs of >2; however, the $^{206}Pb/^{238}U$ dates for these samples overlap within uncertainty, and we interpret the age estimates as robust.

Data for five additional samples do not yield similar high-precision results. It seems likely that some combination of Pb loss and inheritance resulted in both spreading of the data along concordia and obvious outliers caused by Pb loss (e.g., fraction C, Fig. 2I) and inheritance (e.g., fraction B, Fig. 2J).

### Was There a Half Dome Magma Chamber?

These data plus data from Coleman and Glazner (1997) show a pattern of monotonically decreasing age toward the exposed center of the suite (Fig. 2L). This pattern is mimicked by the Half Dome Granodiorite, which is as old as 92.7 Ma near its outer contact with the Kuna Crest Granodiorite and as young as 88.8 Ma at its inner contact with the Cathedral Peak. Together, the data indicate that the time for emplacement of the Tuolumne Intrusive Suite may have exceeded 10 m.y. and that emplacement of the Half Dome pluton required nearly 4 m.y.

Thermal models show that a crustal magma chamber of the size (~10 km half width; Fig. 1) and composition of the Half Dome Granodiorite should solidify rapidly, cooling by conduction below 700 °C in <1 m.y. and even more rapidly if the magma convects. Because 700 °C should be well below the closure temperature for Pb in zircon (>900 °C; Cherniak and Watson, 2001), 1 m.y. is the maximum possible range of U-Pb zircon dates in a pluton of this size emplaced as a single intrusion. Consequently, the geochronologic data do not allow the possibility that the Half Dome Granodiorite ever existed as a single magma chamber.

Lateral age variation in the Tuolumne Intrusive Suite is consistent with field evidence for dike or sheet intrusion of at least the outer units of the suite (Templeton et al., 2000; Taylor, 2004). The pattern of dikes and sheets at the margins of the suite, passing into a more homogeneous interior, is consistent with thermal models of incremental pluton growth that predict a transitory sheeted-dike stage followed by formation of a central (possibly small and ephemeral) steady-state magma chamber (Hanson and Glazner, 1995; Yoshinobu et al., 1998).

The observation that contacts between units in the Tuolumne may be locally gradational or sharp is readily explained if locations with gradational contacts mark places where there is little or no difference in the ages of adjacent rocks, and locations with sharp contacts mark places where there is a significant difference in the ages of adjacent rocks. For example, samples of the Kuna Crest Granodiorite and Half Dome Granodiorite collected from near the gradational contact on the eastern side of the suite yield nearly indistinguishable ages of 93.5 ± 0.7 Ma (Fig. 2B) and 92.8 ± 0.1 Ma (Fig. 2C). In contrast, the contact between the outer tonalite and the Half Dome Granodiorite is sharp in Yosemite Valley, where the Half Dome is significantly younger (91.7 ± 0.2 Ma; Fig. 2D).

### Implications for the Origin of Large Zoned Intrusions

Emplacement of the Tuolumne Intrusive Suite as a series of intrusions is consistent with the growing recognition that large magma chambers may be uncommon in the crust. For example, at least some large ignimbrites did not exist as large molten bodies until immediately prior to eruption (Mahood, 1990; Bachman et al., 2002). Additionally, geophysical surveys have rarely identified a magma chamber with >20% liquid present even in active volcanic systems (Iyer et al., 1990;

