Tilting, burial, and uplift of the Guadalupe Igneous Complex, Sierra Nevada, California

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ABSTRACT

It is often incorrectly assumed that plutons have a relatively uneventful structural history after emplacement. The 151 Ma Guadalupe Igneous Complex (GIC) in the Foothills Terrane, California, was involved in three post-emplacement events: (1) ~30° of southwest-side–up tilting during ductile regional faulting and contraction, (2) burial of the pluton from ~4 to 12 km during crustal thickening of the wall rocks, and (3) uplift with only minor tilting in the Late Cretaceous. Tilting of the pluton is indicated by (1) southwest to northeast gradational changes from layered gabbros and diorites to granites and granophyres; (2) northeastward dips of layering in gabbro, internal contacts, and bedding of overlying coeval(?) volcanic rocks; (3) northeastward decrease in wall-rock metamorphic grade; and (4) paleomagnetic data from 14 localities across the pluton. We argue that tilting occurred between 146–135 Ma during southwest-northeast–directed regional contraction. This contraction is indicated by widespread folds and cleavages and by reverse motion on the Bear Mountains fault zone (BMFZ), a large northeast-dipping shear zone that bounds the GIC on its southwest side. Burial of the GIC, which overlapped in time but outlasted tilting, is suggested by (1) post-emplacement contractional faulting, folding, and cleavage development; (2) analyses of strains associated with widespread cleavage that indicate vertical thickening of ~100%; and (3) microstructural and mineral assemblage data that indicate shallow emplacement of the GIC, in contrast to mineral assemblage and limited geobarometric data from adjacent 120–110 Ma plutons that indicate moderate emplacement levels. Late Cretaceous uplift is indicated by 95–75 Ma sedimentary rocks that unconformably overlie the 120–110 Ma plutons.

This geologic history is interesting for several reasons. First, although the GIC participated in extensive post-emplacement deformation, it lacks internal structural evidence of these events, except locally along the Bear Mountains fault zone. Second, the agreement between paleomagnetic and structural evidence for tilting suggests that no large latitudinal displacement of the GIC is required. Third, the paleomagnetic data also help to define the geometry of the magma chamber now represented by the GIC. Lack of streaking of paleomagnetic site-mean directions demonstrates that the pluton acted as a single unit after cooling through the blocking temperature (450–560 °C) of low-titanium titanomagnetite; however, variations in the dip of internal layering and contacts, from 70° at the base to 30° near the top of the pluton, indicate that not all of these features were horizontal and planar when they formed. We propose that this variation in dip of layering is most consistent with sidewall crystallization of magma resulting in drape of layering along the walls of the intrusion. Therefore, internal layering within this pluton does not record paleohorizontal.

INTRODUCTION

Geologists sometimes consider plutons to be large "nails" that simply poke through their wall rocks and have a relatively uneventful post-emplacement history. Recent studies have begun to cast doubt on this assumption by documenting the internal deformation of these bodies, or by giving reasonable arguments for translation or tilting of solidified plutons (for example, Barnes and others, 1986; Brown and Burmester, 1991; Butler and others, 1989; Flood and Shaw, 1979; Hopson and Dellinger, 1987). Whether or not plutons are tilted or translated obviously will influence interpretations about the characteristics of magma chambers, local structural histories, and regional tectonic and paleogeographic interpretations.

Definitive evidence for tilting of plutons remains elusive (for example, compare Butler and others [1989, 1990a, 1990b] to Umhoefer and Magloughlin [1990] and Miller and others [1990]), and arguments for, or against, tilting are strengthened by combining structural, paleomagnetic, metamorphic, and geobarometric data. In this paper, we present data for three post-emplacement events, including tilting of the Guadalupe Igneous Complex, and point out that despite extensive involvement in post-emplacement deformation, the complex has little internal evidence of this deformation.

THE GUADALUPE IGNEOUS COMPLEX

The Guadalupe Igneous Complex intrudes the Foothills Terrane of the Sierra Nevada, California (Fig. 1) (for example, Best, 1963; Tobisch and others, 1989). The terrane consists of highly disrupted ophiolitic basement, overlying Mesozoic (Gopher Ridge and Penon Blanco) volcanic sequences, and Late Jurassic slate and graywacke (Mariposa Formation). The Foothills Terrane in the vicinity of the GIC consists of western, central, and eastern belts separated by strands of the Foothills Fault system (Clark, 1964). Although the origin and offset between these three belts remain controversial (for example, Clark, 1964; Schweickert and others, 1984; Tobisch and others, 1989; Miller and Paterson, 1991), there is general agreement that the belts were juxtaposed prior to intrusion of the 151 Ma GIC (Saleeby and others, 1989; Tobisch and others, 1989).

Tobisch and others (1989) and Paterson and others (1991) argued that the GIC intruded into the core of a dome or anticline after initial folding and rigid tilting of units in the Foothills Terrane, during movement on one strand of the Foothills Fault system called the Bear Mountains fault zone (BMFZ), but before widespread cleavage development outside of the BMFZ. Synfaulting emplacement of the GIC is indicated by a variety of features, including the following: (1) highly elongate lenses of trondhjemite along the BMFZ with identical Pb/U zircon ages as the main body of the GIC (Saleeby and others, 1989); (2) folded migmatitic leucosomes

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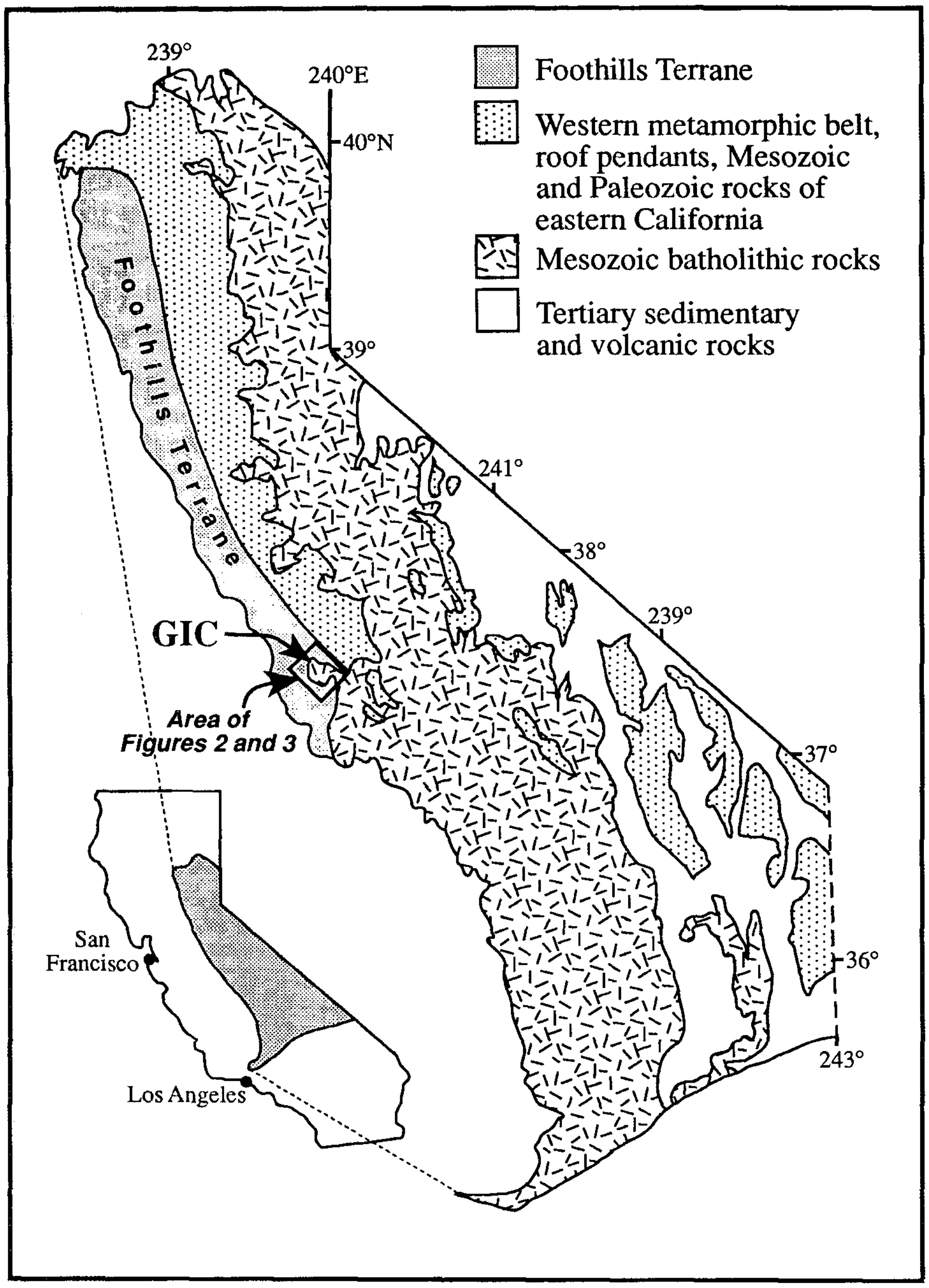

