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Formation of joints in cooling plutons

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Abstract

The geometry, age, and mineralogy of steeply dipping joints in the Lake Edison Granodiorite of California indicate that thermal stresses played a key role in the formation of the joints. Joint traces curve to approach the pluton boundary at high angles at both large and small scales, and they generally terminate at or near the contact with an older pluton. Radiometric dates and the epidote and chlorite fillings of the joints tie jointing to the initial cooling of the pluton. A thermo-mechanical stress analysis assuming two-dimensional conductive cooling predicts thermal stresses of several tens of MPa, the same order of magnitude as plausible fluid pressures, regional stresses, and lateral normal stresses associated with the overburden. The orientation of the joints can be accounted for rather well by the stress field formed by superposing a uniform regional stress field on the predicted thermal stresses. The large-scale pattern of the early joints in many plutons should be predictable based on a pluton's geometry, its age relative to the adjacent rock, and knowledge of the regional stress at the time of initial cooling. These findings bear on issues pertinent to mining, petroleum recovery, nuclear waste repository siting, and ground water flow.

1. Introduction

Fractures strongly influence the strength, anisotropy, and fluid flow characteristics of rock masses (National Academy of Sciences, 1996); they also can be used to infer the stress conditions in the Earth (Olson and Pollard, 1989). It is important to account for large-scale fracture networks in evaluating the flow of groundwater and hydrocarbons, and also in siting and designing nuclear waste repositories. With the onset of fracturing, a rock mass obtains a structure which will further control its mechanical and hydrologic behavior. For example, in many places faults nucleate from pre-existing dikes and joints (Segall and Pollard, 1983b; Martel et al., 1988; Lisle, 1989; Martel, 1990; Martel and Peterson, 1991). Understanding the factors controlling the initial fracturing in a rock mass thus has broad practical and academic significance.

The focus here is on the development of joints in granitic rocks. Joints, or opening mode fractures, are the most ubiquitous type of fracture (Pollard and Aydin, 1988). Joints in granites are of interest for two main reasons. First, in many places granitic rocks form the foundation of continents. Deformation along fractures in the 'basement rocks' will affect the overlying rocks as well. Second, granitic rocks are among the most homogeneous rocks on scales greater than the grain size, and are therefore in many ways simpler from a mechanical standpoint than layered and foliated rocks. An understanding of joints in a relatively simple rock should form a good basis for helping to understand joints in more complicated rocks.

Joints in granitic rock masses can be caused by a combination of extrinsic stresses (e.g. remote tectonic stresses, stresses related to nearby pluton emplacement, or stresses associated with erosion of the overburden) and intrinsic stresses (e.g. pore fluid pressures, thermal stresses associated with pluton cooling). Joints resulting solely from regional loads could be of any age younger than the pluton, could thus cut across the boundaries between plutons, and should form patterns consistent with regional stresses rather than with the

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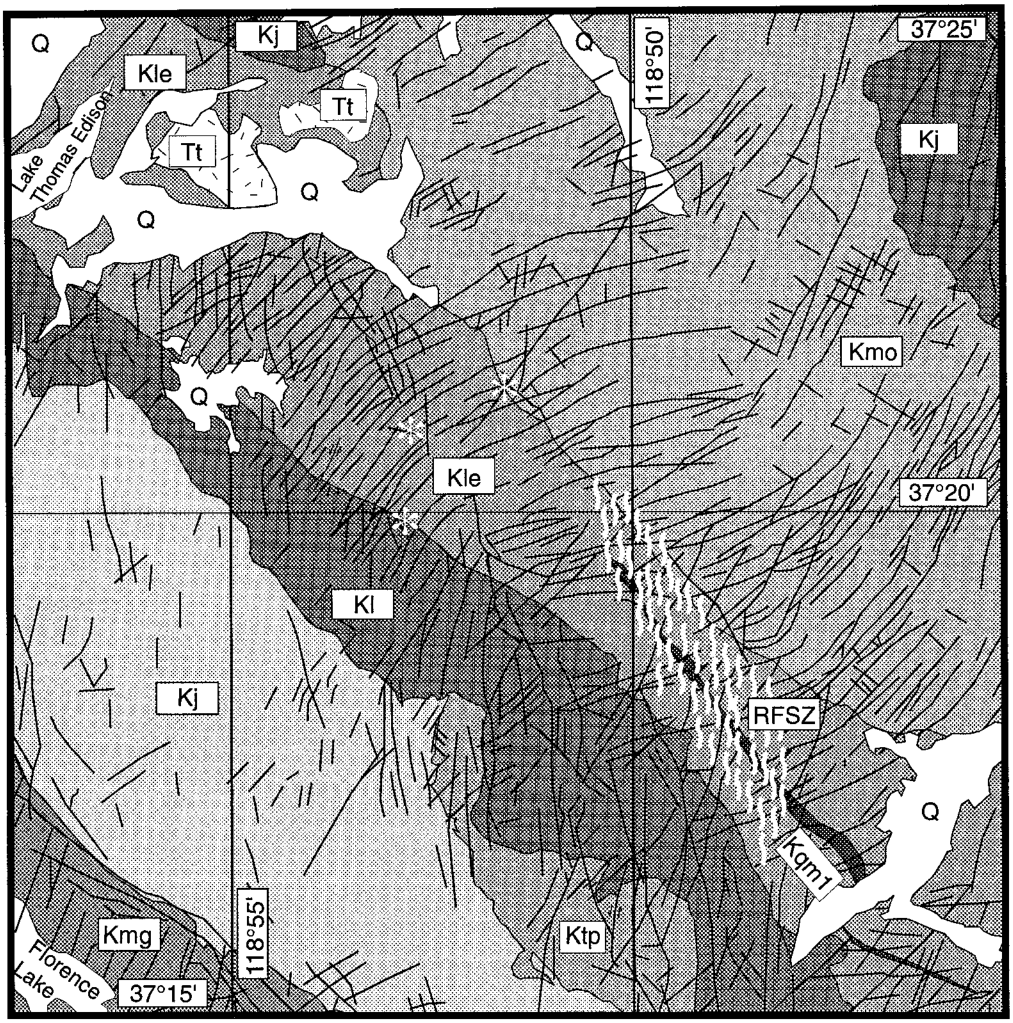

Fig. 1. Map showing the generalized geology of a portion of the Mount Abbot quadrangle and prominent fracture systems (modified from Lockwood and Lydon, 1975). The main geologic units shown are, from oldest to youngest, undifferentiated Cretaceous and Jurassic plutons (Kj), the Lamarck Granodiorite (Kl), the Mount Givens Granodiorite (Kmg), the Lake Edison Granodiorite (Kle), the Mono Creek Granite (Kmo), Cretaceous quartz monzonite and granite (Kqml), Tertiary olivine trachybasalt (Tt), and Quaternary deposits (Q). Sample locations for the radiometric dating are marked by the white asterisks. The locations of both outcrops shown in Fig. 2 coincide with the asterisk at the Kl–Kle contact. RFSZ indicates the Rosy Finch shear zone (Tikoff and Teyssier, 1992).

pluton geometry. In contrast, joints that originate due to cooling should be tied to factors intrinsic to a pluton, such as its age relative to adjacent rocks and its geometry. Joints due to cooling should only be slightly younger than the host pluton, and their geometry should reflect the geometry of the pluton.

This work targets the origin of joints in granitic rocks of the Sierra Nevada batholith of California. The origin of these joints has intrigued geologists for more than 100 years (e.g. Becker, 1892). The joints are manifest on a regional scale as prominent topographic features, and they are superbly exposed in outcrops (e.g. Segall and Pollard, 1983a). Bateman and Wahrhaftig (1966, p. 122) considered that prominent joints in Sierran plutons are regional in origin and formed "after the consolidation of the entire batholith 'because' they cross boundaries between plutons with little or no deflection". Lockwood and Moore (1979) ascribed the fractures to mid-Cenozoic deformation associated with regional extension in the Basin and Range province. Segall et al. (1990), however, presented radiometric evidence indicating that joints of the Lake Edison Granodiorite formed within a few million years of the emplacement of the host plutons.

