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Oblique opening and noncoaxial emplacement of the Jurassic Independence dike swarm, California

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Abstract

Several features of the Independence dike swarm (IDS) indicate that dikes opened obliquely to their walls in a sinistral sense. The IDS is largely latest Jurassic in age (≈ 148 Ma) and has been traced for more than 600 km along its NW–SE strike from east-central to southern California. Field and petrographic observations from the IDS in the Sierra Nevada indicate that: (i) some, and perhaps all, of the dikes initially opened perpendicular to their margins and then were sinistrally sheared; and (ii) sinistral displacement occurred during and shortly after dike injection. Dike emplacement overlapped in time with the formation of wall rock mylonite zones which accommodated shear varying in sense from sinistral to west-side-down reverse. We suggest that the IDS intruded dilatant fractures within a regional sinistral shear system. The swarm is located within or along the eastern flank of the Cordilleran subduction-related magmatic arc. The IDS and associated wall rock deformation may record partitioning into the magmatic arc of the sinistral component of strongly oblique Late Jurassic subduction. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Dikes typically form perpendicular to the least compressive stress σ_3 (Anderson, 1951; Odé, 1957) and are commonly used to map patterns of, and changes in, regional stress fields (e.g. Zoback and Zoback, 1980; Best, 1988; Ernst et al., 1995). However, in some instances dike swarms do not bear a simple relationship to regional stresses. For example, Delaney et al. (1986) and Tokarski (1990) described dikes which were injected along pre-existing fractures or conjugate fracture sets and which opened in a direction oblique to their walls. The relationship between dike geometry and the ambient stress field may also differ from Anderson's prediction when dikes are injected in a zone of noncoaxial finite strain. Tensile cracks within a shear zone initially form normal to σ_3, but bulk noncoaxial strain will cause the cracks to rotate and to accommodate shear strain as finite deformation proceeds. Understanding of these phenomena grew out of observations of hydrothermal veins (e.g. Ramsay, 1980), but synkinematic magma-filled cracks are likely to undergo similar processes.

In this paper we describe field relations which suggest that northwest-striking dikes of the Jurassic Independence dike swarm (IDS) of eastern California (Fig. 1) opened in a north–south direction, oblique to the expected northeast–southwest direction. We propose that the dike swarm intruded a crustal-scale sinistral shear system, localized along the subduction-related magmatic arc, during strongly left-oblique subduction at the end of the Jurassic.

2. The Independence dike swarm

The IDS is a major feature of the Mesozoic Cordilleran magmatic arc of California (Moore and

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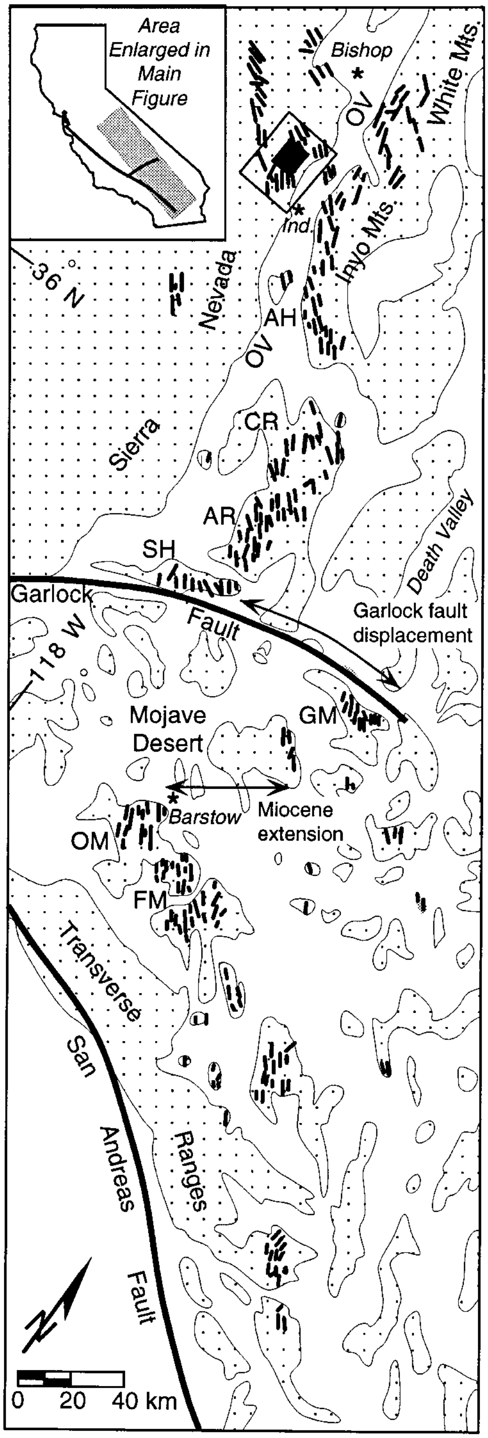