Figure 1. Map of general location of the Guadalupe Igneous Complex (GIC) in the foothills of the Sierra Nevada of California.

in the GIC's contact aureole that also intrude along the axial surfaces of these same folds (Vernon and others, 1989); (3) synkinematic porphyroblasts of andalusite and cordierite located where the BMFZ intersects the contact aureole (Paterson and others, 1991); and (4) subparallel magmatic and high-temperature solid-state foliations in the adjacent, coeval Hornitos pluton, which was also intruded along the BMFZ (Fig. 2) (Vernon and others, 1989).

Post-emplacement development of wall-rock cleavage outside of the BMFZ is supported by the following observations: (1) the cleavage overprints contact metamorphic porphyroblasts around the GIC that do not have internal inclusion trails, (2) the cleavage overprints all nearby 151–147 Ma plutons, and (3) $^{40}Ar/^{39}Ar$ ages of cleavage-parallel hornblende and biotite give ages 5 to 25 m.y. younger than U/Pb ages from the GIC (Tobisch and others, 1989; Saleeby and others, 1989). The age (Saleeby and others, 1989) and structural history (Tobisch and others, 1989) of these wall-rock structures, as well as emplacement of the pluton (Paterson and others, 1991), have been fully discussed elsewhere. Below we wish to discuss new paleomagnetic data from the GIC and examine the post-emplacement history of this body.

POST-EMPLACEMENT DEFORMATION OF THE GUADALUPE IGNEOUS COMPLEX

Below we present evidence that the GIC experienced at least three post-emplacement structural events: (1) ~30° southwest-side–up tilting during faulting and regional contraction, which occurred between ~145 and 135 Ma; (2) crustal thickening and burial of the wall rocks from ~4 to ~12 km by ~115 Ma; and (3) uplift, without significant tilting, during Late Cretaceous time.

Southwest-Side–Up Tilting

The GIC was first studied in detail by Best (1963), who discovered that it is a compositionally layered pluton that grades from gabbro and diorite on its southwestern side to granite and granophyre on its northeastern side (Fig. 3). Internal contacts between petrological units are narrow gradational zones that locally show evidence of magma mingling. Layering in the basal gabbro strikes roughly 330° and dips 70° NE near the western side of the GIC and decreases to 40° NE near the contact between the diorite and granodiorite (Table 1). Internal contacts east of the gabbro dip 25° to 35° E. Poorly preserved silicic volcanic rocks exposed immediately east of the pluton, possibly derived from surface venting of this magma chamber, strike 325° to 335° and dip 15° to 45° NE. The variation in the dip of these volcanic rocks is likely due to different amounts of rotation during regional contraction rather than variation in initial dips. In wall rocks west of these volcanic rocks, which are now exposed north and south of the GIC (Fig. 3), dips of bedding gradually steepen to 70° to 85° NE.

This sequence of rock types and the dip of internal structures suggest that the pluton is a vertically zoned, tilted magma chamber (for example, Flood and Shaw, 1979; Barnes and others, 1986; Hopson and Dellinger, 1987). Best (1963) argued for no more than 10° of tilt because of lack of evidence for tilting in the wall rocks. We argue, however, that because there are no recognized faults separating the volcanic rocks from the intrusion, nor be-