This research examines the possibility that plutonic joints are strongly influenced by stresses due to the initial cooling of the pluton, concentrating on one pluton from the Sierra Nevada, the Lake Edison Granodiorite (Bateman, 1992). This pluton and its neighboring intrusions are well suited for investigating fracture origins because deformation of the granitic rocks there, subsequent to the initial fracturing, gener-

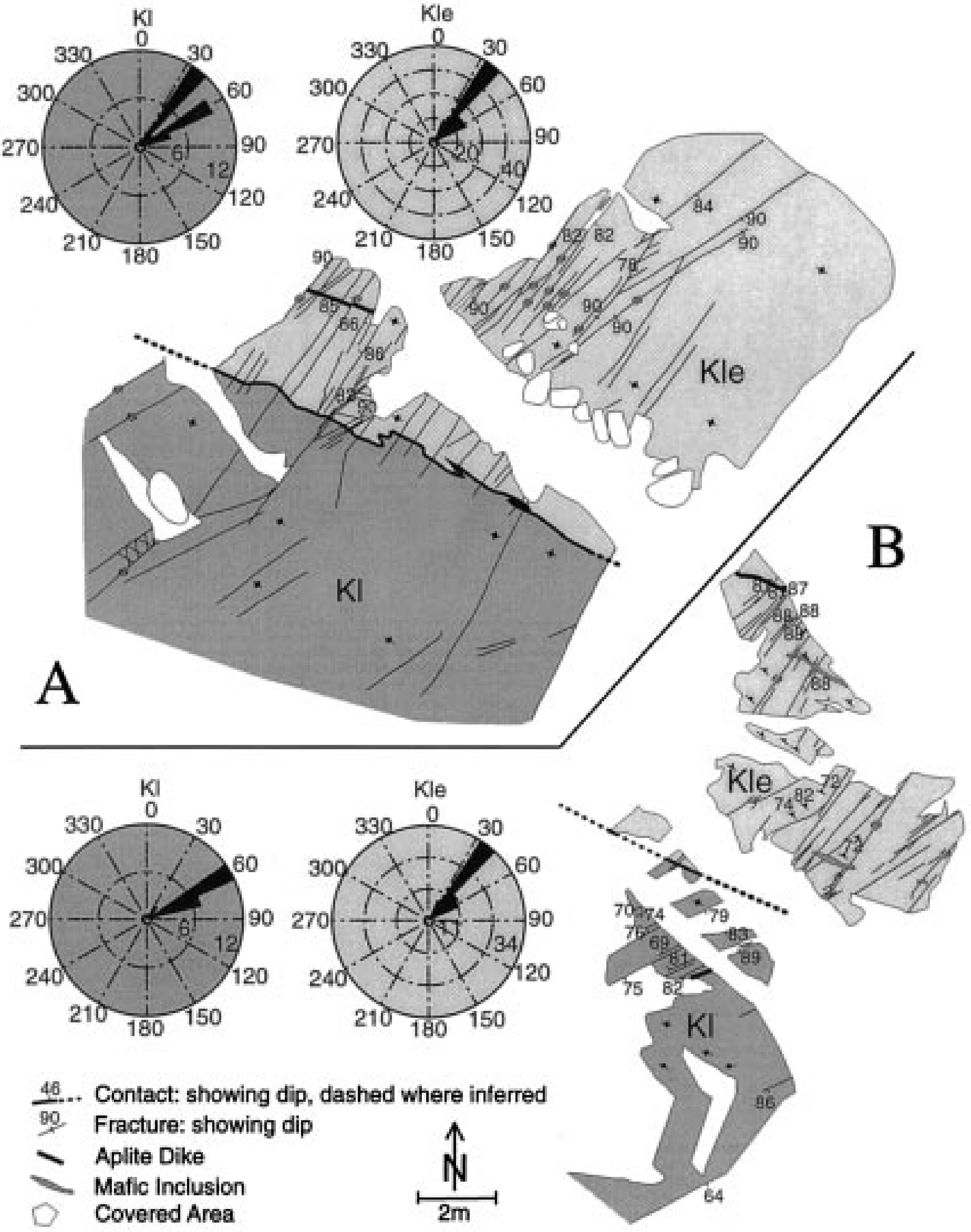

Fig. 2. Maps showing two outcrops at the Kl–Kle contact (white asterisk in Fig. 1) and inset rose diagrams. Outcrop A lies ca. 100 m northwest of outcrop B. Fracture spacing and orientation in both outcrops vary across the contact. Dark and light rose diagrams represent fractures in Kl and Kle, respectively.

ally is small, and a large body of prior field and laboratory research on the rock and its fractures exists (Lockwood and Lydon, 1975; Segall and Pollard, 1980, 1983a, b; Segall, 1984; Martel et al., 1988; Martel, 1990; Segall et al., 1990; Bateman, 1992; Tikoff and Teyssier, 1992; Bürgmann and Pollard, 1994; Christiansen, 1995). We integrate information on the geometry and petrology of the host rock and its fractures, radiometric data, and thermo-elastic modeling results to examine plausible joint-causing stresses. We first discuss the geometry and mineralogy of the host pluton and its fractures, followed by the thermal history of the plutons. Two-dimensional analyses of temperatures and stresses in a cooling elastic plate quantitatively test whether thermal effects are a plausible mechanism for jointing. Although we focus on plutons from the Sierra Nevada, we expect the findings apply to granitic terranes in general.

2. Geometry and mineralogy of plutons and fractures

The Lake Edison Granodiorite is an elongate pluton located between Yosemite and Kings Canyon National Parks. The pluton consists mostly of rather homogeneous, fine- to medium-grained hornblende–biotite granodiorite with abundant sphene (Lockwood and Lydon, 1975). The pluton is slightly more than 50 km long. Its long horizontal axis trends northwest, roughly parallel to the Sierra Nevada crest, and it ranges in width from 1.5 to 4 km. The study area is located about midway between the ends of the pluton (Fig. 1), and lies in the Mount Abbot quadrangle (Lockwood and Lydon, 1975). The pluton has a narrow 'waist' near the center of the quadrangle. To the west, the Lake Edison Granodiorite (Kle) is bordered by the older Lamarck Granodiorite (Kl). The Lamarck Granodiorite is intruded by the Mount Givens Granodiorite (Kmg). To the east, the Lake Edison Granodiorite is bordered by the younger Mono Creek Granite (Kmo) of Bateman (1992). The contacts between the Lake Edison Granodiorite and the adjacent plutons dip steeply. The Lake Edison Granodiorite is for the most part weakly foliated, with the foliation also dipping steeply and striking roughly parallel to the pluton boundaries. Along the Rosy Finch shear zone (Tikoff and Teyssier, 1992; Tikoff and Saint Blanquat, 1997), however, the foliation is more pronounced and cuts across the pluton (Fig. 1). The pluton crops out over an elevation range of about 1500 m, providing a minimum vertical extent for the pluton. Ague and Brimhall (1988) contended that the Sierra Nevada batholith locally had a vertical extent of 30–35 km, so the Lake Edison Granodiorite might have been considerably more than 1500 m tall when it was intruded.