Fig. 1. Distribution of Independence dikes (lines) and pre-Tertiary rocks (stippled) in eastern California, modified from James (1989). Note oblique north direction. The dike swarm likely continues to the north of this figure (see text). The dikes stitch the Mojave region to the eastern Sierra and cross several proposed lithospheric boundaries. Box at north end outlines the Mt Pinchot quadrangle, and solid box within designates the Woods Lake and Twin Lakes areas. Double-headed arrows denote post-dike faulting which offsets the swarm. AH = Alabama Hills, AR = Argus Range, CR = Coso Range, FM = Fry Mts, GM = Granite Mts, Ind. = Independence, OM = Ord Mts, OV = Owens Valley, SH = Spangler Hills.

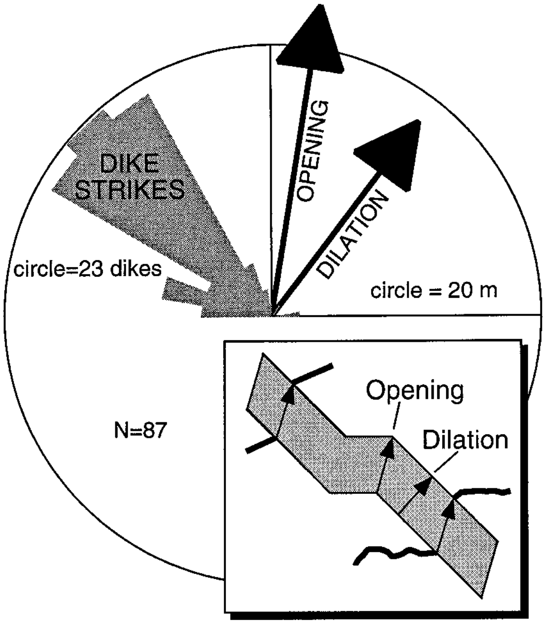


Fig. 2. Cumulative opening and dilation vectors for three traverses across dikes in the Twin Lakes area. ‘Opening’ and ‘dilation’ are illustrated in the inset; opening vectors are measured by two-dimensional matching of points across the dike, whereas dilation vectors are measured perpendicular to dike walls in near-horizontal outcrops. Dilation is, by definition, perpendicular to strike. The mean opening and dilation vectors differ by approximately 30°.

Hopson, 1961; James, 1989; Carl et al., 1998). Mafic, intermediate, and subordinate felsic dikes are exposed over a strike length of more than 600 km, from the east-central Sierra Nevada to the Mojave Desert (Fig. 1). The accepted age of the swarm is ≈148 Ma (Chen and Moore, 1979; James, 1989), although Late Cretaceous dikes of similar orientation and petrography locally occur (Coleman et al., 1994). The swarm has generally been interpreted to indicate a brief pulse of northeast–southwest crustal extension in the Late Jurassic (Chen and Moore, 1979; James, 1989; Schermer, 1993).

Independence dikes are well exposed throughout a large section of eastern California (Fig. 1). In desert exposures east and south of the Sierra Nevada, dikes typically are undeformed or cataclasized, whereas dikes in glaciated exposures along the Sierran crest typically contain ductile fabrics. These differences probably reflect shallower depths of intrusion at exposures south of the Sierra Nevada. For example, dikes exposed in the Fry Mountains, central Mojave Desert, intruded shallow levels and possibly fed surface lava flows (Karish et al., 1987; Schermer and Busby, 1994). At shallower crustal levels, cooler temperatures favored brittle deformation in the southern IDS (Carl et al., 1998).