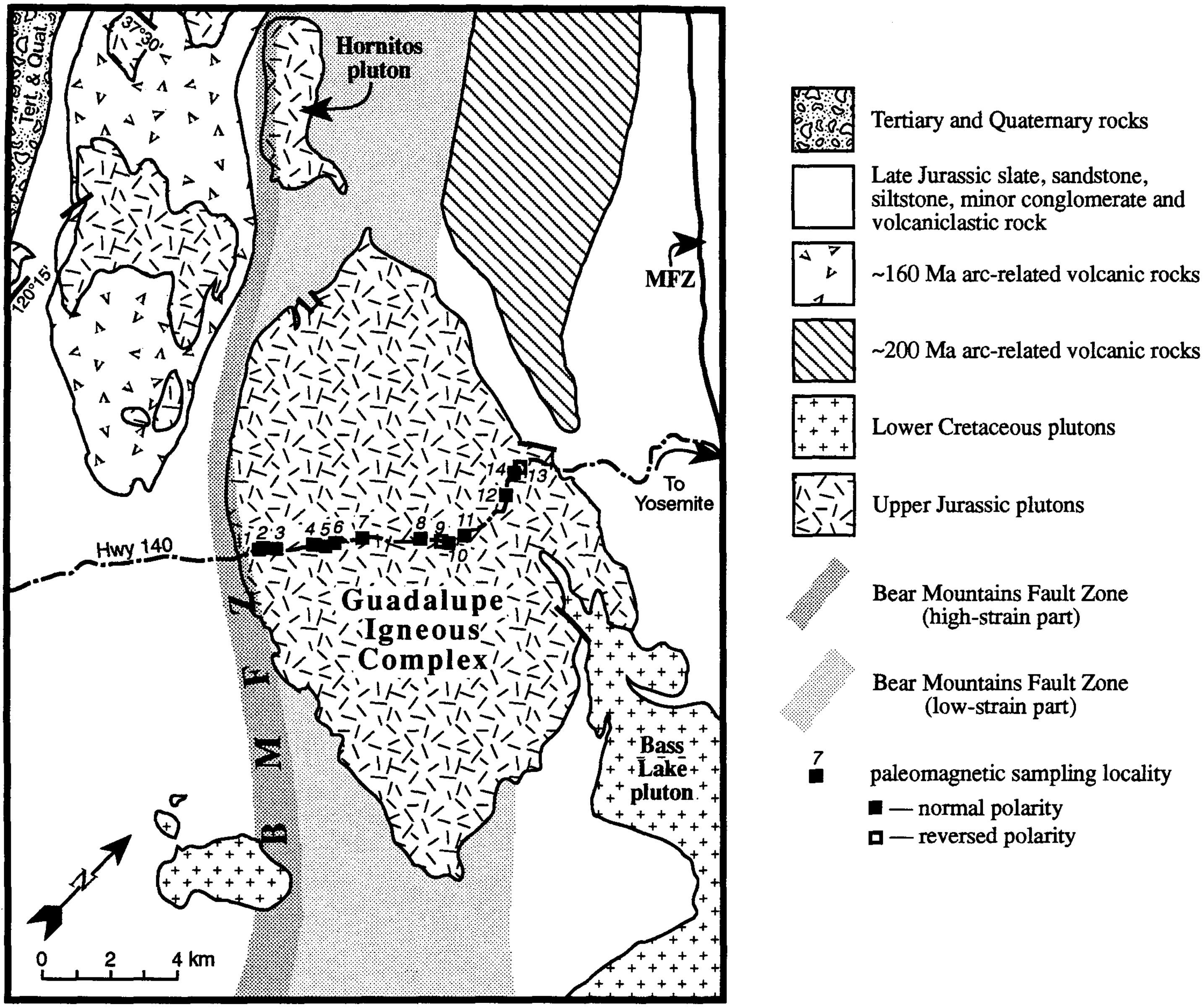

Figure 2. Simplified geologic map of part of the Foothills Terrane, central Sierra Nevada, California, after Tobisch and others (1989). Black squares mark paleomagnetic sampling localities. MFZ, Melones fault zone; BMFZ, Bear Mountains fault zone (boundaries are gradational).

tween internal petrological units, the structural data argue for roughly ~30° ± 10° of southwest-side–up tilt of the GIC. Regional metamorphic grade around the pluton that decreases from lower amphibolite facies in the southwest to lower greenschist facies in the northeast is consistent with southwest-side–up tilting of the pluton, but some of this variation may also reflect increased heat and fluid flow in the BMFZ (Tobisch and others, 1989).

The great majority of regionally developed structures in the Foothills Terrane, including the orientation of nearby syn- to post-emplacement folds, faults, cleavages, and metamorphic isograds, strike between 315° and 335° (Table 1) and dip steeply to the east. Therefore the most likely tilt axis is 325° ± 10°. Other tilt axes should have significantly affected the orientations of these structures, which is not observed.

Paleomagnetic Study. We tested the hypothesis that the GIC was tilted by completing a paleomagnetic study of rocks along a transect across the pluton. Grommé and others (1967) conducted a reconnaissance paleomagnetic study of the GIC, and their data broadly support our conclusions. This early study, however, suffered from a smaller number of samples (56), a much smaller number of localities (3), use of an alternating field (AF) demagnetizer that imparted a spurious component of magnetization on samples, and the lack of a reliable Mesozoic reference pole for North America.

We collected 84 samples from 14 sites (6 samples per site) across the pluton, along California State Highway 140 (Fig. 2). Samples were collected with a portable drill and oriented using a magnetic compass and inclinometer. Magnetic compass readings were checked with a solar compass. Laboratory

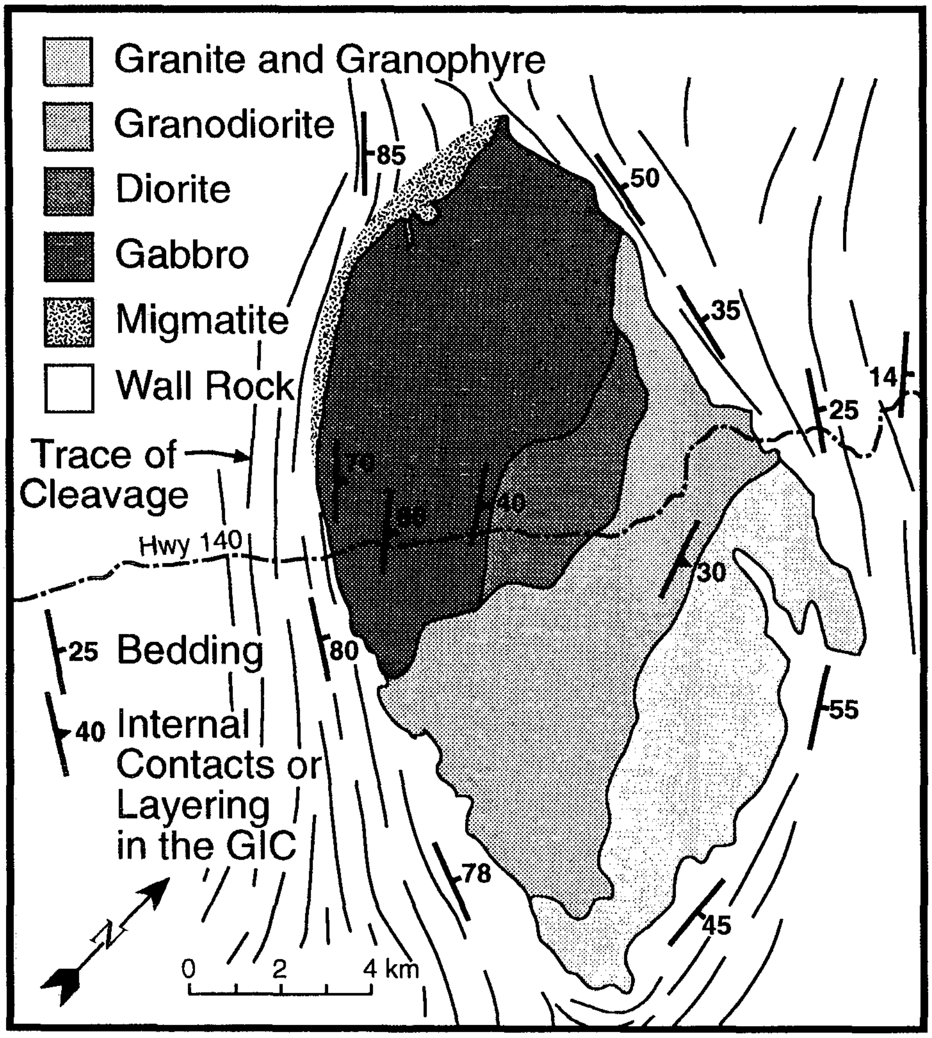

Figure 3. Map of rocks and structural attitudes within, and near, the Guadalupe Igneous Complex. Note how the rocks grade across the pluton from gabbro in the southwest to granite and granophyre in the northeast, which suggests that the pluton is a vertically zoned and tilted magma chamber. Cleavage on the north side of the pluton dips 50°–65° to the north; on the southwest side, cleavage dips 70°–90° to the northeast.

analysis included detailed thermal demagnetization in air, with an average of 16 demagnetization steps for each sample. Remanent magnetizations were measured with a 2G three-axis cryogenic magnetometer in a shielded room at the University of California, Santa Cruz. Results from AF demagnetization obtained from specimens were not as straightforward as those from the same cores that were thermally cleaned (compare Figs. 4A and 4B), and therefore all samples were thermally demagnetized. The orientation of different components of magnetization was determined by a least-squares fit of the linear part of the demagnetization path on a vector diagram.

TABLE 1. GEOLOGIC EVIDENCE FOR TILTING

Evidence	Orientation	
	Strike	Dip
(1) Contacts and layering in basal gabbros	330° ± 15°	40°–70° NE
(2) Overlying volcanic rocks	330°	15°–25° NE
Limitations on tilt axis orientations		
(3) Regional folds, axial planar surfaces, faults, and cleavages	320°–340°	70°–80° NE
(4) Trend of the Bear Mountains fault zone	330°–340°	70°–90° NE
(5) Metamorphic isograds	315°–325°	

We found one low-temperature component of magnetization and two high-temperature components in samples with well-defined demagnetization paths (Figs. 4 and 5; Tables 2 and 3). The low-temperature component is removed at unblocking temperatures <~300 °C and at coercivities <20 mT. The mean low-temperature component direction lies approximately between the recent (last several million years) and present-day geomagnetic field directions (Table 2 and Fig. 5A). Three sites (5, 9, and 10) did not clearly display this direction, either because the high-temperature component dominated the directions or because the lower temperature directions were poorly defined.