Fractures in the Lake Edison Granodiorite dip steeply and strike predominantly ENE–NE. The most prominent ones are reflected in Fig. 1 as photolineament traces. The mapped photolineaments might not reflect the actual fracture density everywhere within the pluton because Cenozoic deposits cover parts of the intrusion; no photolineaments are shown there. Fractures consist of dikes, parallel joints, small faults, and fault zones (Segall and Pollard, 1983a; Segall, 1984; Martel et al., 1988; Martel, 1990). At the scale of an outcrop, the fractures in the Lake Edison Granodiorite and adjacent plutons have straight traces. The longest joint traces and the longest fault zone segments on flat or gently inclined outcrops are about 50 m long. The longest joint traces on canyon walls appear to extend for a comparable vertical distance. The spacing between fractures ranges from several decimeters to several meters. The joints generally have maximum apertures of no more than a centimeter; commonly the apertures are less than a millimeter. They are filled with a mineral assemblage dominated by undeformed epidote and chlorite, with trace amounts of sericite, muscovite, calcite, and zeolite (Segall and Pollard, 1983a). Based on the spacing of the joints and their apertures, Segall and Pollard (1983a) calculated that the strain accommodated by opening of joints in the nearby Mount Givens Granodiorite is from 10^{-4} to 5×10^{-4}.

Fig. 2 shows two maps of fracture traces in outcrops along the contact between the Lake Edison Granodiorite and the Lamarck Granodiorite. The inset rose diagrams show the distribution of fracture strikes in those locations. At these outcrops the two plutons can be distinguished based on differences in their color and texture, allowing the location of the contact to be resolved within several centimeters. Markers (e.g. igneous dikes and xenoliths) that are cut by fractures but not visibly offset in a lateral sense permit joints to be distinguished from strike-slip faults. Fractures in both plutons strike at high angles to the contact. However, the fracture spacing is distinctly different on opposing sides of the contact, being less in the Lake Edison Granodiorite. Although most joints that extend into the adjacent intrusion terminate within one meter of the contact, some joints do not. The nucleation points of joints that cross the contact cannot be established owing to the absence of plumose structure on the rough joint faces. In contrast to the joints, several fault zones near these outcrops do cross the Kle–Kl contact and extend well into both plutons.

The rose diagrams (Fig. 2) also reflect differences in the fracture patterns. In the rose diagrams, a fracture that extends into both plutons is accounted for twice, once for each pluton. More than twice as many fractures exist in the younger intrusion (Kle). Additionally, the overall strike of the fractures differs on opposing sides of the contact. Whereas joints in the Lake Edison Granodiorite strike roughly N40E, joints in the Lamarck Granodiorite exhibit strikes closer to N60E. The strong contribution of fractures striking approximately N40E in the Lamarck Granodiorite in outcrop A reflects a suite of fractures that extend for only a short distance into the pluton.

At the scale of the pluton the fractures are displayed as vegetated lineaments and grooves in the topography (Fig. 1). The average strike of the fractures within the Lake Edison Granodiorite is roughly at right angles to the long axis of the pluton. Neither the fracture traces

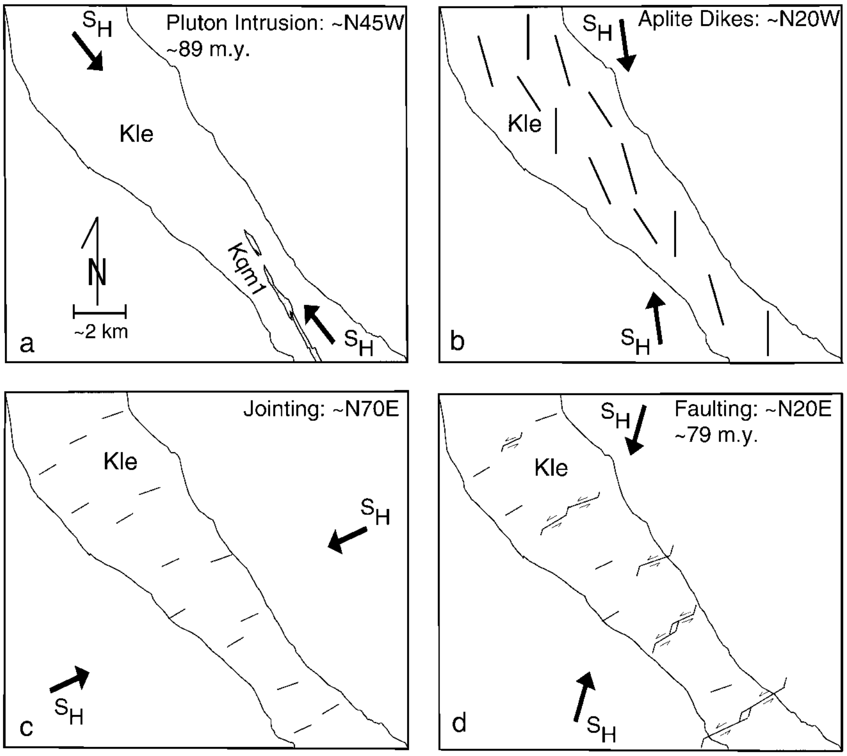

Fig. 3. Most compressive horizontal stress directions (S_H) in the Lake Edison Granodiorite (Kle) inferred from field observations (modified from Christiansen, 1995), when (a) the pluton intruded, (b) the first set of igneous dikes intruded, (c) the joints opened, and (d) the faulting occurred.

nor the pluton contacts are straight at the scale of the pluton. The fracture traces northwest of the 'waist' of the pluton near the center of Fig. 1 are concave to the south, whereas the fracture traces southeast of the 'waist' are concave to the north. The fractures thus maintain a roughly orthogonal relationship to the pluton boundary even where the boundary orientation changes. A similar geometric relationship between photolineaments and pluton boundaries exists in several other plutons throughout the Sierra Nevada, for example the Granodiorite of Cartridge Pass in the Sierra Nevada (Bergbauer et al., 1998), and the southwest margin of the Mono Creek Granite (Fig. 1).

3. Structural history of the Lake Edison Granodiorite

The oldest structure in the pluton is its weak foliation, interpreted to be synmagmatic and resulting from magma flow during crystallization (Bateman, 1992; Christiansen, 1995). Two sets of igneous dikes cut the foliation. One well-defined set strikes approximately N20W. The second, younger set contains dikes with a broad range of strikes (Christiansen, 1995). These dikes are in turn cut and offset by ENE-striking joints and faults. Segall and Pollard (1983b) and Martel et al. (1988) concluded that the faults and fault zones evolved from the joints. They inferred that a change in principal stress orientation caused some joints to subsequently slip left-laterally. Fault zones then developed by the linkage of smaller faults. Eventually, some fault zones grew across pluton boundaries and accommodated slip of as much as several tens of meters (Lockwood and Lydon, 1975; Martel, 1990). Because the faults and fault zones formed from the preexisting joints, the large-scale orientations of all these younger structures, as represented by the photolineaments, reflect the orientation of the original joints.

Geometric factors suggest that the pluton was not emplaced under isotropic regional stresses. The long horizontal axis of the Lake Edison Granodiorite trends northwest, and several steep, dike-like bodies of late Cretaceous age within the pluton strike northwest (Kqm1 in Figs. 1 and 3), suggesting that the least compressive horizontal stress was oriented northeast during their emplacement (Fig. 3a). These orientations are compatible with plate tectonic reconstructions. The least compressive tectonic horizontal stress a couple of hundred kilometers inland from a subduction zone commonly parallels the displacement direction of the subducted plate (Nakamura and Uyeda, 1980), and during late Cretaceous time the Farallon plate was being subducted to the northeast beneath the North American plate (Engebretson et al., 1985).

Based on the work of Christiansen (1995), three major changes in principal stress orientation can be distinguished in the pluton after its emplacement (Fig. 3b–d). The first generation of dikes strikes approximately N20W. The direction of the most compressive horizontal stress (S_H) during their formation must have paralleled their strike. Owing to the wide range of strike directions for dikes in the second set, a single direction for the least compressive stress cannot be inferred from those dikes (not shown in Fig. 3). When the ENE-striking joints opened, S_H was oriented N65E–N75E. Left-lateral faults and fault zones then developed with the most compressive horizontal stress oriented NNE. This stress orientation is indicated by the orientation of secondary fractures at the ends of strike-slip faults. These fractures commonly strike 15–30° counterclockwise from the faults (Segall and Pollard, 1983b; Martel et al., 1988).