Outstanding exposures are found in the Woods Lake and Twin Lakes Basins of the Mt Pinchot quad-

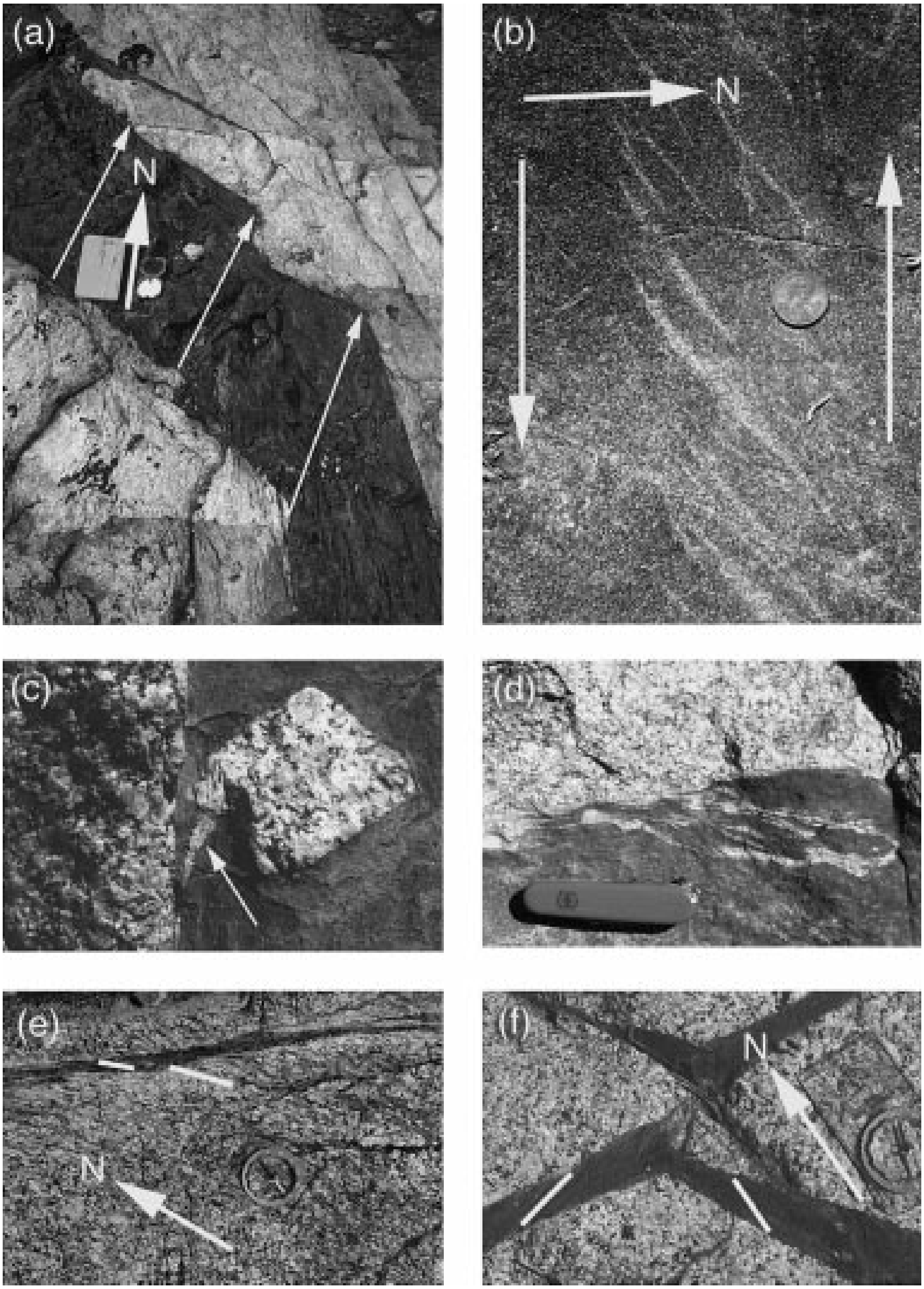


Fig. 3. Dike features in Woods Lake, Twin Lakes, and Rae Lakes Basins. (a) Typical sinistral separation of wall rock markers across a mafic dike. Matching distinctive jogs in dike margins of older aplite dike defines an opening vector of approximately 020°, strongly oblique to the dike's strike. Field book is 19 cm tall; Twin Lakes Basin. (b) Close-up of a west-striking dike, approximately 1 m wide, showing sinistral gash fractures filled with quartz–feldspar mixture interpreted as residual liquid from the crystallizing diorite. These fractures imply sinistral deformation before the dike had completely solidified. Note that most dikes in this area (near Dollar Lake, approximately 3–4 km north of Rae Lakes, 6 km southwest of Woods Lake) strike anomalously westerly relative to the rest of the swarm and may be rotated (Moore, 1963). In contrast, west-striking dikes conjugate to the common northwest-striking dikes locally show dextral fabric (see photo f). (c) Small block of granodiorite (approximately 2 cm on a side) separated sinistrally from the wall and connected to it by a thin stringer of partially melted granodiorite. In all observed cases the sense of shear implied is sinistral. Woods Lake Basin. (d) Wispy granitic streaks in diabase, again defining a sinistral sense of shear. See Philpotts and Asher (1994) for similar features. Knife is 10 cm long; Woods Lake Basin. (e) Thin, highly sheared dike with sinistral shear fabric also defined in the host granodiorite. White line segments parallel fabric in the dike and host rock. Compass circle is 4 cm in diameter; Woods Lake Basin. (f) Conjugate dikes in Woods Lake Basin; northwest-striking dike has a sinistral solid-state fabric, and east-striking dike has a complementary dextral fabric. White line segments parallel fabric in dikes. Compass circle is 4 cm in diameter.

