Geology and paleomagnetism of El Potrero pluton, Baja California: Understanding criteria for timing of deformation and evidence of pluton tilt during batholith growth

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Abstract

The 102 Ma El Potrero pluton, in the western foothills of Sierra San Pedro Mártir, in north-central Baja California, was emplaced during a long period of contractional deformation bracketed between 132 and 85 Ma that affected this segment of the Peninsular Ranges Batholith. The pluton records regional and emplacement related deformation manifested by: (1) a solid-state fabric developed on its eastern contact, which is produced by eastward lateral pluton expansion; (2) cleavage triple point zones in the host-rock NW and SE of the pluton; (3) subhorizontal ductile shear zones indicative of top-to-the-east transport; (4) magmatic and tectonic foliations parallel to regional structural trends and regional shear zones; (5) variable axial ratios of microgranitoid enclaves close to pluton–wall rock contacts; (6) evidence of brittle-emplacement mechanisms in the western border of the pluton, which contrast with features indicating mainly ductile mechanisms toward the east; and, (7) markedly discordant paleomagnetic directions that suggest emplacement in an active tectonic setting. The overall mean for 9 accepted paleomagnetic sites is Dec=34.6°, I=25.7° (k=88.3, α95=5.5°), and is deviated ∼35° with respect to the reference cratonic direction. This magnetization is interpreted to indicate a combination of tilt due to initial drag during vertical diapiric ascent (or westward lateral-oblique expansion) of the adjacent San Pedro Mártir pluton and later rotation (∼15°) by Rosarito Fault activity in the southwest; this rotation may have occurred as eastward contraction acted to fill the space emptied by the ascending San Pedro Mártir pluton. The Rosarito fault may have tilted several plutons in the area (Sierra San Pedro Mártir, El Potrero, San José, and Encinosa). Magnetic susceptibility fabrics for 13 sites reflect mostly emplacement-related stress and regional stress. Paleomagnetic data and structural observations lead us to interpret the El Potrero pluton as a syntectonic pluton, emplaced within a regional shear zone delimited by the Main Mártir Thrust and the younger Rosarito Fault.

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Keywords: Paleomagnetism; Magnetic fabric; Batholith; Peninsular Ranges; Baja California; Emplacement mechanisms

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1. Introduction

In an orogenic setting, pluton fabrics and geochronology are commonly used in the interpretation of temporal relations between deformation and magmatism. These interpretations are based on the relationships between structural features in the pluton (its interior and its margins) and structural features in the host rock (Brun and Pons, 1981; Paterson and Tobisch, 1988; Paterson et al., 1991; Vernon and Paterson, 1993; Paterson and Vernon, 1995; Paterson et al., 1998; Johnson et al., 1999a; Johnson et al., 2003; Vernon et al., 2004). Plutons can thus be interpreted as pre-, syn-, or post-tectonic. In the Peninsular Ranges Batholith (PRB) of Baja California these observations have been used to suggest that collision of the Alisitos arc with continental rocks of North American affinity took place ca. 110 Ma (Johnson et al., 1999b, 2003). The inferred suture zone between an eastern arc developed on continental crust (North America) and a western oceanic arc terrane (Alisitos) was located between Sierra San Pedro Mártir (SSPM) pluton and the smaller El Potrero and San José plutons (Fig. 1), along the Main Mártir thrust (MMT) of Johnson et al. (1999b). These authors suggested that the non terminal suture is thus stitched by 100–110 Ma tonalitic plutons, but shortening in the continental margin was apparently continuous from about 132 Ma to about 85 Ma (Schmidt and Paterson, 2002).

Because of the complex interaction between magma emplacement and regional tectonic stress, fabric interpretations in plutons may be ambiguous (Paterson and Tobisch, 1988; Vernon and Flood, 1988; Vernon et al., 1988; Paterson et al., 1991). Here we propose that paleomagnetic data, magnetic fabrics, and geochronological data may provide independent tools to assess interpretations of pluton–host rock relations, and better define timing criteria for regional deformation events. The ambiguity of pluton fabrics and inferred reorientation of tectonic fabrics in the host rock by pluton emplacement is evident, for instance, in and around the Encinosa pluton (Fig. 1). The Encinosa pluton, immediately west of El Potrero in the western foothills of Sierra San Pedro Mártir (SSPM), is apparently syntectonic with characteristics of either a pre- or post-tectonic pluton. This is ca.

Fig. 1. Plain view of plutons — simplified geologic map of a segment of Sierra San Pedro Mártir. SSPMP = Sierra San Pedro Mártir pluton; SJ San José pluton; CC = Cerro Costilla pluton; E = Encinosa pluton; PP: El Potrero pluton; RF = Rosarito fault; MMT = Main Mártir thrust; GE = Gulf escarpment. The dashed line shows the transition zone between the western and eastern sectors of the PRB. A solid line shows the approximate position of the cross section illustrated in Fig. 8. Thin arrows indicate assumed directions of pluton expansion.Inset: simplified map of the Peninsular Ranges batholith, showing location of the study area. The dashed line separates the eastern and western sectors of the PRB.
110 Ma mafic pluton was emplaced during the peak of contractional deformation, yet it fails to record significant deformation fabric. Also, contacts of the Encinosa pluton show a highly discordant relation to structural features in the host rock—a characteristic typical post-tectonic plutons (Paterson and Tobisch, 1988).