The high-temperature component of magnetization was isolated between 450 and 580 °C and was oriented either westerly and downward or easterly and upward (Figs. 4 and 5B). Many samples had a narrow (≤40 °C) range of unblocking temperatures near 580 °C (Fig. 4). Because blocking temperatures are high (commonly ~560 °C), but slightly below 580 °C, and because coercivities are moderately high (Fig. 4B), it appears that titanium-poor titanomagnetite is the carrier of the characteristic remanent magnetization.

Localities 9 and 13 have eastward and upward directions that are antipodal to the westerly and downward directions at >95% confidence. We conclude that the characteristic magnetization in the GIC is primary, because of the reversed polarity sites and because there is a discordance between the grouped site mean direction (declination = 279.1°; inclination = 54.8°; α_{95} = 4.3°; see also Table 3) and any expected direction for North America from Late Jurassic time to the present (May and Butler, 1986; Irving and Irving, 1982). Data from sites 12 and 14 were not used in the final analysis, because the sample directions from site 12 did not define a straight line decaying to the center of a vector diagram plot and the directions from site 14 only exhibited the low-temperature component.

The scatter of the grouped site mean directions in the GIC is small (Fig. 5B and Table 3), smaller than that predicted by recent models of geomagnetic secular variation (McFadden and others, 1991). The lack of scatter between sites might be used to argue that secular variation of the Earth's magnetic field has not been averaged. Paterson and Tobisch (1992), however, argue that it took the GIC 1–3 m.y. to cool from 750 °C (approximate solidus) to 450 °C (the lowest short-term paleomagnetic unblocking temperature), which implies that the GIC's cooling history was long enough that secular variation was averaged (that is, >10,000 yr). The presence of reversed directions is consistent with this hypothesis.

Implications of Paleomagnetic Results for the Geometry of a Magma Chamber. The var-

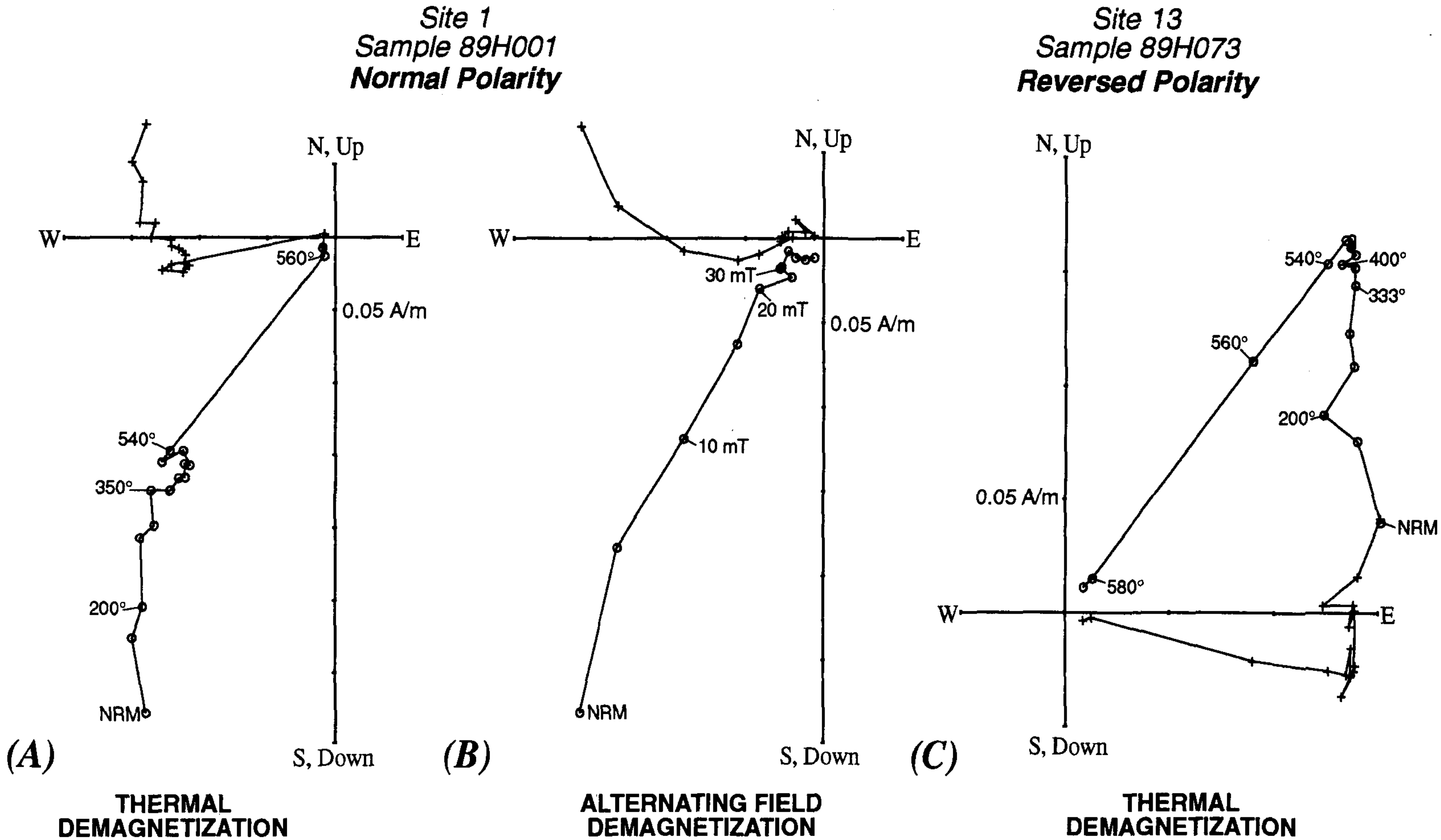

Figure 4. Typical Zijderveld vector diagrams of different components of magnetization in the GIC. The + and O symbols represent the horizontal and vertical components, respectively. Diagrams depict the *in situ* directions. (A) Sample 89H001, site 1, that was thermally demagnetized. The low-temperature (<250 °C) component is oriented similarly to the recent-field direction. The high-temperature component, isolated above 500 °C, is oriented west and downward, which is not similar to any expected Late Jurassic to present direction for North America. (B) Sample 89H001, site 1, that was alternating-field (AF) demagnetized. Neither the high- nor the low-temperature component is as well defined by AF cleaning. The low-temperature component is removed at low peak inductions. (C) Sample 89H0073, site 13, that was thermally demagnetized. The low-temperature (<300 °C) component is oriented subparallel to the recent-field direction, whereas the high-temperature direction is oriented antipolar to the high-temperature directions in most other sites.