rangle (Moore and Hopson, 1961; Moore, 1963; 1—box inset). In this area the dikes intrude a complicated array of Jurassic plutons and pre-Jurassic metamorphic rocks (Moore, 1963). The Jurassic plutons contain abundant heterogeneities (e.g. mafic enclaves and aplite dikes) which make excellent markers for determining dike offsets. The dikes are also commonly bounded by distinctively shaped jogs that permit measurement of separation between initially adjacent points on dike walls.

In this paper we focus on that part of the IDS north of the Garlock Fault. Exposures south of the Garlock Fault are less well studied, less well exposed, dismembered by late Cenozoic faulting (Glazner et al., 1989), and locally rotated about steep axes (Ron and Nur, 1996).

3. Field relations indicating north–south opening and sinistral shear

Field evidence indicates that net opening across many dikes in the area was broadly north–south (Fig. 2). Structural relationships indicate that the lateral component of this opening was accommodated during and shortly after solidification of the dike.

Commonly, wall rock markers are separated sinistrally across northwest-striking dikes and dextrally across rare northeast-striking dikes, such that reconstructing pre-dike geometries requires closing the dikes along vectors oriented approximately north–south. For example, the northwest-striking mafic dike in Fig. 3(a) separates an aplite dike by 70–80 cm, an amount approximately equal to the mafic dike's width. Vectors connecting matched points across the dike trend approximately north–south. This relationship is common in the Woods Lake–Twin Lakes area. Although some of the apparent opening vectors have been modified by post-emplacement shear, dikes that lack ductile fabrics also define oblique opening vectors.

The vertical component of dike opening is difficult to determine owing to the generally planar glacial exposures but, where determinable in rare three-dimensional exposures, it is small. Although shear sense determinations in two dimensions can be misleading (e.g. Wheeler, 1987), most wall rock markers (aplites) away from dikes are steeply oriented and it is unlikely that their apparent separation in horizontal outcrops is opposite to the true shear sense. Close geometric matches between opposing dike walls corroborate a lack of out-of-plane movement in horizontal exposures.

Fig. 3(b) shows a west-striking diorite dike which contains sigmoidal segregations filled with a feldspar-rich phase of the host diorite. We interpret these segregations as gash fractures that filled with the late-crystallizing residue of the host dike. If this interpretation is correct, then the gashes record sinistral shear along the host dike which occurred before magma had completely solidified.

Compelling evidence for wall-parallel shearing while the dikes were still partially molten comes from stringers of melted wall rock in mafic dikes (Fig. 3c and d). Blocks spalled from dike walls and entrained by magmatic flow are consistently displaced sinistrally from their original sites. The blocks are commonly physically linked to the walls by narrow stringers of intergrown quartz and feldspar that resemble a granitic minimum melt and lack microstructural evidence for solid-state flow. The resulting geometry closely resembles asymmetric boudinage. However, the field and petrographic observations imply that the quartz–feldspar stringers represent wall rock melting by injection of a hot mafic magma and that wall-parallel sinistral shearing occurred before either melt had solidified (see also Philpotts and Asher, 1994).