In this work we show that the El Potrero pluton (Fig. 1), between Encinosa and SSPM plutons, experienced a large magnitude rotation (∼15–20°) and fault rotation during activity of the Rosarito fault (∼15–20°) between ∼100 and 85 Ma. We review relevant structural observations and timing of deformation criteria, and conclude that the El Potrero pluton is better viewed as a syntectonic intrusion. We reject that tilting of the El Potrero pluton could be due solely to Tertiary extensional or transpressive tectonics, because major Tertiary normal faults do not occur near the pluton, nor has significant lateral displacement been proposed for major structures in the study area. Furthermore, no large tilting has been recorded in older plutons located west from the Rosarito fault zone (i.e. San Telmo, Zarza and Burro plutons; Böhnel and Delgado Argote, 2000; Molina-Garza et al., 2003). We propose that the Rosarito fault together with the MMT define a wide shear zone where tilted plutons occur (Molina-Garza et al., 2003), and we propose that these faults alternate their activity between 115 and 85 Ma.

2. Geological setting

Mesozoic rocks in Baja California record magmatism and sedimentation along a convergent margin that faced a large ocean basin (Busby et al., 1998). Volcanic, volcaniclastic and sedimentary rocks of the arc are represented by the Alisitos Formation. Plutonic rocks included in the Peninsular Ranges Batholith intrude the Alisitos Formation as well as pre-Alisitos Paleozoic and lower Mesozoic rocks of the North American margin, and represent deeper crustal levels of the Alisitos arc. The PRB is traditionally divided into an older western sector of isotopically more primitive subvolcanic plutons and an eastern sector of larger, more evolved plutons. The distinction is evident in the geochemistry, structural history, host-rock and level of crustal exposure (Todd and Shaw, 1985; Silver and Chappell, 1988; Todd et al., 1988; Walawender et al., 1991; Gastil, 1993; Thompson and Girty, 1994; Ichinoise et al., 1996; Johnson et al., 1999b; Tate and Johnson, 2000; Schmidt and Paterson, 2002). The transition zone between the eastern and western PRB sectors is several kilometers wide and includes the study area (Fig. 1, inset).

Most interpretations consider the boundary between the eastern and western belts of pre-batholith rocks to be a suture between the North American craton and a fringing arc, possibly separated by a back-arc basin (Rangin, 1978; Gastil et al., 1978, 1981; Phillips, 1993; Busby et al., 1998). Alternatively, the batholith may have formed in-situ across a poorly understood, pre-Triassic suture between oceanic and continental crust (Walawender et al., 1991; Thompson and Girty, 1994). Johnson et al. (1999b) described a major ductile thrust (Main Mártr Thrust, MMT), which they interpreted as part of a broad suture. This thrust is coincident, in the area, with the boundary between the eastern and western PRB proposed by Gastil et al. (1975). Johnson et al. (1999b) suggested that an island arc (Alisitos arc) collided with the North American margin approximately 110 Ma. In their model, this collision caused substantial crustal thickening near the boundary between the two crustal blocks, and this thickened zone was stitched by tonalite plutons such as San José, Cerro de Costilla, and El Potrero plutons; all of them emplaced at ca. 110–100 Ma (Johnson et al., 1999b). This model has been supported by other workers (Wetmore et al., 2003).

The Rosarito fault juxtaposes sedimentary units of the Alisitos Formation with the western volcanic-rich domain of the same unit. It is a steep to moderately NE dipping fault zone active as late as 85 Ma (Schmidt and Paterson, 2002). The fault zone is characterized by steep, NE dipping, spaced to locally penetrative cleavage, shear bands and discrete chloritized faults with predominantly NE over SW shear sense. In the study area, the MMT and the Rosarito fault define the transition between the western and eastern sectors of the PRB (Fig. 1).

3. Methodology and sampling

The present work is based on photo-interpretation and mapping (1:20,000) of an area of ~140 km² that includes the El Potrero, Encinosa, Santa Cruz, and parts of San José and Sierra San Pedro Mártir plutons (Fig. 1; Chávez-Caballo, 1998). It also includes petrographic analysis of ~30 samples from El Potrero and Encinosa plutons, from which modal compositions were determined (van der Plas and Tobi, 1965). Samples were also collected for micro-structural analysis, from both El Potrero pluton and its host rock, with a few additional samples from nearby plutons. Four oriented samples of lithic tuffs from
host-rock of the El Potrero were used for finite deformation analysis. The methodology for characterization of deformation in the host-rock involved undeformed and deformed samples. At about 200 stations in the El Potrero pluton and its surrounding area, foliation orientations were determined. In the case of the stations used for finite-deformation analysis, samples were prepared with faces parallel to the direction of maximum particle elongation, and perpendicular to it. Counting, orientation, and size were estimated for lithic particles in lithic-rich tuffs. We used standard imaging and analysis programs to estimate ellipticity and other fabric parameters. Samples for finite deformation analysis come from the cleavage triple point zone northwest of the pluton, from the western and eastern sides of the pluton (~50 m from the pluton–wall rock contact), and from a few meters west of the MMT located between El Potrero and SSPM plutons (Fig. 2).