Ductile deformation along faults in the Lake Edison Granodiorite becomes more pronounced on faults that near the younger Mono Creek Granite (Bürgmann and Pollard, 1994). This suggests that faulting in the Lake Edison Granodiorite is in some way associated with the intrusion of the younger granite. Because jointing in the Lake Edison Granodiorite preceded faulting, the jointing would appear to precede the intrusion of the Mono Creek Granite. The joints in the granodiorite also formed after the granodiorite was intruded. Based on these field observations it appears that the jointing occurred during the period of late Cretaceous plutonism.

4. Radiometric ages

The $^{40}Ar/^{39}Ar$ dating technique can provide quantitative constraints on the thermal histories of granitic rocks. The dates obtained from this technique can be related to closure temperatures, temperatures below which the diffusion of ^{40}Ar into and out of a mineral ceases. Published closure temperatures are 330 ± 50°C for biotite (Grove and Harrison, 1996), and 535 ± 45°C for hornblende (Harrison, 1981). We obtained radiometric dates for biotites and hornblendes from five samples collected along a traverse across the Lake Edison Granodiorite and the neighboring plutons (white asterisks in Fig. 1). Owing to potassium contamination of the lower temperature gas released in the hornblendes, and to minor age gradients for the biotites (personal conversation, M. Grove), the argon release pattern of the samples did not produce clear age plateaus. The ages we discuss below (see Table 1) are from radiogenic total-gas measurements.

Table 1
Summary of $^{40}Ar/^{39}Ar$ total gas ages for collected samples used in Fig. 4

Sample	Mineral	Total gas age (my)	Standard deviation (my)
KLEF3H	Hornblende	86.5	0.8
KLEF3B	Biotite	83.0	0.1
KLE4H	Hornblende	88.7	0.4
KLE4B	Biotite	80.7	0.2
KLEP5H	Hornblende	85.3	0.7
KLEP5B	Biotite	80.6	0.2
KL2H	Hornblende	90.3	0.7
KL2B	Biotite	80.0	0.2
KMR2H	Hornblende	84.5	0.6
KMR2B	Biotite	81.1	0.1

Fig. 4 depicts the newly obtained dates, K–Ar and $^{40}Ar/^{39}Ar$-dates on Kle-fault zone muscovites (Segall et al., 1990), and radiometric dates for biotites and hornblendes from the local plutons. Heavy crosses and solid rectangles represent dates obtained in this study from hornblende and biotite, respectively. Open squares depict muscovite dates from Kle-fault zones (Segall et al., 1990). Thin crosses and open ovals depict K–Ar dates (Kistler et al., 1965) on hornblendes and biotites, respectively. Open rectangles indicate biotite dates presented by Christiansen (1995). Fig. 4 suggests that the Lamarck Granodiorite cooled through the hornblende closure temperature at around 91 my, fol-

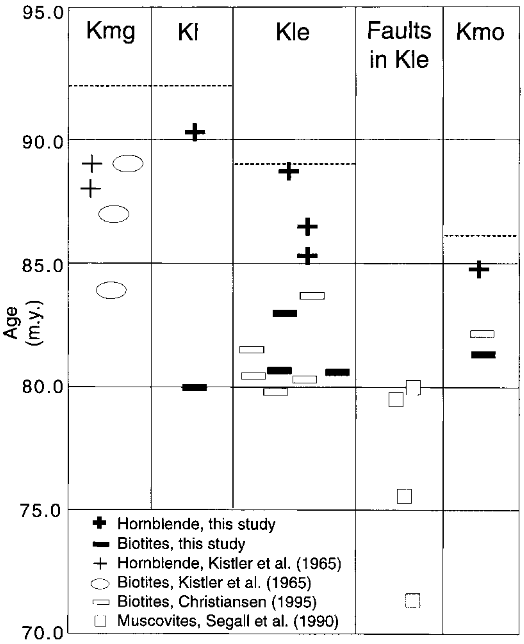

Fig. 4. Ar-diffusion ages of fault-zone muscovites compared with ages of host rock (Kle) and adjacent plutons. Dotted lines indicate intrusion ages assumed for the thermo-mechanical modeling. Joints in Kle are interpreted to have formed between 87 and 86 my.

lowed by the Mount Givens Granodiorite (~89 my), the Lake Edison Granodiorite (~88 my) and the Mono Creek Granite (~85 my). The indicated radiometric age relationships for hornblendes thus are consistent with cross cutting relationships observed in the field (Bateman, 1992). Interestingly, the Mount Givens Granodiorite appears to have cooled through the biotite closure temperature of 330°C before the other three plutons (Kl, Kle, Kmo), including the apparently older Lamarck Granodiorite. Those three plutons appear to have cooled together through the biotite closure temperature during the interval from 84 to 80 my. The dating results could reflect, at least partially, reheating of the two younger plutons (Kle, Kl) during intrusion of the extensive Mono Creek Granite. The scatter of the biotite dates within each pluton suggests that the ambient temperature of the area was below but close to the biotite closure temperature, so that local temperature disturbances were able to delay cooling through the biotite closure temperature. Radiometric dating of muscovite obtained from secondary fractures within two fault zones in the Lake Edison Granodiorite yielded a mean age of 79 my (Segall et al., 1990), very close to the radiometric ages of biotite in the host rock. The radiometric constraints obtained from these fault zones also represent the youngest possible formation age for the joints and ties the jointing to the period of late Cretaceous plutonism in the Sierra Nevada.

5. Pressure and temperature conditions

Solidus and liquidus temperatures of the granodiorites can be inferred by geochemical means. Geobarometric studies in the central Sierra Nevada indicate confining pressures during pluton emplacement between 100 and 390 MPa and emplacement depths between 3.5 and 14 km (Bateman, 1992; Ague, 1997). Experimental studies by Robertson and Wyllie (1971) and Piwinskii (1968) show that solidus temperatures in granodiorites are unaffected by magma water content in the range from approximately 0.5% by weight (water deficient) to 15% by weight (water excess). Both studies describe solidus temperatures ranging from 750°C at a confining pressure of 100 MPa to 680°C at a confining pressure of 350 MPa. Liquidus temperatures, however, depend on the water content of the magma under water deficient conditions (below 6.5% by weight). Lowest liquidus temperatures of 980°C are obtained for granodiorites with water contents above 6.5% by weight and confining pressures of 100 MPa, and highest liquidus temperatures of more than 1100°C are measured if water is absent for confining pressures of 300 MPa.

Once cooled through the solidus temperature, a pluton is certainly able to sustain tensile stresses. However, as the pluton approaches the solidus, it cools through a temperature at which the crystal–liquid admixture constitutes a crystal-bonded aggregate. Such aggregates can transmit seismic shear waves (Sinton et al., 1992) and so behave in some ways as solids. At this temperature the viscosity increases exponentially (Marsh, 1989; Bergantz, 1990). According to McBirney (1984) this point is reached over a crystallinity interval of 40–70%. Based on Piwinskii's experiments (Piwinskii, 1968) under water-saturated conditions, 40–70% crystallinity in a granodiorite magma is reached at temperatures between 740 and 700°C at 300 MPa and between 840 and 830°C at 100 MPa confining pressure. We assume that cooling through 800°C enabled the Lake Edison Granodiorite to sustain tensile stresses.

The mineral assemblage in the joints, primarily of undeformed epidote and chlorite with minor amounts of calcite, muscovite, sericite, and zeolites (Segall and Pollard, 1983a), is consistent with the minerals having precipitated under lower greenschist pressure–temperature conditions. The temperature for the greenschist facies at confining pressures of 200–500 MPa ranges from 300 to 570°C (Hyndman, 1985, p. 588). According to Best (1982), Sierran magmas contained enough water to precipitate epidote and chlorite in the joints, but not enough water to react hydrothermally with the granite to yield extensive quantities of epidote and chlorite outside the joints.