Fig. 3(e) shows a thin diorite dike with a strong sinistral mylonitic fabric. The fabric is weakly developed in the host granodiorite near the dike margins, whereas ductile fabrics are common in mafic dikes in this region (Moore and Hopson, 1961; Carl et al., 1995). The relation is perhaps surprising in that diorite, being composed mainly of hornblende and plagioclase, should be substantially stronger than the quartz-rich granitoid wall rock. This suggests the possibility that the dikes were hotter than their wall rocks when sheared, in turn implying that solid-state shearing occurred shortly after intrusion. Zulauf and Helferich (1997) interpreted a similar deformation history for a synkinematic trondhjemitic dike which intruded an active transcurrent shear zone. Support for the suggestion comes from cross-cutting relations of dikes in the Woods Lake pluton. Carl et al. (1998) document variably sinistral to reverse-sense mylonite zones cutting the Woods Lake pluton (165 Ma; Chen and Moore, 1982) that both cut and are cut by the IDS. Mylonite zones generally strike northeast and dip southeast, range in size from <1 to >10 m across, and potentially accommodated displacements on the order of 100s of meters (Carl, unpublished data). This observation implies that wall rock ductile shearing overlapped in time with IDS intrusion and that the IDS possibly (at least locally) was emplaced in a transpressional tectonic setting (Carl et al., 1998).

Northeast- to east-striking dikes, conjugate to the dominant set, are also present (Fig. 3f). In this particular exposure, the northwest-striking dikes contain a weak sinistral ductile fabric, and the east-striking dikes have a weak dextral fabric. Restoration of dike walls shows that the net opening vector was approximately north–south.

Some dikes in the Twin Lakes area of the Sierra

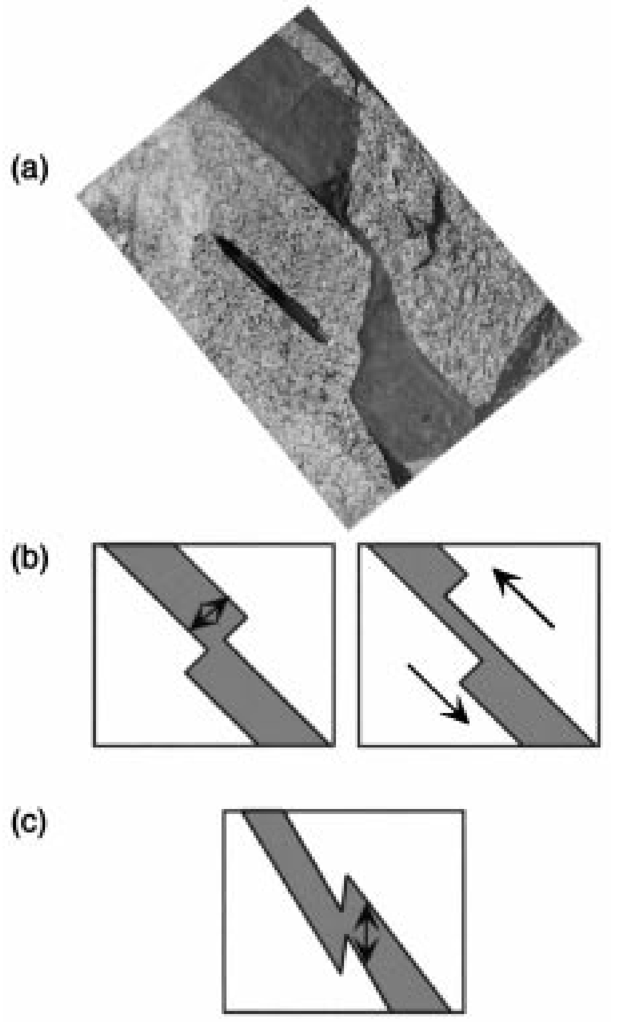


Fig. 4. Field relations suggesting a two-stage history for many dikes. (a) Dike in Woods Lake Basin showing offset of its wall which requires dilation followed by sinistral shear (see text). This geometry is not uncommon. Pencil is 15 cm long. (b) Schematic illustration of two-stage opening history which satisfies field relations of several dikes. (c) Schematic illustration of dike wall geometry which would require one-stage, north–south opening. This dike geometry has not been observed.

Nevada require a more complex displacement path than unidirectional north–south opening. In Fig. 4(a), the distinctive right-angle jog in the dike is sinistrally offset. The dike lacks a solid-state fabric; therefore, the sinistral shear is interpreted to have occurred before solidification of magma in the dike. Geometric interference between the right-angle steps in the dike walls requires that the dike must first have opened perpendicular to its walls far enough for the steps to clear each other, followed by sinistral shear along the dike (unless there was significant out-of-plane movement). Several such examples were observed in the Twin Lakes area, and no counter-examples requiring initial oblique opening were observed (Fig. 4c).