For paleomagnetic and magnetic fabric analysis we collected samples from 13 sites; 10 sites are along the road that crosses the pluton from north to south, two additional sites near its western contact, and a single site located in the east-central segment of the pluton. Samples for \(^{40}\text{Ar}–^{39}\text{Ar}\) dating were collected at every other paleomagnetic site (Fig. 2), but the results of these analyses will be published elsewhere. Five to eight paleomagnetic samples were collected from each site using a portable gas powered drill, and oriented in-situ using magnetic and solar compasses. The samples were cut as standard cylinders 2.1 cm in height, and were subjected to alternating field (AF) and thermal demagnetization up to 200 mT and 500 °C, respectively. We used a JR-5 spinner magnetometer for measurements of the natural remanence; a TSD-25 thermal demagnetizer and a custom high voltage AF demagnetizer were used during the demagnetization process. Susceptibility was monitored during thermal demagnetization in order to recognize mineralogical changes, which were unimportant. For the identification and characterization of magnetic minerals we imparted an isothermal remanence (IRM) and estimated hysteresis parameters, using a pulse magnetizer and a vibrating sample magnetometer, respectively. Magnetic fabric was determined using a KLY-3 Kappabridge susceptibilimeter on specimens not subjected to demagnetization. At each station we collected structural, petrological, and other relevant data; additional hand samples were obtained for geobarometry and geochronology. Equilibrium emplacement pressures were determined using Schmidt’s Al in hornblende geobarometer (Schmidt, 1992). Per-formula total Al was determined on polished sections using a Cameca microprobe at the Instituto de Geofísica (Mexico City).

Geochronological data were obtained from biotite and hornblende separates of a sample in the central part of the pluton, because U–Pb data are already available for this area (Johnson et al., 1999b). These minerals were concentrated and cleaned by standard techniques and later selected by careful handpicking under a binocular microscope to ensure the purity of the samples. Sample fractions ranged in size from 40 to 80 mesh, and were obtained at the mineral separation laboratory of the Centro de Geociencias (Querétaro, Mexico). Mineral separates were loaded into Al-foil packets and irradiated together with Mac-83 biotite as a neutron-flux monitor at the McMaster Nuclear Reactor (Hamilton, Ontario). \(^{40}\text{Ar}–^{39}\text{Ar}\) analyses were performed by standard laser step-heating techniques, described in detail by Clark et al. (1998), at the \(^{40}\text{Ar}–^{39}\text{Ar}\) Geochronology Research Laboratory of Queen’s University, Kingston, Ontario, Canada. The data are given in Table 1 and plotted in Fig. 3. Data have been corrected for blanks, mass discrimination, and neutron-induced interferences. For the purposes of this paper, a plateau age is obtained when the apparent ages of at least three consecutive steps, comprising a minimum of 55% of the \(^{39}\text{Ar}\) released, agree within 2σ error with the integrated age of the plateau segment. Errors shown in Table 1 and on the age spectrum and isotope-correlation diagrams represent the analytical precision at ±2σ.

4. Geology and structural features of El Potrero pluton

The El Potrero pluton intrudes volcanlastic rocks of the Alisitos Formation (Fig. 1) in the transition zone between the eastern and western sectors of the PRB. The most abundant lithologies in the Alisitos Formation are phyllites and low-grade metavolcanic rocks. Volcanic rocks include pyroclastic rocks, lithic tuffs, and porphyritic lavas. Limestone, sandstone, shale, breccia and agglomerate are locally present. The El Potrero pluton is an oval shaped pluton elongated in a north–south direction, with a crystallization age of about 102.5 Ma (U–Pb zircon, Johnson et al., 1999b). The pluton borders are much more regular compared to the adjacent Encinosa pluton (Fig. 2). Compositionally, the El Potrero pluton is very homogenous, but petrographic observations indicate that it consists of a hornblende–biotite tonalite in the northeast half of the pluton and a biotite–hornblende tonalite in the southwest half (Chávez-Cabello, 1998). The mineral assemblage for both units is plagioclase+quartz+hornblende+biotite.

Dikes within the El Potrero pluton are scarce; they vary from mafic to aplitic, and are concentrated in the northeast
Fig. 2. (a) Generalized trend lines of foliation at El Potrero and vicinity. (b–e) Contoured density plots of foliation data for host rock (b–d) and magmatic foliation (e). Magmatic is only discordant to foliations in deformation shadows such as the triple point area northwest of the pluton. We also show paleomagnetic sampling sites (open circles) and locations of samples used for finite strain analysis (hexagons).
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</table>

**Isotope correlation date** = 97.55± 97.78

Initial \(^{40}\)Ar/\(^{36}\)Ar ratio = 347.91± 1704.13

MSWD = 0.47

%\(^{39}\)ArK for CA = 88.56

**Footnotes:**

- Isotope production ratios
  - \(^{39}\)ArK = 0.004025± 0.000028
  - Initial \(^{40}\)Ar/\(^{36}\)Ar ratio = 3787.39± 5778.31
  - \(^{37}\)Ar/\(^{39}\)ArK = 0.0302
  - Ca/K = 1.83×\(^{37}\)ArCa/\(^{39}\)ArK

