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Geometry of Silicic Dikes Beneath the Inyo Domes, California

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Structural geologic evidence in the vicinity of the Inyo Domes indicates that the youngest extrusive products were erupted from a silicic dike that divided into at least three segments which underwent up to 30° of clockwise rotation as they neared the surface. The geometry of ground cracks, explosion craters, and surface structures on the domes suggest that the dike may have propagated laterally from a source beneath Mammoth Mountain, with both the overall dike and the individual segments rising as they moved northward. Structural evidence and tephrochronology also imply that the actual vents may have migrated northward along individual dike segments as the activity evolved from explosive eruptions to the more quiet emplacement of lavas. Monitoring of changing patterns of ground cracks and faults may assist in predicting the sites and timing of future eruptions.

INTRODUCTION

Increased seismic activity near Mammoth Lakes, California, over the past 5 years has generated concern about possible new eruptions of silicic magma. Interpretations of deformation data have placed intrusions at several possible alternative locations, including a region beneath the resurgent dome of Long Valley caldera [e.g., *Savage and Clark*, 1982; *Rundle and Whitcomb*, 1983], another east of Mammoth Lakes along the south moat of the caldera [*Cockerham and Savage*, 1983; Savage and Cockerham, 1984], and a third farther west along the trend of the rhyolitic Inyo Domes [*Whitcomb and Rundle*, 1983]. Recognition that the extrusion 550 years ago of the three largest Inyo Domes and associated pyroclastic products occurred nearly simultaneously from several vents along a linear trend [*Miller*, 1983, 1985] supports the idea that dike intrusion is a likely precursor to future eruptions in the Mammoth Lakes area.

In order to improve the ability to predict hazards associated with such dike-fed activity, it is important to be able to delineate the geometry of dikes that were the sources of previous silicic eruptions. This paper will address structural geologic evidence indicating that the youngest of the Inyo Domes were fed by a silicic dike that propagated laterally from the area beneath Mammoth Mountain. The dike broke up into segments that rotated about southwardly dipping axes as they approached the surface, in response to depth-dependent changes in stress or fracture orientations. Changes in ground crack orientation that reflect this near-surface rotation of dike segments might be used to supplement other geophysical techniques used to predict the timing and location of future eruptions.

Fink and Pollard [1983*a*] cited three types of structural geologic evidence that indicate the presence and orientation of dikes beneath silicic extrusions: (1) gross alignments of vents and elongate shapes of domes, (2) ground cracks and faults surrounding domes, and (3) distinctive structural and textural patterns on dome surfaces. The Inyo Domes represent an excellent site at which to apply these criteria for evaluating conduit geometry [*Fink and Pollard*, 1983*b*]. Vents for the domes are clearly aligned, ground cracks and faults associated with the extrusions are abundant, and the young domes have numerous surface structural features that can be used to deduce vent orientations. In addition, the Continental Scientific Drilling Project (CSDP) is currently undertaking a drilling program along the trend of the Inyo Domes [*Eichelberger et al.*, 1984]. The second of three drill holes intersected the conduit beneath Obsidian Dome, and the third is planned to penetrate the dike between two of the domes. Future analysis of the drill core will allow models of dike geometry to be tested and in situ stress measurements to be made.

The Inyo Domes are part of a 9-km-long volcanic chain containing silicic domes and flows, explosion pits, and a series of faults and cracks all roughly aligned N07°W [*Wood*, 1977]. To the north the domes are contiguous with the Mono Craters, and to the south the system is generally considered to terminate near the Inyo Craters, about 6 km NW of the town of Mammoth Lakes. The trend of the Inyo Domes crosses the northwest margin of Long Valley caldera without any apparent deviation. The dome alignment is intersected by one of the NNW striking frontal faults of the Sierra Nevada Range (the Hartley Springs fault) which does not appear to have had a major influence on the loci of recent eruptions.

The Inyo volcanic chain includes at least six rhyolitic vents classified into three groups on the basis of age relations among associated pyroclastic deposits [*Miller*, 1983, 1985]. The oldest activity emplaced a small dome north of Deadman Creek several thousand years ago. The next events included extrusion of Wilson Butte and eruption of associated pyroclastic products at the north end of the chain, around 1100 years ago. The most recent activity, approximately 550 years ago, culminated in the formation of the three largest domes (Obsidian, South Glass Creek, and South Deadman domes) as well as the Inyo explosion craters around Deer Mountain and possibly a small dome (North Glass Creek Dome) between Obsidian and South Glass Creek domes.