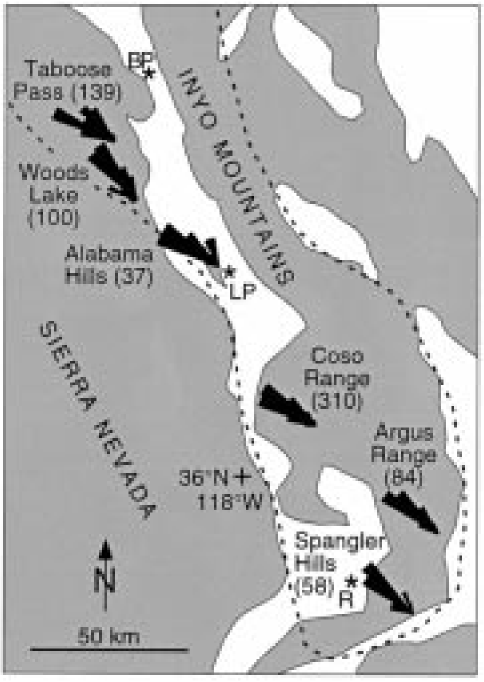


Fig. 5. Rose diagrams of dike strikes in several areas north of the Garlock Fault; number of measurements in parentheses. Data from this study, Smith (1962) for Argus Range, and R. Whitmarsh (personal communication, 1997) for the Coso Range. BP = Big Pine, LP = Lone Pine, R = Ridgecrest. Dashed line outlines approximate extent of the dike swarm.

4. Dike orientation

Dikes in the IDS typically strike west-northwest, with a mean of 307° and a standard deviation of 20° (Fig. 5). Nearly all of the dikes were intruded into Jurassic plutonic rocks. The belt of Jurassic plutons in eastern California strikes approximately 320° (Bateman, 1992) and the overall trend of the IDS is approximately 320–335° (James, 1989), although the original limits of the Jurassic batholith and IDS are difficult to determine owing to obliteration by Cretaceous intrusions and post-Jurassic deformation. Based on these data, it appears that individual dikes typically strike 10–30° more westerly than the Jurassic batholith and than the overall trend of the dike swarm.

5. Summary of key features

Data summarized above emphasize the following important features of the IDS:

1. Net opening vectors of many dikes in the central Sierra Nevada are oriented roughly north–south, oblique to the expected dike-perpendicular northeast–southwest direction. At least some dikes initially opened at a high angle to their walls and then

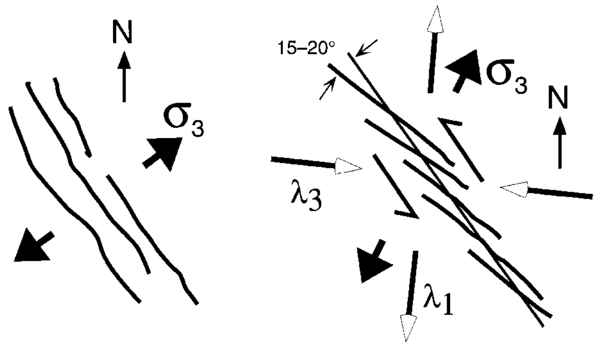
were sheared parallel to their walls. Sinistral shearing occurred in many cases while the dikes were still molten and in others after solidification.

2. Northwest-striking dikes which were solid when sheared contain a strong sinistral ductile fabric that is especially pronounced along dike margins. Rare northeast-striking dikes commonly show a complementary dextral fabric. Several lines of evidence suggest that the solid-state fabric formed close in time to dike emplacement. Therefore, we suggest that the variable development of a solid-state fabric in dikes that record oblique net opening reflects relatively minor variations in the relative timing of solidification vs shearing.
3. Relations of the IDS to ductile deformation of the Woods Lake pluton imply that the dike swarm was intruded, at least locally, in a transpressional tectonic environment.
4. Dikes north of the Garlock fault typically strike 10–30° more westerly than the overall trend of the swarm, rather than parallel to it, as is common for large dike swarms (Ernst et al., 1995). The dikes form a right-stepping en échelon pattern.
5. The IDS was injected predominantly along the axis of the Jurassic batholith and spans a similar compositional range; it is not predominantly basaltic, as are many rift-related dike swarms (Hopson, 1988).