- Volume \(^{39}\)ArK = 106.26
- Integrated date = 85.03± 1.40
- Plateau date = 93.62± 1.35
- %\(^{39}\)ArK for PA = 68.29

**Notes:**

- \(^{39}\)ArK for PA = 88.56
Nearly all the mafic and some intermediate dikes in the pluton strike perpendicular to foliation planes; aplitic and some intermediate dikes are principally parallel in strike to foliation, but dip perpendicular to foliation planes. Mafic dikes locally show evidence of plastic deformation. Mafic microgranitoid enclaves (following Vernon, 2005) within the pluton are of two types: porphyric enclaves (with hornblende and plagioclase phenocrysts) and equigranular enclaves. The later occur throughout the pluton, but the porphyric enclaves are larger (5 cm up to 2 m). Xenoliths (stopped blocks of the country-rocks) were recognized only in the southern part of the pluton in the biotite–hornblende tonalite, where discordant relationships with the wall rocks of the Alisitos Formation are accentuated.

The regional orientation of tight reclined folds (axial plane 345°/65° E) changes around El Potrero to a 300°/65° E orientation in the north and 15°/75° in the southeast (Fig. 2). These structures and zones of cleavage triple point developed northwest and southeast of the pluton are the most distinctive structures in the host rock. Another evident feature is the variation in the magnitude of shortening recorded by the host rock around the pluton. On the western margin, folds are open to tight, between Encinosa and El Potrero plutons, but along the eastern margin folds are very tight to isoclinal, close to the MMT and the SSPM pluton (Fig. 4c and d).

El Potrero pluton is characterized by a well-developed magmatic foliation. Magmatic foliation is defined by the orientation of hornblende and biotite crystals and cross-cuts the petrographic contact between the hornblende–biotite and biotite–hornblende tonalites in the pluton (Fig. 2). Foliation follows closely the shape of the pluton, and decreases in intensity from both the eastern and western borders towards the interior where it nearly disappears (Fig. 2a). At both the eastern and western margins, magmatic foliations strike nearly parallel. Foliations dip to the east at angles of 75° in the east and in the 55° in the west (Fig. 2e). Crystal-plastic deformation occurs only in the eastern and northern borders of the pluton and is defined by recrystallization of quartz and, to a lesser extent, feldspar (Fig. 4a). This fabric extends about 250 m into the pluton interior. To a large degree, magmatic and solid-state fabrics maintain the orientation of the regional host rock foliation and the pluton major axis (NW–SE to NNW–SSE).

The pluton is also intensely fractured and contains enclaves with highly variable axial ratios. Microgranitoid enclaves are generally elongated parallel to the magmatic foliation. Both, porphyric and non-porphyritic enclaves show variations in frequency and amount of flattening from the interior to the pluton margins. In the western margin of the pluton axial relations of enclaves

Fig. 3. \(^{40}\)Ar–\(^{39}\)Ar data for El Potrero pluton. Figure includes Ar release spectra for hornblende and biotite, as well as sample location.
vary from 2:1, to 3:1 (Fig. 2), in the center are nearly equal (up to 1.5:1), and in the eastern margin they show extreme axial ratios of up 15:1, averaging 8:1 — all in plan view. A large number of enclaves occur within the solid-state carapace on the pluton’s eastern border.

Variable axial ratios in plutons can be related to magma chamber flow, but they can be used also as strain marker indicators when crystal plastic deformation can be documented (Vernon et al., 1988; Paterson et al., 2004). Although microgranitoid enclaves show extreme axial ratios in the area of solid-state deformation of the tonalite in the eastern parts of the pluton, we cannot demonstrate whether this is related to deformation during or after emplacement. A microstructural analysis in the microgranitoid enclaves was not carried-out. Certainly, the extreme axial ratios in the zone of crystal-plastic deformation may be caused by melt-assisted sliding, but it seems to us that the asymmetry of enclave shape when the east and west sides of the pluton are compared, and the coincidence of more elongated
enclaves with the zone of plastic-deformation in the tonalite, suggests that part of the elongation may be related to post emplacement deformation. The degree of elongation is thus a reflection of fabric intensity, and a qualitative indicator of the shape of the strain ellipsoid. This observation is consistent with this being the area of greatest deformation, and where rotation of regional structural features in the host rock occurred. This is similar to what is observed in the northern sector of San José pluton (Johnson et al., 2003).

The El Potrero pluton contains three types of fractures: (a) curvilinear fractures, generally parallel to magmatic foliation; (b) planar fractures that intersect the curved fractures associated with foliation (forming a near reticular drainage pattern); (c) NE trending fractures that cut both the pluton and the host rock. Because NE fractures cross the pluton and the host rock, it appears that the fracture pattern is not solely related to cooling, and it could be associated with post-magmatic regional tensile stress. Alternatively, the NE–SW fractures could also be related to contractual deformation, as they are parallel to the direction of Late Cretaceous maximum shortening. On the other hand, small subhorizontal ductile shear zones with top to the east sense of shear were observed locally affecting mafic dikes (Fig. 4b).