6. Constraints on potential mechanisms for jointing

A mechanism suggested for the formation of the ENE-striking joints in the Lake Edison Granodiorite should be consistent with the age, geochemistry, and geometry of the joints and of the pluton. Whereas the faults formed from preexisting joints, the dates obtained from the fault zones tie joint formation to the initial cooling of the pluton. Moreover, the joints must have opened during the age window represented by the Kle–hornblende and Kle–biotite dates because the joint fillings precipitated under greenschist-facies conditions with temperatures between 300 and 550°C. This allows us to constrain the jointing age between approximately 87 and 81 my (Fig. 4). This range can be narrowed by considering geometric factors. Photolineaments of the Lake Edison Granodiorite curve to approach the Kle–Kmo contact at high angles. This 'feeling' of the contact indicates that jointing in the Lake Edison Granodiorite occurred before the intrusion of the younger Mono Creek Granite (86 my), for with granodiorite on both sides of the contact, the contact should be mechanically invisible once the plutons are cooled. This suggests that the joints formed before approximately 86 my. Integrating all the information suggests that the Kle-joints opened between 87 and 86 my.

The radiometric data tie the jointing to the time when the pluton was cooling, but they do not prohibit fracturing as a result of regional effects. Geometric data, however, do strongly support a cooling origin. Columnar joints in a lava flow are well known to form perpendicular to their boundaries (DeGraff and Aydin, 1993, and references therein). Likewise, the overall orientation of the Kle-fractures at nearly right angles to the pluton boundaries suggests a cooling mechanism. Perhaps more significantly, the orientation of the joints appears to 'track' the orientation of the pluton boundary; as the boundary orientation changes so does the orientation of the joints. This pattern is consistent with a cooling origin but is difficult to reconcile with a uniform regional mechanism.

We now turn to the stresses during joint formation. We infer that the effective most compressive stress (S_v) at the time of jointing was vertical, that the effective intermediate (S_H) and least compressive stresses (S_h) were horizontal, and that S_H and S_h were parallel and perpendicular to joint strike, respectively. These orientations are consistent with the nearly vertical dip of the joints and the relative displacement across them. We define a Cartesian coordinate system with its x-axis perpendicular to and the y-axis parallel to the opening fracture in the horizontal plane, and the z-axis pointing upwards. In order for a joint to open, the following condition must apply (Pollard and Segall, 1987):

$$\sigma_{xx}^{\text{remote}} - \sigma_{xx}^{\text{crack}} > 0, \tag{1}$$

where $\sigma_{xx}^{\text{remote}}$ is the remote normal stress that acts perpendicular to the plane of the joint, and $\sigma_{xx}^{\text{crack}}$ is the normal stress on the joint walls; tensile values of σ_{xx} are positive. Possible contributions to $\sigma_{xx}^{\text{remote}}$ include extrinsic (S^{regional}) and intrinsic (S^{thermal}) tensions normal to the joint, and extrinsic stresses acting in the horizontal plane due to the overburden ($S^{\text{overburden}}$). The fluid pressure in the joint $P^{\text{fluid}} = -\sigma_{xx}^{\text{crack}}$ (Pollard and Segall, 1987). Eq. (1) thus can be recast as:

$$S^{\text{overburden}} + S^{\text{regional}} + S^{\text{thermal}} + P^{\text{fluid}} > 0. \tag{2}$$

The first two terms on the left side of Eq. (2) most likely are compressive and hence negative. We define the driving stress (ΔS) using the terms on the left side of Eq. (2):

$$\Delta S = S^{\text{overburden}} + S^{\text{regional}} + S^{\text{thermal}} + P^{\text{fluid}}. \tag{3}$$

Segall and Pollard (1983a) calculated a driving stress of 1–40 MPa to initiate joint growth in the Mount Givens Granodiorite.

According to Olson and Pollard (1989), joints develop straight traces if the differential stress in the horizontal plane during joint propagation exceeds twice the driving stress. The differential stress equals twice the maximum shear stress ($\tau_{\max}$):

$$S_H - S_h = 2\tau_{\max} = 2\Delta S. \tag{4}$$

The occurrence of joints with straight traces thus relates the maximum shear stress ($\tau_{\max}$) to the driving stress:

$$\tau_{\max} \geq \Delta S. \tag{5}$$

The joint traces in the Lake Edison Granodiorite are generally straight in outcrops, so the maximum shear stress acting in the intrusion at the time of joint formation would therefore be no less than 1–40 MPa (i.e. the driving stress of Segall and Pollard, 1983a).

Evaluating stresses in the horizontal plane due to the effect of overburden ($S^{\text{overburden}}$) and possible fluid pressures (P^{fluid}) for the Lake Edison Granodiorite is challenging, for these stresses span a wide range of possible magnitudes. Bateman (1992) and Ague (1997) inferred vertical stresses due to the overburden (S_v) for Sierran plutons in the range from 100 to 390 MPa. The latter figure sets a maximum bound for $S^{\text{overburden}}$. By assuming a laterally confined Earth, a minimum value of one third of S_v, or 30–130 MPa, is obtained for $S^{\text{overburden}}$. Possible stresses in the horizontal plane due to the effect of overburden therefore range from 30 to 390 MPa. In comparison, plausible fluid pressures range from 0 to 500 MPa (Burnham, 1979).

The criteria of Eq. (2) bear on whether or not joints open, but another important factor in our analysis is the orientation of the joints. The fluid pressure and horizontal stresses due to the overburden will not affect the strike of the joints. However, stresses that influence joint strikes are the regional horizontal stresses and the thermal stresses. To assess the thermal stresses, we now turn to a thermo-mechanical analysis.

7. Thermo-mechanical analysis

A two-dimensional thermo-elastic numerical analysis tests the mechanical viability of a cooling mechanism for jointing in the portion of the Lake Edison Granodiorite shown in Fig. 1. The first part of the analysis is to calculate temperature distributions by numerically solving the diffusion equation for two-dimensional conductive cooling (Carslaw and Jaeger, 1959). The second part of the analysis entails calculating thermo-elastic stress magnitudes and orientations from the temperatures. Thermal stresses in the modeling domain are assumed to be zero when the Lake Edison