STRUCTURES SURROUNDING AND ON THE YOUNGEST INYO DOMES

The most recent extrusions along the Inyo trend are young enough that structural evidence for their emplacement should still be preserved. Figure 1 shows outlines of the Inyo Domes and nearby explosion craters, locations of ground cracks surrounding the domes, and surface structures on the domes. Those cracks that clearly display vertical displacements are marked as faults; others are marked as lineations. The positions of the Long Valley caldera margin and the Hartley Springs fault are also shown, although these structures are not

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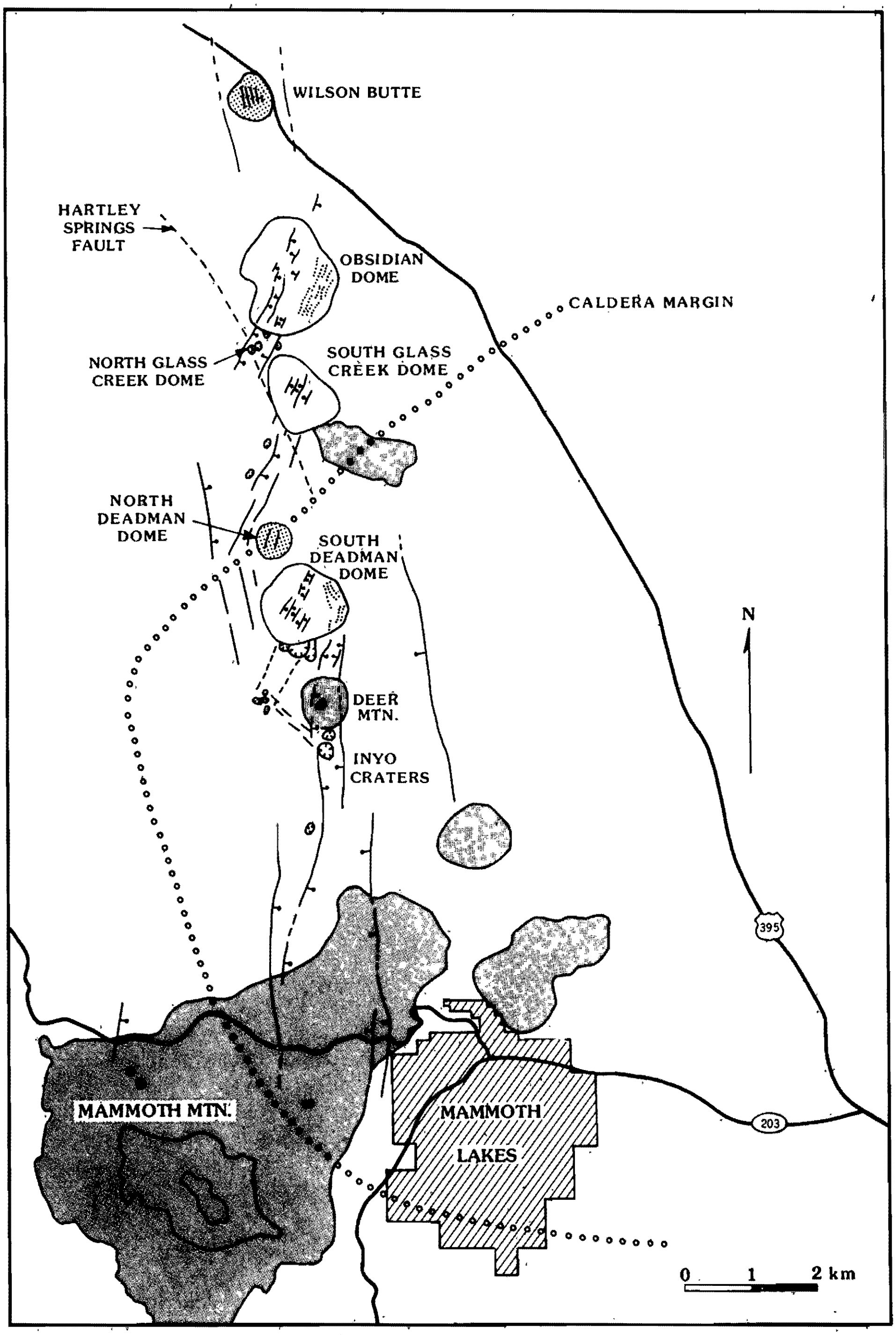

Fig. 1. Map of western portion of Long Valley caldera and the Inyo Domes. Heavily shaded areas represent older rim rhyodacites and moat rhyolites. Lightly shaded areas are older domes of the most recent eruptive episode [*Miller*, 1985]. Faults and ground cracks shown as solid lines (dashed where inferred or concealed); solid circles on downthrown blocks. Axes of surface folds on domes shown as dotted lines. Contours on Mammoth Mountain are 1000 feet (305 m).

believed to play a major role in vent localization along the Inyo trend. Structural features were delineated on the bases of field observations and air photo interpretation. The continuity of ground cracks and fracture trends on domes are more easily seen on aerial photographs where they are less obscured by vegetation and local relief. However, detailed maps constructed in the field allow offsets and the en echelon nature of segmented and sinuous cracks to be identified.

The well-preserved upper surfaces of the Inyo Domes can be used to infer vent orientations, which in turn reflect subsurface conduit geometry. On the three youngest large domes, overall dome shapes, fracture and topographic patterns at the summits, ridge and crack orientations in the distal areas, and the distribution of textures all suggest vent elongation directions between N15°E and N25°E, in contrast to the overall N07°W alignment of the domes. This preferred northeast orientation is shared by structures surrounding the domes.