There are clear geometrical distinctions between the western and eastern contacts of the El Potrero with its host-rock. The contact is discordant in the west, but becomes gradually concordant along the east border. To the south and southwest, the relations are strongly discordant with older structures, abruptly cut by the pluton. The south and southwestern areas of El Potrero also contain clear evidence of stopping, as stratified blocks of the host-rocks occur within the tonalite. To the northwest and southeast of the pluton the angle between foliation of the host-rock and the pluton border is small or nearly parallel. Zones of cleavage triple point are evident in the host-rock in areas northwest and southeast of the pluton (Fig. 2). Furthermore, isoclinal folds in the host-rock become parallel to the pluton margins in the east and southeast. Cleavage triple-point zones and reoriented isoclinal folds define a transition zone between areas where the pluton–host rock contacts are concordant and areas where they are discordant (Fig. 2). The areas of discordant relations correspond to areas of greatest strain. In these areas it is even possible to see strongly deformed magma injections within the host-rock and boudins of minor bodies of magma and host rock strata. The region most deformed by shortening in the host-rock occurs NE of the pluton, between the Sierra San Pedro Mártir and El Potrero plutons; this zone contains the MMT. However, where major rotation of the regional foliation occurs is in the cleavage triple-point zones; here, the foliation was transposed to a NE–SW strike perpendicular to the regional strike. This may suggest that the pluton behaved as a rigid unit, analogous to a large-scale porphyroblast, within the deforming Alisitos Formation. However, cleavage triple points are commonly used as evidence of syntectonic or post-tectonic ballooning (Paterson and Tobisch, 1988).

5. Paleomagnetism

Natural remanent magnetization (NRM) of El Potrero samples is of relatively high intensity, of order about 10^2 mAm/m, and demagnetization behaviour is relatively straightforward. The characteristic magnetization (ChRM) is a northeast-directed and moderately shallow remanence of high coercivity (>100 mT) and high unblocking temperature (>550 °C), that most likely resides in hematite (Fig. 5). The ChRM is locally overprinted by a soft overprint, of random orientation that can be easily removed with inductions of about 20 mT (Fig. 5a). Maximum unblocking temperatures could not be determined because samples regularly exploded in the furnace when heated above 500 °C, but in most samples no significant change in direction nor intensity was observed upon heating to that temperature, which is interpreted as a stable end-point direction (Fig. 5b and c). ChRM directions were calculated from stable end points reached after AF or thermal demagnetization anchored to the origin. Although linear trends to the origin were not observed before samples were destroyed during demagnetization, we are confident that the magnetization isolated is free of significant secondary overprints.

Site means are well-defined with precision parameter values typically greater than 100 and small confidence intervals (<8°). Between-site dispersion is also low, but the site mean distribution is slightly streaked along a NE trending axis (Fig. 5d). The magnetization is of uniform normal polarity as expected for the age of the pluton. The overall mean is of Dec=34.6°, I=25.7° (k=88.3, α95=5.5°; N=9 sites).

IRM acquisition curves are characterized by steep initial slopes, typical of multi-domain magnetite, but samples fail to saturate with maximum inductions of 2 T. Between 20% and 50% of the IRM is induced above 0.2 T, indicating that a high coercivity phase contributed significantly to the IRM acquisition curve. This observation and the high coercivity of the NRM suggest the hematite contributes significantly to the natural remanence. Microscope observations of polished sections confirm the presence of large hematite grains with ilmenite lamellae and a third phase forming sigmoidal lenses interpreted as pseudobrookite.
The mean obtained for the El Potrero pluton (Fig. 6; Table 2) is compared with the PRB mean reported by Hagstrum et al. (1985) calculated for a locality at 30.5°N–115°W, and with the mean direction reported by Böhnel and Delgado Argote (2000) for San Telmo pluton, located about 40 km west of the Rosarito fault zone. We also plot recalculated directions for the poles obtained for the Testerazo pluton and San Marcos dikes, in northern Baja California (Böhnel et al., 2002), and for a subset of the PRB sites reported by Hagstrum et al. (1985) that only includes sites collected south of the US–Mexico border, in the same general sector of the PRB as the El Potrero. Those sites are in the vicinity of Cataviña, about 100 km south of El Potrero. All directions are also compared with the expected direction, calculated from

![Fig. 5. (a–c) Orthogonal demagnetization plots of selected samples, after Zijderveld (1967). Solid (open) symbols are projections on the horizontal (vertical) plane; (d) stereographic plot of site mean directions with confidence intervals (small circles), the overall mean (square), and the expected Cretaceous direction (star). Solid symbols in the stereoplot are lower hemisphere projections.](image)

![Fig. 6. Summary of paleomagnetic data for the Peninsular Ranges Batholith. Data summarized include the San Telmo pluton (ST, Böhnel and Delgado Argote, 2000), the combined Testerazo pluton and San Marcos dikes (T-SM, Böhnel et al., 2002), and the result for La Posta (LP) pluton after Symons et al. (2003). Solid symbols are projections in the lower hemisphere.](image)

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<th>inc (°)</th>
<th>k</th>
<th>α95 (°)</th>
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Here, n (nd) is the number of samples used (samples demagnetized) in the calculation of the site mean; dec and inc are the declination and inclination, whereas k and α95 are the precision parameter of the Fisher distribution and the confidence interval.
the mid-Cretaceous cratonic reference pole located at 72.7°N−191.1°E. The San Telmo mean is relatively close to the expected direction, whereas all other results are rotated clockwise up to 14° with respect to the reference direction. Inclinations are 2° to 5° more shallow than expected. In contrast, the El Potrero gives a markedly discordant mean direction (Fig. 6). The significance of this discordance is discussed below.