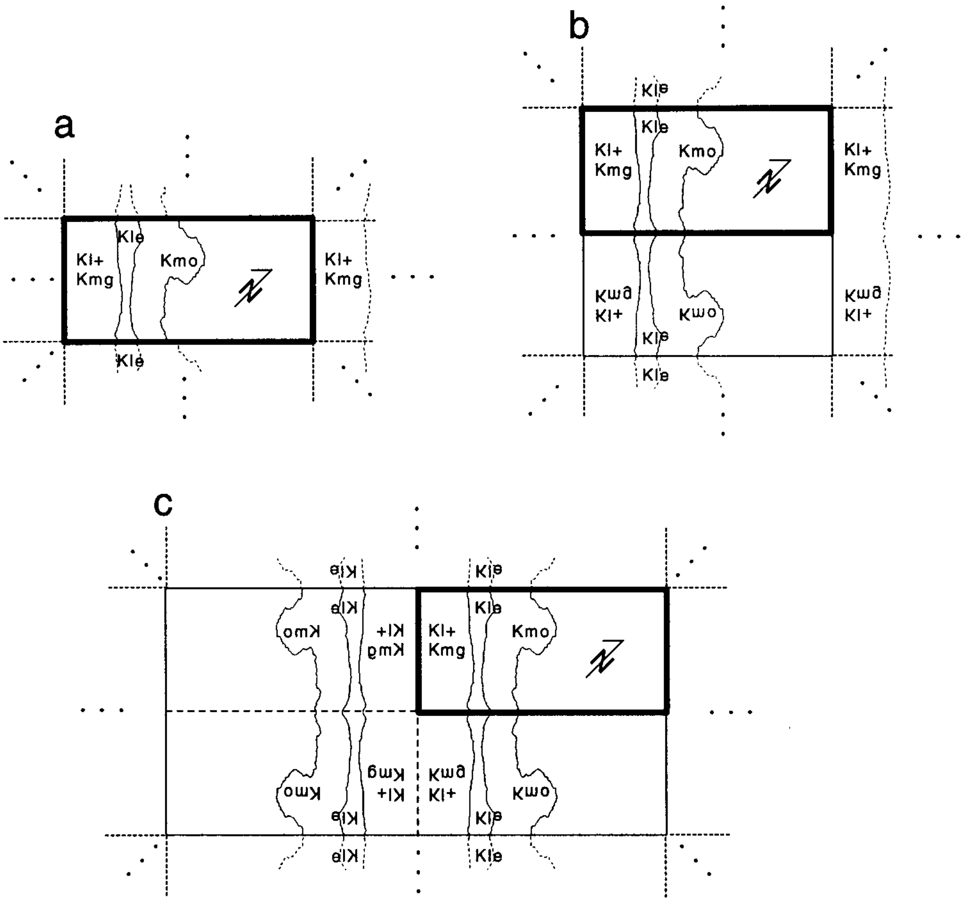

Fig. 5. Boundary conditions for the fast Fourier transform-based code. No-heat-flow boundary conditions are modeled using the 'method of images'. (a) The original modeling domain, (b) the modeling domain after imaging once, and (c) after imaging twice. Three dots symbolize the infinite repetition of the modeling domain in space. The NE-extension of the modeling domain is not shown in scale.

Granodiorite was emplaced, and the far field (i.e. regional) stresses are also set to zero. Regional stresses are considered subsequently. Pluton emplacement is assumed to be rapid relative to the time required for substantial cooling. The geometry of the Lake Edison Granodiorite and its fractures, the depth at which the plutons cooled, and the likely vertical extent of the plutons indicate that a two-dimensional plane analysis is appropriate. The thermo-elastic analyses do not account for stress redistribution or relaxation associated with fracturing. The interested reader is referred to Bergbauer et al. (1998) for a more detailed discussion of the modeling technique.

In these calculations Poisson's ratio ν is set to 0.25 (Carmichael, 1989), Young's modulus E to 3×10^4 MPa, and the coefficient of thermal expansion α to $8 \times 10^{-6}\,^{\circ}\mathrm{C}^{-1}$ (Skinner, 1966). Pluton intrusions are simulated by assigning intrusion temperatures of 800°C to the grid points that lie within the pluton. This intrusion temperature is 100 K less than the intrusion temperature used in similar calculations on hydrous tonalite magmas by Knapp and Norton (1981). The ambient temperature field is set to 230°C. This is below the biotite closure temperature of 330°C and, considering a geothermal gradient of 28°C/km, simulates the ambient temperature at a depth of 8 km. A series of trials shows that this combination of intrusion and ambient temperature in conjunction with a thermal diffusivity κ of $2.45\mathrm{e}^{-6}\,\mathrm{m}^2/\mathrm{s}$ yields cooling curves that agree well with the temperature–time conditions established above for the plutons by their hornblende and biotite ages. The thermal diffusivity is twice the value given by Carslaw and Jaeger (1959) for unfractured granite. The difference might indicate that some cooling in the nearby country rock occurred not only by conduction, but also by convection.

Boundary conditions for the thermo-elastic analyses are defined by the periodicity of the fast Fourier transforms (FFT) used to solve the necessary equations. The FFT-based spectral code assumes that the modeling domain is periodic in the plane of the analysis. Boundary effects with this method can be minimized by placing the area of interest in the center of a modeling domain large enough so that very little heat

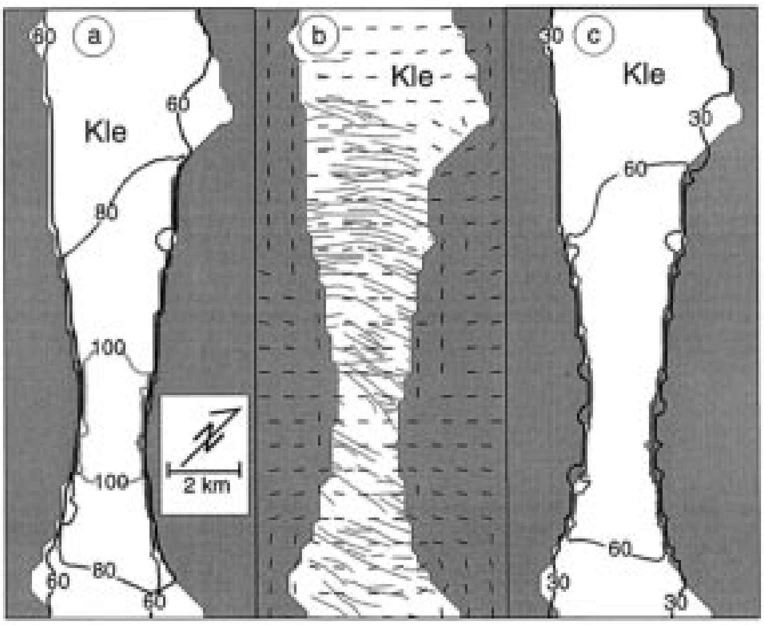

Fig. 6. Calculated thermal stresses (MPa) for the Lake Edison Granodiorite (Kle) at 86 my. (a) Magnitudes of the most tensile horizontal thermal stress. (b) Trajectories of the most compressive horizontal thermal stress (heavy ticks) and Kle-photolineaments from Fig. 1 (thin lines) for comparison. (c) Magnitudes of the maximum horizontal thermal shear stress. Stress trajectories in the shaded area show the directions of the horizontal most compressive stress in the adjacent rock due to the cooling of Kle, and need not match the photolineament pattern there. No photolineaments are shown at locations where Kle is covered by younger deposits (see Fig. 1 for comparison).

reaches the boundaries. However, geologic considerations allow for a smaller modeling domain to be used by invoking no-heat-flow boundary conditions. No-heat-flow boundary conditions were simulated by the method of images (Fig. 5) and assigned to the northwest, southwest, and southeast boundaries of the modeling domain. The no-heat-flow boundary conditions at the northwest and southeast boundaries are reasonable given the pluton's extent in either direction along its trend. Resulting errors at the study area introduced by this simplification are small in magnitude, as the study area is located roughly half way between the northern and southern ends of the modeling domain. A no-heat-flow boundary condition at the southwest margin is assigned considering the size of the two almost concurrent plutons to the west of the area of interest (Kmg and Kl) which are modeled as one single pluton for simplicity. The size of the two plutons together would have resulted in a large modeling domain in order to prevent heat from reaching the domain boundaries. Therefore, half of the surface area of the two combined plutons is modeled, with a no-heat-flow boundary located roughly along a plane that halves the combined plutons. The northeast boundary, however, is sufficiently distant from the modeled portion of the pluton such that very little heat reaches the boundary. After setting up the modeling domain (Fig. 5a), it is imaged once in order to enforce a no-heat-flow condition at the southeast boundary (Fig. 5b). Further imaging (Fig. 5c) yields a no-heat-flow condition at the southwest boundary. Because of the periodicity of the modeling domain, no-heat-flow conditions are thus enforced at all boundaries.

The radiometric dates provide constraints on the initial conditions (e.g. temperature distribution at the time of intrusion) for modeling the cooling and stress evolution of the Lake Edison Granodiorite. We model the Mount Givens Granodiorite and the Lamarck Granodiorite intruding simultaneously at 92 my with a temperature of 800°C. The calculations indicate that by about 91 my the Lamarck Granodiorite cools through the hornblende closure temperature, consistent with the radiometric data. After 3 my of cooling (at 89 my), the intrusion of the Lake Edison Granodiorite is simulated by assigning a temperature of 800°C to the region of the pluton. The plutons are then allowed to cool for another 3 my before the intrusion of the Mono Creek Granite at 86 my. Intrusion ages given by Tikoff and Saint Blanquat (1997) for the Lamarck Granodiorite, the Lake Edison Granodiorite, and the Mono Creek Granite are consistent with intrusion ages used here. Calculated cooling temperatures within the Lake Edison Granodiorite are consistent with the radiometric ages of Fig. 4.