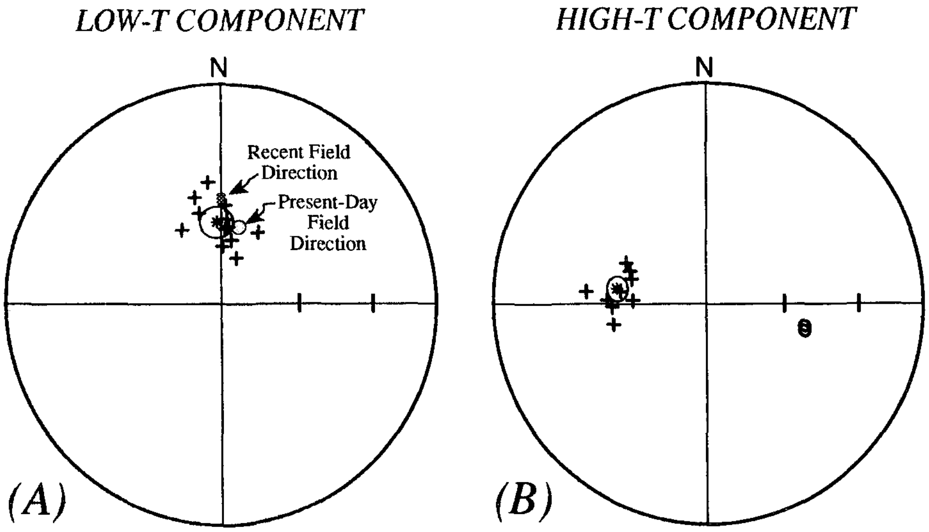

Figure 5. Equal-area stereograms of site-mean directions from the GIC and the α_{95} circle of confidence about the mean. The lower and upper hemisphere directions are represented by + and ○ symbols, respectively; the mean direction, with an asterisk. (A) The low-temperature component is oriented near the recent-field direction. (B) The high-temperature component, which we interpret to be primary. We contend that the eastward and upward directions (sites 9 and 13) are reversed. The mean direction in sites 9 and 13 is inverted through the origin.

iable orientations of gabbroic layering, interpreted by Best (1963) to be cumulate layering, and contacts within the GIC indicate that it is either internally deformed or that the structures formed with different initial orientations. The lack of scatter between paleomagnetic sites across the pluton (Fig. 5B) indicates that compositional layers within the pluton cooled through the blocking temperature of titanium-poor titanomagnetite (450–560 °C) in their present orientation with respect to each other. Deformation of igneous layers while below the blocking temperature of magnetite is not compatible with the paleomagnetic data nor with the lack of evidence for high-temperature solid-state deformation of the pluton (outside of the BMFZ), widespread mafic enclaves in the pluton that are randomly oriented, and internal compositional contacts of the pluton that are nonplanar (Best, 1963; Paterson and others, 1991). These data argue that the present configuration reflects a frozen magma chamber that has not been internally disrupted while below the solidus.

We prefer a "wall drape" model to explain the variation in the orientation of the layering within the GIC (see Fig. 7 below). We envision the GIC as a vertically zoned magma chamber in which the igneous layering formed during crystallization along the walls and floor of the intrusion, their geometry mimicking the curvature of the bottom of a large, but shallow, container, which was later tilted, uplifted, and eroded. In this model, after moderate tilting of the GIC, steep dips would be found at the base of the pluton and shallower dips near the top, as depicted in Figure 7 and as observed in the field (Fig. 3).

Layering in intrusions is now thought to form by a variety of mechanisms, including flow differentiation (Komar, 1972), intrusion of multiple magmatic pulses (Hardee, 1982; Husch, 1990), and postcumulus processes (Sparks and others, 1985), as well as by the better recognized processes of sidewall crystallization, convection, and crystal settling. Turner and Gustavson (1981) and Swaka and others (1990), among others, specifically point out that some of these processes can form compositional layers at low angles to the walls of igneous bodies. We have not examined the layering in the GIC carefully enough to distinguish by which mechanism(s) they formed but wish to emphasize that the wide variation in orientation of compositional layers in the GIC indicates that some of the layers could *not* have formed parallel to paleohorizontal.

Tectonic Interpretation of Paleomagnetic Results. The interpretation of paleomagnetic directions from any pluton is complicated by the general lack of paleohorizontal markers. Thus, when comparing the characteristic magnetization direction in a pluton to a reference direction, two end-member scenarios can explain any observed deflection from expected directions. The anomalous direction was caused by either (1) latitudinal translation and vertical axis rotation of the pluton and wall rocks or (2) tilting of the pluton, where the tilt axis is commonly assumed to be horizontal (for example, Irving and others, 1985). Clearly, a combination of these processes can occur.

To evaluate these models, we need to compare the mean paleomagnetic direction in the GIC to the appropriate paleomagnetic reference pole for North America. Late Jurassic time was a period of rapid apparent polar wander (APW), and therefore it is important to first assess the cooling history of the pluton in order to choose the best reference pole. Three 151 Ma Pb/U zircon ages from the GIC (Saleeby and others, 1989) record crystallization of the pluton through the closure temperature for zircon, which is thought to be around 750 °C. There is also a 144 Ma $^{40}Ar/^{39}Ar$ age on a biotite separate from the intersection of the BMFZ and the southwestern margin of the GIC (Saleeby and others, 1989). This age may reflect cooling of the base of the

TABLE 2. PALEOMAGNETIC DIRECTIONAL DATA FOR THE LOW-TEMPERATURE COMPONENT IN THE GIC

Site	Lat. (°N)	Long. (°E)	N	R	α_{95}	k	I	D
1	37.410	239.875	6/6	5.95941	6.1	123.2	58.8	330.5
2	37.412	239.873	6/6	5.87294	10.8	39.4	72.1	18.4
3	37.413	239.880	5/6	4.91453	11.3	46.8	69.2	0.7
4	37.418	239.885	6/6	5.82442	12.8	28.5	62.8	1.8
6	37.422	239.890	6/6	5.95744	6.2	117.5	55.3	344.8
7	37.430	239.900	5/6	4.94373	9.1	71.1	58.8	3.4
8	37.439	239.915	6/6	5.96199	5.9	131.5	48.9	344.8
11	37.449	239.929	4/6	3.91587	15.6	35.7	66.4	8.9
12	37.464	239.930	4/6	3.71827	29.5	10.6	43.7	353.1
13	37.471	239.927	5/6	4.98235	5.1	226.6	61.9	3.3
14	37.470	239.927	6/6	5.87409	10.8	39.7	53.8	2.0
Mean	37.436	239.903	11	10.71757	6.1	57.4	59.8	355.7

Note: Lat., latitude; Long., longitude; N, number of samples used for site mean direction out of total number of samples collected at a locality; I, *in situ* inclination; D, *in situ* declination. Unlisted sites either did not exhibit this component or, within the site, the component was poorly defined. The mean of the virtual geomagnetic poles (VGPs) from each site is Lat. = 84.9°N; Long. = 207.6°E; α_{95} = 7.8°; K = 35.4; R = 10.71757; N = 11.

TABLE 3. PALEOMAGNETIC DIRECTIONAL DATA FOR THE HIGH-TEMPERATURE COMPONENT IN THE GIC

Site	Lat. (°N)	Long. (°E)	N	R	α_{95}	k	I	D	P
1	37.410	239.875	6/6	5.98812	3.3	420.8	53.1	258.0	N
2	37.412	239.873	6/6	5.64665	18.5	14.2	59.7	287.8	N
3	37.413	239.880	6/6	5.91120	9.0	56.3	61.6	272.8	N
4	37.418	239.885	6/6	5.99638	1.8	1379.3	56.4	277.9	N
5	37.419	239.888	6/6	5.91936	8.6	62.0	55.7	295.9	N
6	37.422	239.890	4/6	3.93921	13.2	49.4	58.5	284.0	N
7	37.430	239.900	6/6	5.98550	3.6	344.7	53.2	268.4	N
8	37.439	239.915	6/6	5.87277	10.8	39.3	42.5	275.6	N
9	37.444	239.925	6/6	5.99616	1.9	1302.4	−51.6	102.8	R
10	37.446	239.928	6/6	5.94824	6.9	96.6	51.5	271.8	N
11	37.449	239.929	2/6	1.98479	31.3	65.7	58.0	292.1	N
13	37.471	239.927	5/6	4.99781	1.8	1823.0	−51.1	105.2	R
Mean	37.431	239.901	12	11.89250	4.3	102.3	54.8	279.1	—

Note: Lat., latitude; Long., longitude; N, number of samples used for site mean direction out of total number of samples collected at a locality; I, *in situ* inclination; D, *in situ* declination. The first number in the N column is the number of samples within a site that exhibited this component, and the number after the slash is the total number of samples in the site. Unlisted sites either did not exhibit this component or, within the site, the component was poorly defined. P stands for polarity, and our interpreted polarity is listed: N = normal and R = reverse. The mean of the virtual geomagnetic poles (VGPs) from each site is Lat. = 27.2°N; Long. = 175.5°E; α_{95} = 5.4°; K = 65.8; R = 11.83281; N = 12.