6. Structural interpretation

The observations above suggest two end-member alternatives: either the dikes opened in a north–south direction oblique to their walls, or the dikes opened perpendicular to their walls and then underwent sinistral shear parallel to their walls. The simpler interpretation for most of the dikes is oblique opening. This is most likely to occur if the magma was injected along pre-existing fractures that were not perpendicular to the minimum horizontal compression at the time of their emplacement. However, this interpretation does not account for dikes that initially opened at a high angle to their walls and then were sheared (Fig. 4). The only clear difference between such dikes and the remainder is the right-stepping jogs that demand a two-stage history. Conversely, we have observed no dikes whose wall geometry requires oblique opening, precluding such a two-stage history (Fig. 4c). Therefore, normal dilation followed by shear may have occurred along all of the dikes, an interpretation which, although more complex, accounts for all of the observations.

Such a two-stage history may be explained if the principal axes of finite strain related to dike emplacement were oriented counterclockwise relative to the principal stress axes; that is, if the dikes were emplaced in a sinistral noncoaxial strain field. We therefore propose that the Independence dike swarm formed in a regional zone of sinistral shear along the Jurassic arc (Fig. 6). Once a dike formed, the resulting plane of weakness could be exploited by ongoing shear.



(a) Coulomb-Anderson interpretation

(b) Shear zone interpretation

Fig. 6. Comparison of standard Coulomb–Anderson dike interpretation with the shear zone model proposed here. In the shear zone interpretation the dikes fill fractures that are similar to Riedel shears (e.g. Sylvester, 1988) and form a right-stepping en échelon array. Note that the maximum finite elongation (λ_1) and the minimum compressive stress (σ_3) are not parallel, as is the case in noncoaxial deformations.

Simultaneous sinistral shear and injection of subvertical dikes suggests a transtensional bulk strain regime. However, the dikes both cut and are cut by mylonite zones in the Woods Lake pluton that vary from WNW-striking and sinistral sense to NNE-striking and reverse sense (Carl et al., 1998). Therefore, sinistral shear, dike injection, and horizontal contraction all affected the same rock volume at nearly the same time. The contrasting structures can be combined into a unified kinematic framework characterized by a WNW-trending maximum horizontal shortening axis, a NNE-oriented maximum horizontal extension axis, and vertical thickening (Fig. 6). Whether, in a horizontal plane, the shear zone accommodated overall transtension, transpression, or nearly pure strike-slip, depends on the relative magnitudes of dilation across the dikes vs contraction across thrust-sense mylonite zones. In traverses across the most dense parts of the swarm, the dikes accomplish ~10% dilation (Carl, unpublished data). Contraction across thrust-sense mylonite zones has been determined for only a small fraction of those observed, but present measurements suggest that horizontal contraction of 10% or more is possible. Therefore, as yet we are unable to quantify the strains sufficiently to determine whether the bulk dike-related strain is transpressive or transtensional.

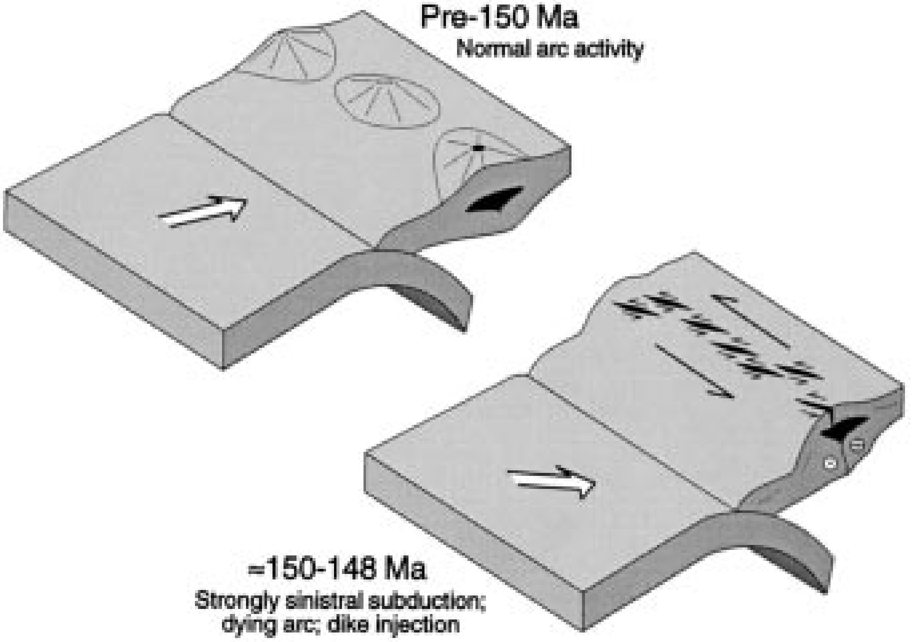


Fig. 7. Schematic plate tectonic setting of the IDS. In the Jurassic prior to about 150 Ma a well-developed continental margin arc was developed. At about 150–148 Ma, the time of the J2 cusp, the IDS was injected and the arc shut down as subduction switched to strongly sinistral oblique. The IDS exploited an en échelon array of fractures developed in the brittle carapace above the arc.