In relation to the controversy over proposed northward displacement of Baja peninsula since Cretaceous time new paleomagnetic data for the El Potrero pluton demonstrates that a single paleopole for the entire PRB as inferred by Hagstrum et al. (1985) is of little tectonic significance. This is because the batholith has been subjected to internal deformation. Whether or not segments of the batholith are uniformly tilted westward, as suggested by Böhnel et al. (2002), can only be determined with more detailed sampling of individual plutons. San José pluton, north of El Potrero, also records statistically significant tilt in the same direction as El Potrero (Molina-Garza et al., 2003).


Samples of the El Potrero pluton have weakly developed but well-defined magnetic fabrics. Anisotropy of magnetic susceptibility is low, with percent anisotropy values (P) around 1.15. Lineations (susceptibility maximum axes) are tightly grouped, particularly in sites that record prolate fabrics. Most of the sites along the north–south transect record this type of fabric with T values ranging between weakly prolate −0.038 and strongly prolate −0.639 (Fig. 7). Magnetic foliations are generally parallel to regional structural trends (striking NNW–SSE to NS), and lineations dip at moderately high to steep angles east–southeast to northeast. Oblate fabrics are observed at four sites, all near a pluton margin. At the northernmost and southernmost sites (21 and 12, respectively), foliations are steep and parallel to the pluton border, but at the westernmost sites (1 and 2) they dip at shallow angles and strike at oblique angles to the contact.

We interpret fabrics in the pluton interior to record primarily steep magma ascent, expansion of the pluton to the east, and regional eastward directed compression. Fabrics near the northern and southern pluton margins are parallel to contacts and thus record deformation that resulted from magma–wall rock interaction. We interpret oblate fabrics observed in sites along the western pluton border to reflect deformation imposed by the magma chamber roof. This is supported by the greater abundance of low angle (decompression?) fractures in this area, which in turn supports the notion that shallower facies of the pluton are exposed along its western margin. This conclusion was independently reached by evidence of stopping, by the presence of large host-rock xenoliths on the southwest sector, and by the rather irregular contour of the western contact.

7. Discussion

The El Potrero pluton is a good example of a pluton with both post- and syntectonic features. Features common but not limited to syntectonic plutons include: (1) the pluton is foliated and it also contains a solid-state fabric, (2) these fabrics are parallel to regional cleavage, (3) the host-rock contains cleavage triple points, (4) the pluton presents minor shear zones, and, (5) the pluton’s long axis is parallel to major regional structure. These features can be interpreted to indicate post-tectonic intrusion and deformation by expansion. Also, the Cerro Costilla, a pluton of nearly the same age as El Potrero, cross-cuts the MMT (Johnson et al., 1999b).

The discordance of the paleomagnetic direction in the El Potrero pluton is interpreted to indicate pluton tilt synchronous with deformation of the Alisitos Formation. The pluton’s close spatial relation with the SSPM pluton suggests that an important drag along the eastern margin of El Potrero, associated with diapiric ascent or by westward lateral-oblique expansion of the large SSPM pluton, may have provided a mechanism to tilt a large crustal segment delimited by the MMT in the east and the Rosarito fault in the west. We must point out that magnetic fabrics in SSPM pluton suggest westward asymmetrical expansion owing to an oblate fabric in the west and a non-oriented fabric in the eastern zone (Molina-Garza et al., 2003). This could suggest that a diapiric emplacement model could fail; however, we argue that an asymmetrical westward expansion could account for tilting of El Potrero pluton. Additionally, tilting could be achieved by activity and rotation of the Rosarito fault to the west. Rotation of the Rosarito fault may explain proposed 15° of tilt of SSPM pluton (Ortega-Rivera et al., 1997).

We suggest that eastward asymmetric (non-concentric) lateral expansion of the El Potrero pluton was controlled by a rheological contrast between the dioritic Encinosa pluton and the tuffs and pelitic rocks of the Alisitos Formation close to the MMT, west and east, respectively, of the initial area of emplacement. Murray (1978) and Johnson et al. (2003) also suggested lateral asymmetric expansion of San Jose pluton, northwest of El Potrero. Lineation magnetic fabrics also provide good evidence of eastward expansion of the magma chamber. This emplacement mechanism has been described
elsewhere, as in the Flamanville granite by Brun et al. (1990), the Ardara pluton (Holder, 1979; Siegesmund and Becker, 2000), Papoose Flat pluton (Sylvester et al., 1978; Morgan et al., 1998), Birch Creek pluton (Nelson and Sylvester, 1971), and Cannibal Creek pluton (Bateman, 1985), among others. We believe that dikes
were the principal mechanism of magma ascent, because in the western sector of the pluton highly discordant relationships with the host predominate. Also xenoliths of the host rocks are present, and few tonalitic dikes intrude into Encinosa. Within El Potrero pluton, we did not observe annular synclines or vertical shear zones; prolate deformation is not present around the pluton in the host, which could indicate diapirism.