8. Model results

Fig. 6(a–c) depicts the modeled thermal stresses in the Lake Edison Granodiorite at 86 my, just before the intrusion of the Mono Creek Granite. Contours in Fig. 6(a) show the magnitudes of the most tensile horizontal thermal stress. Within the pluton the most tensile thermal stresses range in magnitude from 60 to 123 MPa. The calculated stresses are of the same order of magnitude as plausible fluid pressures and pressures due to overburden, and therefore must be an important contribution to the jointing process. Thermal stresses, assumed to be zero before the intrusion of the Lake Edison Granodiorite, reach maximum values where the pluton has cooled the most and where it is the thinnest.

Ticks in Fig. 6(b) illustrate the direction of the most compressive horizontal thermal stress. If a joint were to form it would propagate in the direction of the most compressive horizontal stress. The overall orientations of the predicted most compressive thermal stress in the pluton compare fairly well to the photolineaments (gray lines). The fit is best in the northwest half of the study area. Not only do the orientations of the most compressive stress change across the pluton to approach its contacts at high angles, they also exhibit the same concavity across the pluton as the photolineaments. Note that Fig. 6(b) shows the photolineaments from Fig. 1 except those trending north to N15E. Those photolineaments are most abundant in the southeast part of the study area (Fig. 1). Owing to their distinctly different orientation we consider those to be part of a separate fracture set, and our model will not account for them. We have no independent evidence for disregarding the north-striking fractures other than their orientation, although some joints that strike NNW are demonstrably younger than those that strike ENE (Martel et al., 1988). The remaining photolineaments and predicted most compressive stress orientations in Fig. 6(b) match rather well.

Fig. 6(c) depicts the magnitude of the maximum shear stress in the intrusion due to cooling. Maximum shear stress magnitudes within the pluton generally range from 30 to 60 MPa, but reach peak values of 102 MPa. These values are of the same order of magnitudes as driving stress magnitudes of Segall and Pollard (1983a). Joint traces are expected to be the straightest where thermally induced shear stresses are highest. Predicted shear stresses are lowest at the northwest and southeast ends of the modeled portion of the Lake Edison Granodiorite.

A quantitative least-median-square (LMS) analysis quantifies the misfit between predicted and observed photolineament orientations. The azimuths of the photolineaments are compared to the orientations of the most compressive horizontal stress within the pluton at grid-points closest to the observations. The LMS-misfit for the thermal stress analysis of Fig. 6 is about 18°.

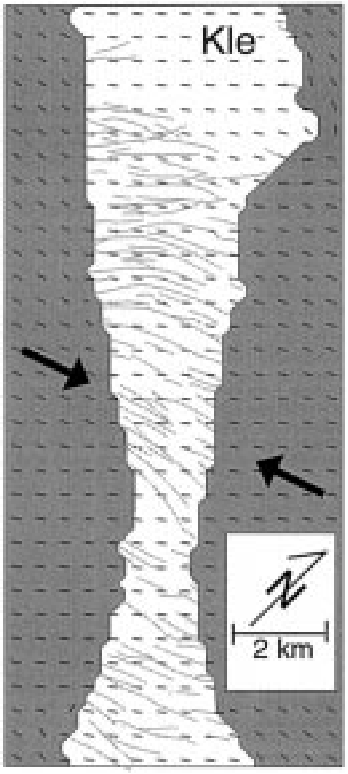

Fig. 7. Trajectories of the most compressive stress (heavy ticks) for the Lake Edison Granodiorite (Kle) at 86 my, calculated by superposing a regional stress field upon the thermal stresses. The regional most compressive horizontal stress (black arrows) trends N70E and exceeds the least compressive stress by 40 MPa. Thin lines represent Kle-photolineaments from Fig. 1 for comparison.

In a series of trials we superpose different uniform regional (extrinsic) stress fields upon the intrinsic thermal stresses to evaluate whether the observed photolineament pattern can be better matched. These applied stress fields represent the combined effects of tectonic stresses and the reaction of the country rock against the intrusion of the pluton. Our focus is on the intruding pluton, not the adjacent country rock. A visual inspection of the case where the most compressive horizontal regional stress ($S_{\mathrm{H}}^{\mathrm{regional}}$) trends N70E and the regional differential stress ($S_{\mathrm{H}}^{\mathrm{regional}} - S_{\mathrm{h}}^{\mathrm{regional}}$) is 40 MPa (Fig. 7) reveals a better fit than where regional stresses are absent (i.e. Fig. 6). The differences between Fig. 6(b) and Fig. 7 are subtle, but upon close inspection one can see that trajectories generally match the photolineaments better in Fig. 7. This effect is most pronounced at the northeast contact of the Lake Edison Granodiorite with the younger Mono Creek Granite, however, it can be observed throughout the entire modeled pluton. A N70E-direction of the most compressive regional stress squares with the most compressive stress direction proposed by Christiansen (1995) at the time the joints formed (Fig. 3c). Applying a greater differential regional stress than

40 MPa would force the predicted most compressive stress trajectories to cross the pluton with almost no deflection, and would therefore not match the observed curvature of the photolineaments in the pluton as well. Applying a smaller regional differential stress would better model the curvature of the photolineaments, however, the photolineaments near the waist of the pluton would not be matched very well.

The LMS-misfit is 14° if a regional differential stress of 40 MPa, with the most compressive stress at N70E, is superposed upon the thermal stresses. This decreases the misfit of observations and predictions by 4° compared to the analysis for thermal stress only. This finding is consistent with the orientation of the joints being governed by a combination of thermal and regional stresses. LMS-misfits for uniform regional stresses alone are comparable to the misfits computed for the cited combination of thermal and regional stresses, but the stress trajectories are straight and completely fail to account for the observed curvature of the photolineaments. Considering the simplicity of our model, we do not expect a misfit of zero. We consider the LMS-misfit of 14° to be small and to support the idea that thermal stresses played an important role in the jointing process.

We also calculate the strain arising from thermal cooling. Using Hooke's law for thermo-elastic materials (Timoshenko and Goodier, 1970), a coefficient of thermal expansion α of 8×10^{-6}°C^{-1}, and the average temperature in the Lake Edison Granodiorite at 86 my, the average thermal strain associated with cooling of the pluton is 1.3×10^{-3}. This is roughly an order of magnitude greater than the joint-accommodated strain determined by Segall and Pollard (1983a) for outcrops in the Mount Givens Granodiorite. The calculated strains associated with cooling are thus more than sufficient to account for the documented strains.

9. Discussion

The preceding analyses demonstrate that thermal stresses during the initial cooling of the Lake Edison Granodiorite are of sufficient magnitude to significantly effect jointing in the pluton. The general conclusions are robust even given the uncertainties in temperatures and pressures during cooling. For example, even if uncertainties in these temperatures resulted in an overestimation of the temperature drop by 100 K, the error introduced in the computed most tensile stress would only be approximately 20 MPa. This would not change our conclusions qualitatively considering the calculated most tensile thermal stresses have magnitudes of 60–123 MPa. Furthermore, the solid elastic thermo-mechanical parameter ($E\alpha$) of 0.24 MPa/°C used here is half that of Gerla (1988). Adopting his value would double the thermal stress magnitudes calculated here. Even though the fluid pressures and regional loads are only weakly constrained, they are unlikely to dwarf thermal stresses of the magnitudes calculated.