The field observations thus conflict with rift interpretations of the IDS but are consistent with intrusion into a crustal-scale zone of sinistral shear. We hypothesize that the dikes were intruded into the brittle carapace above active Jurassic plutons in a shear zone localized by thermal weakening of the lithosphere along the magmatic arc. This interpretation accounts for the oblique opening direction, the associated mylonite zones, and the en échelon geometry of the dikes. It is also consistent with long-standing proposals that Late Jurassic tectonics of the Cordilleran orogen were characterized by sinistral oblique plate convergence (e.g. Oldow et al., 1984).

7. Tectonic setting during IDS injection

The IDS was intruded at the end of the Jurassic, during important magmatic and tectonic transitions in the western United States. Magmatism waned nearly to the point of extinction before a resumption in the middle Cretaceous (Stern et al., 1981; Chen and Moore, 1982; Glazner, 1991). The IDS appears to represent the last gasp before this magmatic hiatus.

The Nevadan orogeny (Bateman and Clark, 1974; Ingersoll and Schweickert, 1986) affected much of central California in Late Jurassic time. The plate-tectonic cause of the Nevadan orogeny remains a subject of debate, but some workers attribute it to collision of an island arc with the North American continental margin.

Hot-spot reconstructions suggest sinistral convergence during the active Jurassic arc (Glazner, 1991). Wolf and Saleeby (1995) noted that injection of the Independence and several other northwest-striking dike swarms coincided in time with a cusp in the apparent polar wander path of North America. This event, the J2 cusp of May and Butler (1986) and May et al. (1989), marked a time when the northward component of North America's velocity increased to 150 km/Ma or more. Although the trajectory of the plate west of North America is unknown, the implied large increase in the northward component of North America's velocity makes it likely that there was a significant sinistral shear between North America and the oceanic plate(s) to its west (May and Butler, 1986; May et al., 1989).

Hopson and coworkers (in Dickinson et al., 1996) argue that the plate stratigraphy of the Coast Range ophiolite in California requires dextral oblique subduction in the Late Jurassic (see Dickinson et al., 1996 for alternative viewpoints). These data provide a novel approach to understanding plate kinematics, but we find the structural evidence for sinistral shear during at least the latest Jurassic compelling (e.g. Oldow et al., 1984; Wolf and Saleeby, 1995; this study).

8. Tectonic model

The apparently brief duration of IDS emplacement (Chen and Moore, 1979; James, 1989) suggests triggering by a discrete plate-tectonic event. There are two clear candidates for such a discrete event: arc–continent collision or an abrupt latest Jurassic change in plate kinematics. In either case, the IDS and its unusual characteristics formed in response to an increase in the transmission of sinistral shear into the magmatic arc (Fig. 7).

Strongly oblique convergence in modern arcs is commonly expressed by strike-slip faults along the arc (Fitch, 1972; Jarrard, 1986). The arc is a likely place for lithospheric failure because the geothermal gradient is high and therefore the lithosphere is thin and weak. Either a rapid increase in the lateral component of subduction (cf. McCaffrey, 1992) or a sinistral–oblique collisional event could therefore have induced sinistral shear along the arc. Failure of the cooler, relatively strong upper crust above a throughgoing deformation zone would produce discrete tensile fractures (akin to Riedel shears; e.g. Sylvester, 1988) which were then injected by magma from the dying arc and exploited as discrete surfaces of sinistral shear.

9. Conclusions

Field data from the IDS indicate that dikes in the swarm opened in a north–south direction, oblique to the opening direction predicted by Coulomb–Anderson theory. The dikes appear to be magma-filled cracks, formed in tension and then exploited in shear, within a Late Jurassic crustal-scale sinistral shear zone. Paleomagnetic data suggest that subduction along the North American Cordillera was strongly left-oblique in the Late Jurassic. This interpretation implies that the Independence dike swarm and associated deformation may reflect partitioning of sinistral shear into the active magmatic arc either during oblique subduction or during oblique arc–continent collision during the Nevadan orogeny.

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