GIC through the argon closure temperature for biotite (~300 °C) but also might reflect cooling of this part of the BMFZ (Tobisch and others, 1989). A less reliable K/Ar date of 139 Ma (recalculated by Schweickert and others, 1984) on biotite from near the center of the GIC was published by Curtis and others (1958). These data indicate that the GIC cooled through the blocking temperature for titanium-poor titanomagnetite sometime between 151 and 144 Ma. If the pluton remained at temperatures close to the magnetite blocking temperature for millions of years, the magnetization may have been acquired below short-term unblocking temperatures (Pulliah and others, 1975).

A simple estimate of the cooling history of the GIC suggests that the magnetization was acquired closer to 145 Ma than to 150 Ma. If the intrusion was at ~750 °C at 151 Ma and cooled at 75 °C/m.y. (Paterson and Tobisch, 1992), then the pluton would cool through the blocking temperature of magnetite around 148 Ma. The rate of cooling likely decreased with time, however, tending to make the age of the final locking in of magnetization slightly younger. Therefore, we argue that the magnetization was locked in at ~146 Ma.

We compare the paleomagnetic direction in the GIC to three Late Jurassic reference poles for North America favored by May and Butler (1986), to infer the amount of latitudinal transport and vertical axis rotation of the GIC (Table 4). These reference poles are the Glance Conglomerate pole, which is dated by the Rb/Sr method as 151 ± 2 Ma; the Lower Morrison pole, which has an early Tithonian age (~149 Ma); and the Upper Morrison pole, which has a late Tithonian age (~145 Ma). Comparison of the characteristic remanence in the GIC to the favored Upper Morrison pole indicates no significant latitudinal transport and a counterclockwise rotation of 52° ± 6°. Comparison to other reference poles indicates minor southward displacement and a similar amount of rotation. Although we do not have data to assess the validity of the inferred latitudinal transport, there are no indications of significant vertical axis rotations in the vicinity of the GIC. Volcanic and sedimentary rock units strike into the GIC from both the northwest and the southeast, with only minor deflection near the intrusion. Ductile structures and associated kinematic indicators near the GIC are compatible with northeast-southwest–directed contraction and not with large vertical axis rotations. Removal of 52° of counterclockwise rotation would reorient the pluton long axis, internal layering and contacts, and volcanics to a strike of N 40° E, unlike the orientations of all other regionally developed structures in the Foothills Terrane.

We can assess the possibility that the GIC was tilted about a horizontal axis by comparing the orientation of possible tilt axes from the paleomagnetic data to our structural, petrological, and metamorphic data. We compare the paleomagnetic direction in the GIC to the same three Late Jurassic reference poles discussed above and assume that the tilt axis is horizontal (Fig. 6 and Table 5). As can be seen in Figure 6 and Table 5, the earlier that the magnetization was acquired, the more east-west trending is the inferred tilt axis; conversely, the later the magnetization was acquired, the more northwest-southeast trending is the inferred tilt axis. No matter which reference direction is used, the amount of tilt for the GIC remains constant at ~30° up-to-the-southwest. As noted above, we favor the interpretation that the GIC cooled through the blocking temperature of magnetite around 146 Ma. Therefore, the inferred amount of tilt is 29° up-to-the-southwest about a horizontal axis trending 311° (Table 5). This axis and amount of tilt are very similar to the ~30° up-to-the-southwest tilt about an axis oriented ~325° ± 10° that was inferred from the structural data (Table 1).

We conclude that the paleomagnetic data are most consistent with geological data if the GIC was tilted as a single entity 30° up-to-the-southwest. Because the geologic and paleomagnetic data agree closely in the amount and direction of tilt, this precludes the need to call upon large latitudinal transport of the Foothills Terrane with respect to North America after ~146 Ma.

How and When Did Tilting of the GIC Occur? We believe that tilting of the GIC occurred during the northwest-southeast contraction that formed the slatey cleavage in the Foothills Terrane. If tilting occurred after cleavage development, then a domain of southwest-dipping cleavage should exist near the pluton, but this is not observed (Paterson and others, 1991). The timing of cleavage development around the GIC is limited by the ages of deformed plutons (151–147 Ma), $^{40}Ar/^{39}Ar$ ages from syncleavage metamorphic biotite and hornblende (147–137 Ma), and a late syncleavage pluton dated at 123 Ma (Saleeby and others, 1989; Tobisch and others, 1989; Paterson and others, 1991). Our best estimate

TABLE 4. INFERRED DISPLACEMENT AND ROTATION FOR THE GIC ASSUMING IT WAS NOT TILTED

Pole	Age	Age (Ma)	Displacement (°N)	Rotation (°CW)
Upper Morrison*	Late Tithonian	145	3.0 ± 5.2	−52.3 ± 6.5
Lower Morrison	Early Tithonian	149	−6.8 ± 5.3	−48.0 ± 6.4
Glance Conglomerate	Rb/Sr	151 ± 2	−10.5 ± 6.5	−52.1 ± 7.5

*Favored reference pole.

Note: The uncertainty of the displacement and rotation are calculated using the methods of Demerest (1983), using the factor C = 0.78 consistently. The mean site latitude is 37.44°N, and longitude is 239.91°E. Reference poles used are from May and Butler (1986). CW stands for clockwise.

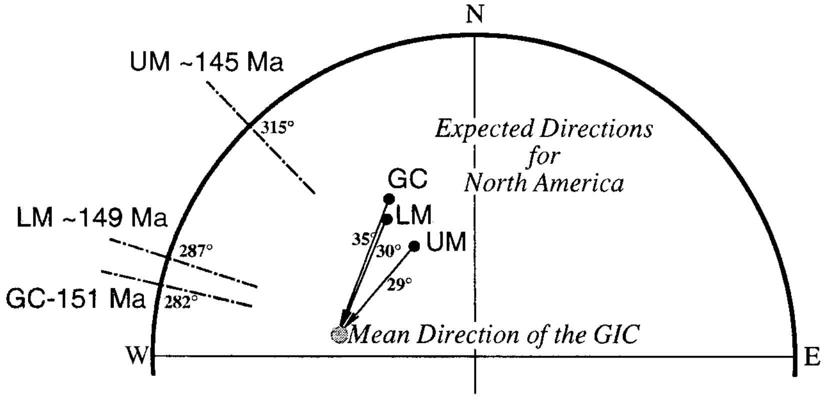

Figure 6. Stereogram of the mean direction of the GIC and calculated expected directions for North America for the interval from 151 to 145 Ma. Abbreviations for the expected directions for North America refer to the reference pole they were calculated from: GC = Glance Conglomerate; LM = Lower Morrison; UM = Upper Morrison (May and Butler, 1986). Dot-dashed lines depict the inferred horizontal tilt axes about which the expected direction for North America can be brought into concordance with the observed paleomagnetic direction in the GIC. The small numbers near these lines give the trend of the tilt axis. The small numbers near the arrows give the amount of tilt. Data are listed in Table 5. Our preferred interpretation is that the magnetization was acquired around 145 Ma, and thus the Upper Morrison pole should be used.

of the time when most of the cleavage formed and by inference the minimum age of tilting of the GIC is ~135–145 Ma (for example, Tobisch and others, 1989).