Bateman and Wahrhaftig (1966) stated that the joints in Sierran plutons formed "after the consolidation of the entire batholith" because "they cross pluton boundaries with little or no deflection". Faults and fault zones indeed do extend well across pluton contacts, but our field documentation demonstrates that numerous joints terminate near the Kl–Kle contact, and that joint geometry across that contact varies significantly. A cooling pluton with concave-in contacts (e.g. plutons shaped like hourglasses) can induce most compressive stresses in the adjacent rock that are normal to the contact (Bergbauer et al., 1998). This would permit some joints to extend straight across a pluton boundary for some distance. Positive driving stresses that would open a joint in one pluton could also drive the joint some distance into a neighboring rock even if a joint-normal compressive stress acted there (Pollard and Muller, 1976). Thus a thermal stress source does not necessarily require joints to terminate exactly at a pluton boundary.

A uniform regional stress field alone cannot account for the observed curvature of the photolineaments in Fig. 1. In spite of its simplicity, the model used for the thermo-mechanical analysis reproduces the observed joint pattern reasonably well. If photolineaments that trend from north to N15E do represent a separate fracture set and are removed from the data set (Figs. 6b and 7), the match between model predictions and observations is good. Discrepancies between observations and predictions in the southeastern part of the study area may reflect material heterogeneity and anisotropy: a dike-like intrusion of late Cretaceous age (Kqm1 in Fig. 1) strikes parallel to the long axis of the pluton there, and the Rosy Finch shear zone also crosses the pluton in this area. Both could have perturbed the stress field in this area during fracturing. If the shear zone formed before the joints, it could have influenced joint propagation. At this point the relative ages of the joints and the shear zone remain an outstanding issue.

Other possible explanations for the discrepancies are somewhat problematic. For example, we assume that the pluton cooled with its contacts as shown on the geologic map. The position and shape of the east contact of the Lake Edison Granodiorite could have been different when the Mono Creek pluton intruded: the existing geometry of the Kle–Kmo contact might not reflect the geometry of the contact at the time the Lake Edison Granodiorite cooled and fractured. However, the observed flow-foliation within the Lake

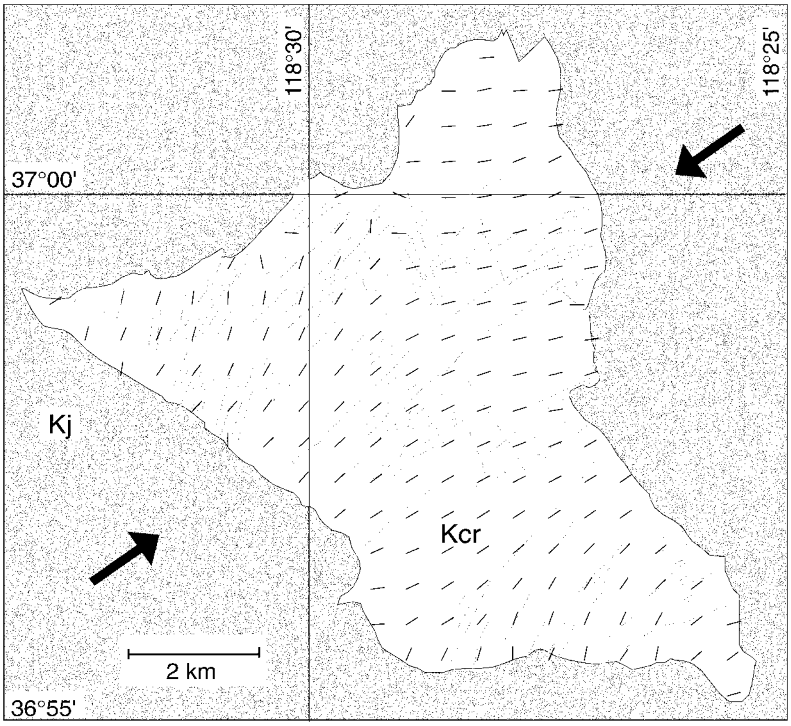

Fig. 8. Photolineament map (after Moore, 1963; Moore, unpublished data) and modeled most compressive horizontal stress directions (black ticks) for the Granodiorite of Cartridge Pass (Kcr) after 0.9 my of cooling. All geologic units older than Kcr are labeled Kj. The most compressive regional horizontal stress, which acts at N55E and exceeds the least compressive regional horizontal stress by 30 MPa, is superposed upon the thermal stresses. The 11 photolineaments west of 118°32′ or wholly north of 37°00′ are from our examination of aerial photographs.

Edison Granodiorite parallels the contact, indicating that the contact geometry might not have changed significantly due to the intrusion of the Mono Creek Granite. In addition, we did not account for stress redistribution due to the fracturing process. Opening of a joint can rotate the principal stresses near it by as much as 90° (Pollard and Segall, 1987). This could result in multiple fracture orientations where induced thermal stresses are high and driving stresses are sufficient in magnitude to produce more than one set of joints. However, this possibility does not account for the good match in the northwest half of the study area.

We inferred the magnitude of the regional differential stress by trying to match the observed curvature of the photolineaments and by minimizing the calculated LMS-misfit between observed and predicted fracture orientations. Considering a proposed value of 50 MPa by McGarr (1980) for the differential stress at 3 km depth, and a differential stress of approximately 50 MPa measured in the KTB deep-borehole in Germany at a depth of 8 km (Brudy et al., 1997), the value for the differential stress of 40 MPa in Fig. 7 is not unreasonably large. A larger differential stress would force the most compressive stress direction to cross the pluton with less deflection, which would not be in agreement with the observed photolineament curvature. However, the effect of the remote differential stress on the most compressive stress direction depends partially on the magnitude of the thermally induced most tensile stresses. If thermal stresses in the pluton were greater in magnitude than we predict (e.g. the actual solid elastic thermo-mechanical parameter was greater than the value we used), a greater remote differential stress magnitude could be applied and would still be consistent with the observed photolineament pattern.

To test the generality of our model, an additional pluton from the Sierra Nevada batholith was modeled, the Granodiorite of Cartridge Pass (Fig. 8, Moore, 1963, 1978; Bateman, 1965, 1992; Bergbauer et al., 1998). This pluton is younger than all its surrounding neighbors. A regional differential stress of 30 MPa, with the most compressive stress at N55E, was superposed on the thermal stresses to produce the model result shown in Fig. 8. Photolineaments in this pluton, shown in thin lines, are broadly curved and are consistent with our calculations. These results indicate that our model is useful and support our contention that thermal stresses in cooling plutons can strongly influence the development of joints.

10. Conclusions

The age, mineralogy, kinematics, and geometry of east-northeast-striking joints in the Lake Edison Granodiorite are consistent with the joints originating when the pluton cooled. Fracture geometry on different scales suggests stresses intrinsic to the pluton are responsible for the formation of the vertical joints. Radiometric, geochemical, and kinematics data tie the formation of the joints to the time when the temperature in the pluton was between the hornblende and the biotite closure temperatures. A two-dimensional thermo-elastic stress analysis indicates that thermal stress magnitudes of 60–123 MPa could have been attained. These would contribute significantly to the driving stress for jointing. The modeled orientation of the most compressive thermal stress trajectories within the pluton are grossly consistent with the orientation of the joints as revealed by the photolineaments. If the most compressive horizontal regional stress was oriented at N70E and exceeded the least compressive stress by 40 MPa, the stress field in the pluton allows for an improved match of the observed photolineament pattern. Moreover, maximum shear stresses calculated for the pluton agree with proposed driving stresses for the formation of straight joints. Finally, calculated average strains from the thermal stresses are more than sufficient to account for the strain accommodated by the joint openings. Thermal stresses thus appear to contribute significantly to the formation of the joints in a cooling pluton. If our conclusions apply to other plutons as well, then the general orientations of the early-formed joints in a pluton could be predicted mainly from its geometry and age relative to the adjacent rocks and the regional stresses at the time of cooling.

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