In order to define the temporal relationship of a pluton with respect to structural features developed by regional deformation, certain structural characteristics must be present both in the borders and within the pluton. Yet, much controversy exists about what these characteristics must be, because the development of specific structural features depends on such factors as: the rheology of the host rock, the composition of the pluton, the velocity of emplacement, and the duration and intensity of the deformation event (Paterson and Tobisch, 1988). Some of the features observed in the borders and within the El Potrero pluton can be similar to those of plutons emplaced forcefully after a deformation event (Paterson and Tobisch, 1988). We notice, however that there are various examples throughout the world of plutons where the relative importance of emplacement-related versus deformation-related features has been misinterpreted. This is particularly the case of plutons that had been previously considered post tectonic and forcefully emplaced. Recently reinterpreted examples include: Cannibal Creek, Papoose Flat and Ardara plutons (Paterson, 1988; Paterson et al., 1991; Vernon and Paterson, 1993; respectively). The new interpretations are supported by more strict criteria such as the kinematics of porphyroblasts in contact aureoles as well as comparison of metamorphic mineral ages outside the aureole with crystallization ages in the intrusive. These two observations are considered key to defining temporal relations between deformation and emplacement (Paterson and Tobisch, 1988). We believe that paleomagnetic evidence is, in this case, a similarly diagnostic criteria.

Porphyroblasts are poorly developed at the El Potrero pluton margins, and any interpretation derived from them would be ambiguous. We note, however, that crystallization (U/Pb: 102.5 ± 1.6 Ma; Johnson et al., 1999b) and cooling ages (40Ar–39Ar hornblende age — ca. 101 Ma; 40Ar–39Ar biotite age — ca. 93.4 Ma; Fig. 3, this study) for the pluton fall within the interval of regional deformation (132–85 Ma). The ages imply rapid initial cooling rates after emplacement, and somewhat slower cooling rates before reaching biotite closure temperatures (≈300 °C). Cooling ages are also close to minimum metamorphism ages (Late Cretaceous) determined for biotite schist in SSPM area, and to the east in San Felipe (Iriondo et al., 2003). This suggests that pluton cooling and metamorphism to the east are contemporaneous. Cooling rates for the El Potrero appear somewhat slower than for the much large SSPM pluton (Ortega-Rivera et al., 1997). This may reflect a faster uplift rate for the SSPM pluton than for El Potrero. Alternatively, the ca. 94 Ma dates for biotites at El Potrero may reflect thermal resetting by SSPM pluton. On the other hand, a key observation is provided by the paleomagnetically determined ∼35° rotation of El Potrero pluton along a subhorizontal axis oriented NNW–SSE. This, combined with structural observations, provides strong support to the hypothesis of a syntectonic relation of El Potrero with respect to deformation observed in the zone between the Rosarito fault and the MMT (Fig. 8).

It is known that downward flow of aureole rocks may fill space below an ascending pluton (e.g., Saleeb, 1990; Stein and Paterson, 1996; Johnson et al., 1999a). This occurs in an apparently simple process controlled by density contrasts between ascending magma and host rocks. Another mechanism that may occupy space emptied by an ascending diapir is tectonic shortening. For the study area we consider that the relatively fast cooling rate determined for SSPM pluton (40 °C/Ma; Ortega-Rivera et al., 1997) between 97 and 88 Ma is evidence of fast magma ascent which in turn produced drag and rotation of ∼20° of the El Potrero pluton (Fig. 8b). We also believe that diapiric ascent may have been accelerated by contraction. This result corroborates the proposal of Ortega-Rivera et al. (1997), who suggested that tilt of SSPM pluton postdates closure of the biotite Ar system in samples on the east side of SSPM (ca. 88 Ma). Nonetheless, our new data suggest that the 15° tilt proposed for SSPM occurred by ∼85 Ma, and also affected the crustal block containing the El Potrero pluton. Thus, rotation of SSPM contributes to the approximately 35° of rotation observed paleomagnetically in the El Potrero pluton. Shortening and rotation of the Rosarito fault, southwest of the plutons, provides a simple mechanism to “fill” the space left by the ascending SSPM pluton and accommodate rotation of a large crustal block (Fig. 8c).

Fig. 7. Stereographic projection of magnetic fabric data and results of finite deformation analysis in lithic tufts of the host rock (inset). Squares, triangles and circles are the directions of maximum, intermediate and minimum susceptibility. Mean directions are plotted as large symbols within their 95% confidence interval. Shape parameter (I) and percent anisotropy (P) for each of the sites are also shown along the line the links the stereoplot to the site. Principal susceptibility axes are plotted in the lower hemisphere projection. A plot of magnetic lineation vs. magnetic foliation is shown in the lower right hand corner.
Post-tectonic plutons rarely record large-magnitude rotations; such rotations are limited to areas affected by intense extensional deformation, or transtensional/transpressional tectonics. There are observations of normal and strike-slip faulting in the Sierra San Pedro Mártir region (Delgado-Argote et al., 2003). The dominant orientation is consistent with structures related to Neogene opening of the Gulf of California. This style of deformation in the Sierra San Pedro Mártir area is more intense towards the east. In the San José and El Potrero regions we do not find evidence that transpression or transtension might have affected the plutons. Demonstrating the syntectonic nature of the El Potrero based solely on field and petrographic observations is difficult, but as mentioned earlier emplacement and cooling ages fall within the span of regional deformation. Besides, the ~35° tilt of the pluton cannot be explained by post-tectonic extension and is consistent with the dip of the main regional shear zones within this sector of the PRB.