We contend that the BMFZ, a northeast-dipping fault zone with dominantly reverse motion (Miller and Paterson, 1992), was the likely structure along which the tilting was accommodated because (1) it is a large shear zone that extends both northwest and southeast of the GIC, (2) it bounds the pluton on the southwest side, and (3) geologic evidence indicates that it was active during and after emplacement of the GIC (Tobisch and others, 1989; Saleeby and others, 1989). There are several mechanisms by which the GIC may have been tilted. If the BMFZ is listric at depth (Cady, 1975; Miller and Paterson, 1992), then reverse motion would have caused the GIC, which lies in the hanging wall of the fault, to be tilted southwest-side up. Alternatively, heterogeneous crystal-plastic flow of material up the BMFZ, which is indicated by increasing intensities of strain towards the base (western edge) of the BMFZ (Paterson and others, 1989), could also have induced tilting of the GIC whether or not the BMFZ is listric. Finally, and the most likely to us, regional northeast-southwest contraction could have caused the BMFZ, which prior to cleavage formation had a shallower dip (Paterson and others, 1989), to rotate to its present steep dip. Continued southwest-directed movement in the fault zone plus rotation of the fault caused the hanging wall and GIC to rotate. At the present time, we are unable to distinguish between these hypotheses, because little direct information is available about the nature of the BMFZ at depth and because the strong northeast-southwest contractional event overprinted any existing older structures.

TABLE 5. POSSIBLE TILT AXES FROM PALEOMAGNETIC DATA FOR THE GUADALUPE IGNEOUS COMPLEX

Pole	Age	Age (Ma)	Lat. (°N)	Long. (°E)	α_{95}	Inc.	Dec.	Tilt	Axis
Upper Morrison*	Late Tithonian	~145	67.6	161.9	3.9	58.0	331.5	29°	311°
Lower Morrison	Early Tithonian	~149	61.4	142.3	4.2	47.8	327.2	30°	287°
Glance Conglomerate	Rb/Sr	151 ± 2	62.7	131.5	6.3	43.2	331.3	35°	282°

Guadalupe mean direction: Dec. = 279.1°, Inc. = 54.8°

*Favored interpretation.

Note: Late Jurassic reference poles for North America and their expected directions at the mean site latitude and longitude are listed. Data are from May and Butler (1986). The inferred orientation of a horizontal tilt axis that restores the observed direction in the GIC, with the expected direction for North America, and the amount of tilt (southwest side up) are also listed. Our preferred interpretation is that the magnetization was acquired around 145 Ma, and thus the data should be compared to the Upper Morrison pole.

Crustal Thickening and Burial

Paterson and others (1991) argued that the tops of the GIC and other Late Jurassic plutons in the Foothills Terrane were emplaced at shallow depths, probably between 2–6 km. The narrow high-T/low-P aureoles, local hypabyssal textures within dikes and higher compositional units in the pluton, the low grade of regional metamorphism, and the presence of overlying volcanic rocks adjacent to and east of the GIC all support the contention that the top of the GIC was intruded at shallow crustal levels. Paterson and others (1989) argued that strains associated with cleavage formation, continued folding, and continued reverse movement on faults caused the crust in the Foothills Terrane to more than double in thickness between 151 and 123 Ma. After this deformation had largely ceased (Saleeby and others, 1989; Tobisch and others, 1989), a suite of early Cretaceous plutons (123–110 Ma) was emplaced; these plutons are now exposed at the same crustal level as the GIC. Metamorphic assemblages in wider, dynamothermal aureoles around the Early Cretaceous plutons and pressures of 3–4 kbar based on the Al-in-hornblende barometer (Ague and Brimhall, 1988) indicate that these plutons were emplaced at depths of 10–14 km. Because one of these plutons intruded the eastern part (top) of the GIC, and because timing relations indicate that crustal thickening occurred after emplacement of the GIC, we argue that the GIC was also buried to depths of 10–14 km by 110 Ma. This crustal thickening and burial of the GIC occurred simultaneously with tilting.

Late Cretaceous Uplift

The fact that the Late Jurassic and Early Cretaceous plutons are now exposed at the Earth's surface attests to uplift and erosion of 10–14 km. Many workers have noted the close compositional links between Late Jurassic to Cretaceous sedimentary rocks in the Great Valley sequence and rocks in the Sierra Nevada and thus have argued for Mesozoic uplift and erosion of the Sierra Nevada (Dickinson, 1981; Ingersoll, 1978). More specifically, Bateman and Wahrhaftig (1966) noted that the Eocene Ione Formation and locally older units lie unconformably on the Bass Lake intrusive suite, the Early Cretaceous pluton that intrudes the GIC. Estimates of the ages of the oldest units above this unconformity indicate that the Bass Lake intrusive suite and this part of the Foothills Terrane were exposed by 75 Ma and possibly as early as 95