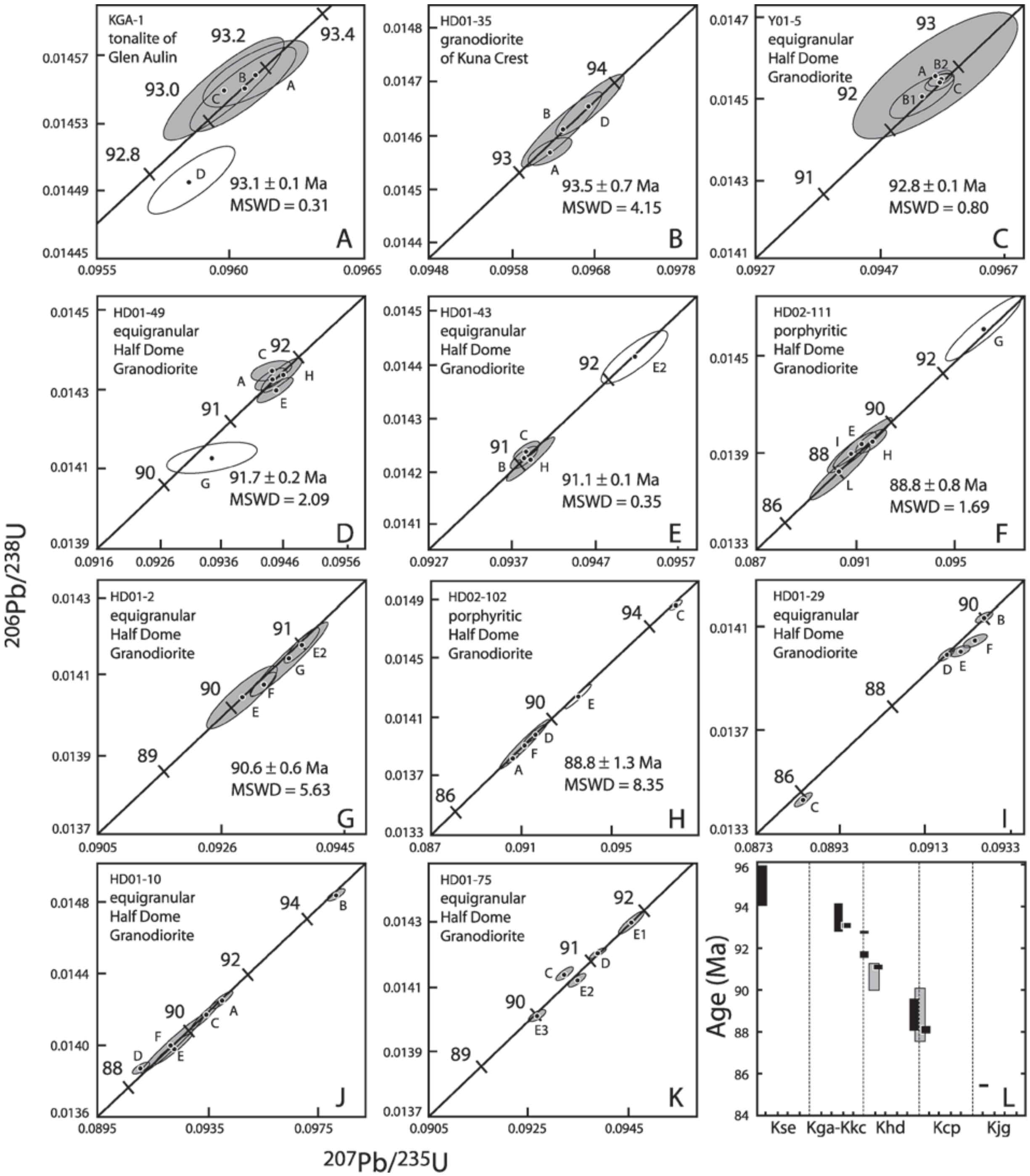


**Figure 2. Conventional concordia diagrams for zircons from Tuolumne Intrusive Suite (A–K) and summary of ages (L). Ages are weighted mean $^{206}Pb/^{238}U$ dates for concordant and clustered analyses (solid gray error ellipses); also shown are mean squares of weighted deviates (MSWD). Age tick marks are labeled in millions of years along concordia; zircon fractions are indicated by letters (Table DR1; see footnote 1 in text). Panel L shows summary of ages arranged from outermost (Sentinel Granodiorite; left) to innermost (Johnson Granite porphyry; right) map units, including samples from this study (A–H), and Coleman and Glazner (1997). Gray symbols indicate samples with MSWD >5. Unit designations as in Figure 1. Horizontal scale is not linear distance, but places samples according to fractional distance from outer to inner contact of individual units. For example, sample plotting halfway between dashed lines on figure was collected from halfway between outer and inner contacts of that unit.**

Schilling and Partzsch, 2001). Together, these observations suggest that large magma chambers may be ephemeral features in the crust. Furthermore, if the geochronologic results for the Tuolumne prove to be generally applicable, two important corollaries follow.

1. The geochemical evolution of zoned intrusions must be re-evaluated. If there was never a large Half Dome magma chamber, then geochemical variation in the Half Dome Granodiorite (and by inference, in the Tuolumne Intrusive Suite as a whole) could not have been controlled by fractional crystallization of, or mixing between, exposed units. The Tuolumne could represent shallow equivalents of a deeper magma chamber that was undergoing fractionation and mixing, but this requires a magma chamber capable of differentiation for at least 10 m.y., in contradiction to thermal arguments. A second possibility is that the geochemical variation of the suite reflects regular changes in

the composition of magmas generated at the source. Zoned intrusive suites of nearly identical petrography, chemistry, and sequence of emplacement were intruded in the Sierra Nevada over >400 km of arc length between ca. 98 and 86 Ma (Fig. 1 inset; Bateman, 1992). Generation of similar magmas and a similar sequence of magmas could reflect similarities in source composition and crustal and thermal structure over a significant length of the arc. If so, the compositional zoning observed in Sierran plutons and elsewhere reflects processes occurring at the source of the magmas rather than processes occurring at the final level of emplacement.

2. Commonly held views of emplacement mechanisms, rates, and fabric development in plutons must be reconsidered. For example, diapirism and stoping (e.g., Pitcher, 1993; Miller and Paterson, 1999) cannot occur if a large magma chamber did not exist during growth of a pluton. A related implication is that strain rates associated with pluton emplacement may be significantly lower, and more geologically reasonable (Petford, 1996), than diapirism permits. Finally, if plutons are fundamentally diachronous, fabrics in plutons must be diachronous (Hutton, 1988) and/or the result of postemplacement strain (Paterson and Vernon, 1995).

## CONCLUSIONS

New geochronologic data for the Tuolumne Intrusive Suite indicate that crystallization of the magmas occurred over time periods far too long for individual plutons to have existed as fractionating, mixing magma chambers. Instead, the data are consistent with emplacement as a series of small intrusions, perhaps as sheets or dikes. These results combined with new interpretations of data for large ignimbrites and geophysical surveys suggest the possibility that large magma chambers may be uncommon in the crust. Additional high-precision geochronologic data from other zoned intrusions will help test the possibility that incrementally assembled plutons may be the norm, rather than the exception. If so, reevaluation of models to explain chemical variation in zoned intrusions is necessary.

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