We note that the estimated tilt angle of El Potrero is close to the difference that exists between magmatic foliation and the vertical, or the angle between local tectonic foliation in the pluton and regional foliation in the host rock, and the vertical. This in turn suggests that the tilt developed during activity of the regional shear zones (Rosarito fault and MMT). The observed structural relations could be produced if the pluton had been emplaced post-tectonically by forceful emplacement, within a pre-existing weakness zone, although the large magnitude of tilt could not develop in such a setting.

Additional evidence for the El Potrero pluton that support tectonically controlled fabrics, and lateral expansion of the magma chamber towards the east before complete crystallization, are the asymmetric distribution of the degree of flattening in microgranitoid enclaves, as well as the asymmetry in the development of the intensity of magmatic foliation and solid-state fabric. Additional evidence is the existence of greater shortening in the host rocks in the eastern border of the pluton. The observation of different emplacement mechanisms and exposure of different metamorphic facies of the host rocks were thus possibly controlled by regional shear zones (Rosarito fault and MMT), which control the regional uplift of progressively higher-grade facies toward the east. Higher temperatures and emplacement of more voluminous plutons towards the east appears controlled by the shear zones as well. Emplacement levels change systematically, from relatively shallow depths west of Rosarito Fault ca. 2.3±0.6 kbar in the Zarza intrusive complex (Johnson et al., 1999a), to ca. 4.0±0.6 kbar in the El Potrero pluton (average of four determinations from this study), and ca. 5.0±0.5 kbar in the Sierra San Pedro Mártir pluton west of the MMT (Ortega-Rivera et al., 1997).
faults delimit crustal blocks that expose deeper crustal levels towards the east. Similarly, emplacement mechanisms vary from primarily brittle (stopping and faulting that produce discordant relations to host rock, both south and west of the San José and El Potrero plutons), to primarily ductile in the east (showing ductile shortening of the host rock, folding, and rotation of regional structures). Plutons in the vicinity of the MMT expanded laterally or oblique towards this structure (El Potrero, San José and San Pedro Mártir, Fig. 1). The contact relationships for the San José and El Potrero plutons are discordant towards the west and south, areas more distant to the MMT, but are concordant on the borders nearer the MMT.

We thus suggest that emplacement of the El Potrero pluton and expansion towards the east was facilitated by the presence of a “heated” shear zone, the MMT of Johnson et al. (1999b). Even more, in the study area accretion of the Alisitos arc (Griffith and Hoobs, 1993; Phillips, 1993) is fully documented, as is the development of a Cretaceous continental arc that migrated landward (Gastil et al., 1975; Silver and Chappell, 1988). Although timing of arc accretion (ca. 103±4 Ma; Griffith and Hoobs, 1993; Johnson et al. 1999b). Even more, in the study area accretion of the Alisitos arc (Griffith and Hoobs, 1993; Phillips, 1993) is fully documented, as is the development of a Cretaceous continental arc that migrated landward (Gastil et al., 1975; Silver and Chappell, 1988). Although timing of arc accretion (ca. 103±4 Ma; Griffith and Hoobs, 1993) and development of specific shear zones (ca. 115–108 Ma; MMT de Johnson et al., 1999b) differ slightly, these ages are all contained within the span of regional shortening that affected the region between 85 and 132 Ma (Schmidt and Paterson, 2002).

8. Conclusions

We interpret that eastward asymmetric lateral expansion of the El Potrero pluton was controlled by rheological contrast between the dioritic Encinosa pluton and the tuff and pelitic rocks of the Alisitos Formation, west and east, respectively, of the initial area of emplacement. On the other hand, fold axes in the Alisitos Formation are deviated by the El Potrero, the western contact is highly discordant to regional deformation features, and no clear conclusions can be drawn from aureole porphyroblasts. The El Potrero pluton experienced a rotation of ∼35° with respect to the reference direction and it is interpreted to indicate a combination of initial drag during vertical diapiric emplacement or westward lateral-oblique expansion of the adjacent San Pedro Mártir pluton (∼20°) and later rotation (∼15°) by Rosarito Fault activity in the southwest, affecting several plutons in the area (SSPM, El Potrero and Encinosa). Magnetic susceptibility fabrics reflect mostly emplacement-related stress and regional stress. Pluton fabrics and structures and their relationship to the host-rock, as well as regional observations, suggest that the El Potrero pluton is best interpreted as a syntectonic pluton emplaced inside of a regional shear zone delimited by the Main Mártir Thrust and the younger Rosarito fault.

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