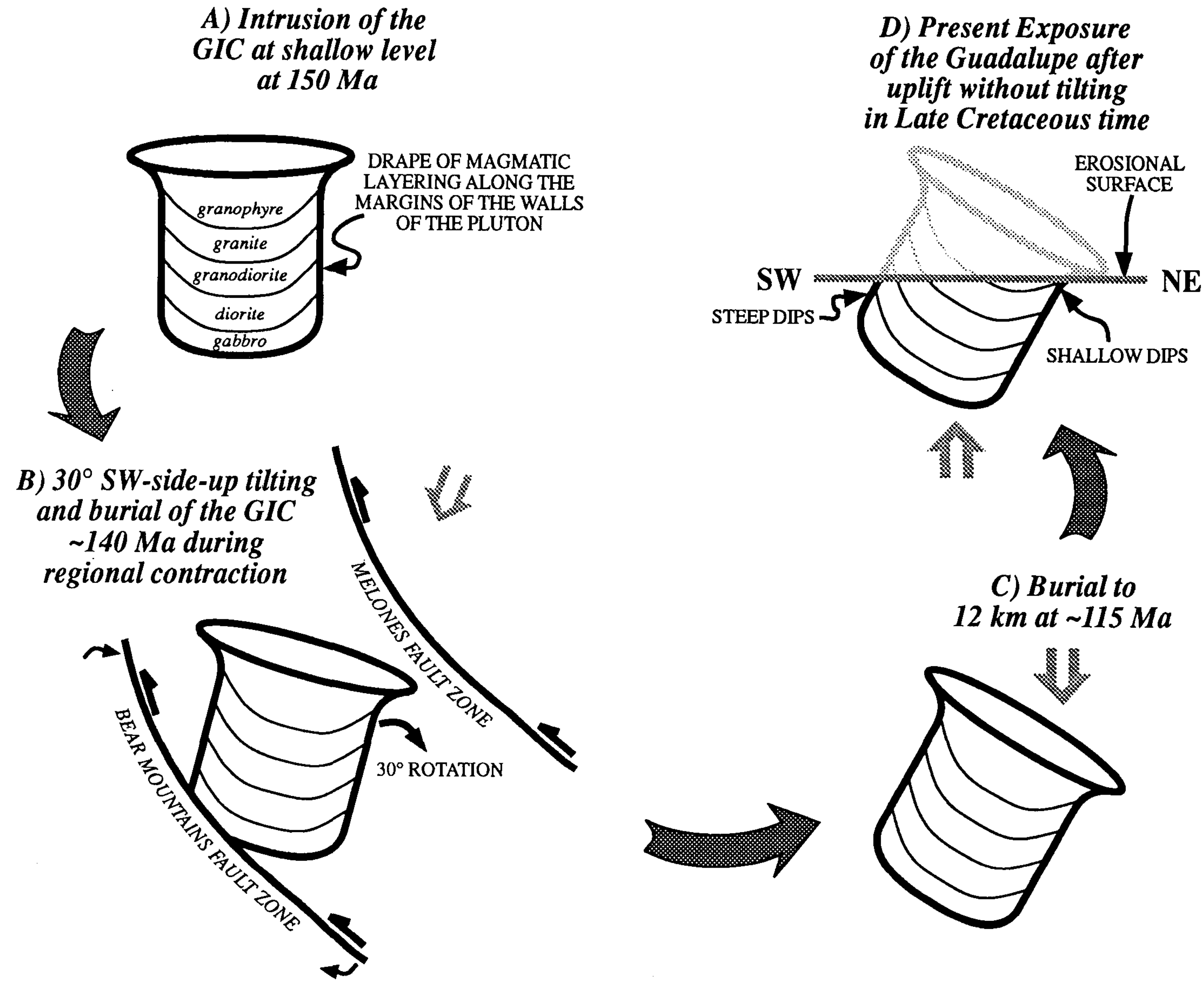

Figure 7. Cartoon summary of the structural history of the GIC. Pluton is depicted as a flat beaker with layers draping along beaker sides.

Ma (Bateman and Wahrhaftig, 1966). This unconformity and overlying units are still preserved short distances (8 km) to the west of the GIC.

A small amount of northeast-side–up tilt of the Sierra Nevada is indicated by both geomorphic (Huber, 1981, 1990) and geophysical evidence (Chase and Wallace, 1986). The amount of tilt inferred by these studies, however, is very small, ~1.2° in the last 10 m.y. or ~1.9° in the last 50 m.y., calculated by Huber (1981). These data are consistent with a paleomagnetically undetectable amount of tilt of the Cretaceous Sierra Nevada batholith (Frei, 1986). Paleomagnetic data from mid-Cretaceous intrusions in the central part of the batholith do not have directions that are scattered about an axis parallel to the trend of the Sierras and are not easily interpreted in terms of tilting of the batholith. Therefore, the uplift and erosion of the GIC and Foothills Terrane in Late Cretaceous time occurred without paleomagnetically detectable tilting.

IMPLICATIONS OF GIC HISTORY

Removal of 30° southwest-side–up tilt brings most of the internal contacts within the GIC back to approximately horizontal along with bedding in the overlying volcanic rocks. In this configuration, the GIC consists from bottom to top of a large ductile shear zone, local migmatite in amphibolite-grade wall rocks, layered gabbro, diorite, mingled diorite and granite, granophyres, and overlying felsic volcanic rocks and slate and graywacke (Best, 1963; Paterson and others, 1991). Cumulate-like layering in the gabbro was subhorizontal at some localities, but layering dipping 30° to 40° was common. Felsic and mafic dikes in the GIC have variable orientations from subhorizontal to subvertical. These features describe a frozen, vertically zoned, fractionated magma chamber (Best, 1963). We see no evidence of a "dioritic cap" as suggested by Best (1963) and instead argue that his "agmatite" represents magma mingling between fractionated magma and mafic dikes. Much of the overlying volcanic sequence must have been eroded away, the de-

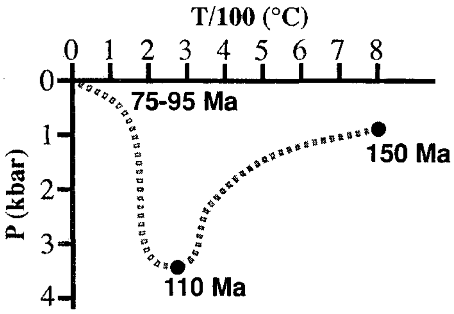

Figure 8. A pressure-temperature-time path for the geologic history of the GIC. Dashed line is intended only as a guide for the reader's eye between data points.

tritus now residing in the volcanic-rich Mariposa Formation (Bogen, 1983) or in the Great Valley sequence.

We propose a four-stage history for the GIC as follows (Fig. 7): (1) the pluton was emplaced in the hinge of a fold at 151 Ma, during which time fractionation and side-wall crystallization caused vertical compositional zoning and draping of layers in the magma chamber (Fig. 7A); (2) the pluton was subsequently tilted in the interval between 145–135 Ma by simultaneous reverse movement and rotation of the eastern hanging wall along a listric or steepening Bear Mountains fault zone (Fig. 7B); (3) during and for a short while after tilting, the GIC was buried to depths of 10–14 km (Fig. 7C); and (4) the pluton was uplifted without major tilting and was exposed between 75 and 95 Ma. Figure 8 shows an estimated pressure-temperature-time path for the geologic history of the GIC. This history shows that the top of the pluton was intruded near the Earth's surface, buried to 3–4 kbar at 110 Ma, and uplifted and exposed in Late Cretaceous time.

The GIC is thus an example of a pluton that (1) has been emplaced during folding (Paterson and others, 1991); (2) has resided in wall rocks that subsequently underwent continued folding, faulting, and cleavage development; (3) has been tilted by 30°; and (4) has been uplifted and eroded *without* developing any widespread solid-state fabrics within the pluton. The southwestern margin of the pluton does show strong deformation within about 100 m of the contact where the BMFZ is adjacent to the GIC. The remainder of the pluton, however, lacks solid-state foliations, folds, and throughgoing faults and has only minor microstructural evidence of solid-state deformation (undulatory extinction in quartz, kinking in biotite). Minerals generally have igneous microstructures, although some static recrystallization has occurred, possibly due to late fluid flow during cooling of the pluton (Best, 1963). Apparently, plutons should not always be viewed as static, nondeformed bodies simply because the plutons do not appear deformed.

Others have argued that motion along faults makes space for plutons in zones of local extension. Such emplacement models do not work for the GIC for the following reasons: (1) the only recognized fault near the GIC is the BMFZ, which passes by this pluton without any bending or step-over; (2) the northern, eastern, and southern margins of the GIC show no evidence of faulting and are often discordant at the scale of individual exposures; (3) randomly oriented mafic enclaves are widespread in the GIC, sometimes occurring within a few meters of the contact; (4) there are no magmatic or solid-state foliations within the GIC outside of the BMFZ, and layering occurs only in the gabbro unit—the randomly oriented enclaves and lack of foliations argue against synemplacement shearing; (5) the GIC would have to consist of numerous sheets, as rates of fault motion only allow small batches of magma to be emplaced at any one time, and would require that adjacent units remain above the liquidus for long periods of time, as there is extensive magma mingling between units (there is no evidence of this); and (6) more-evolved magmas would continuously have to be emplaced farther east than less-evolved magmas (for chemistry, see Best, 1963), although there is no evidence that fault motion also migrated to the east.

If our interpretation of tilting is correct, then it argues against any paleomagnetically detectable north-south displacement (≥1,000 km) of the Foothills Terrane after 146 Ma with respect to North America. This places a maximum limit on the total amount of post-146 Ma strike slip on all faults between the Foothills Terrane and the craton. The tilt interpretation also argues against significant normal motion caused by horizontal extension on the BMFZ or for strike-slip motion as has been suggested for parts of the Foothills Terrane. In fact, we see no evidence in this part of the Foothills Terrane that requires extension at any time between 160 Ma and 130 Ma.

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