Obsidian Dome (Figure 2) is the largest extrusion among the Inyo group and exhibits several types of structural evidence indicating the orientation of its conduit. Like many silicic domes, it has an elliptically shaped summit area that is elevated with respect to the rest of the flow surface and elon-

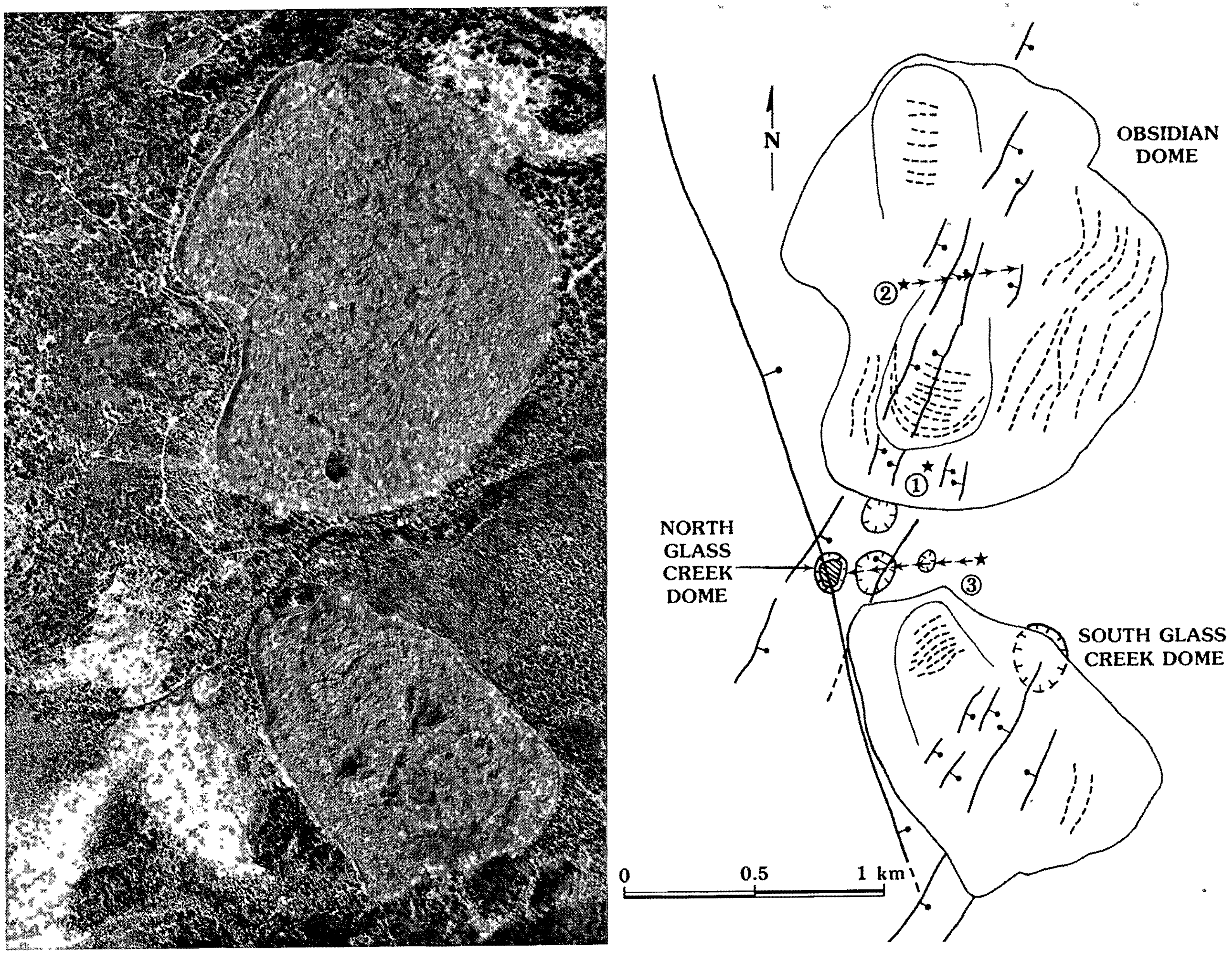

Fig. 2. Photograph and map of Obsidian Dome, North and South Glass Creek domes, and vicinity, showing ground cracks and faults (solid lines), explosion craters, surface folds (dotted lines), and outlines of youngest flow lobes (two on Obsidian Dome, one on South Glass Creek Dome). Stars mark CSDP drill hole sites: 1, October 1983; 2, August 1984; 3, September–November 1984. Holes 2 and 3 were slanted; paths indicated by small arrows.

gated in a direction that may parallel the orientation of the underlying vent [*Fink*, 1983]. A graben up to 5 m deep runs between the southwest and northeast margins of the flow. Both this downdropped zone and the raised area over the vent are elongated along a N20°E trend, although other fractures with a more radial orientation partly obscure these relations in the vent area. Where it intersects the flow front, the downdropped zone is marked by tensional fractures, some of which expose a distinctive black scoriaceous pumice layer. This pumice has a relatively low specific gravity and rises diapirically from within the flow where fractures give it access to the surface [*Fink*, 1980]. Well-developed compressional surface folds on the eastern edge of the flow have axes with an average trend of N18°E. The gentle slopes underlying this portion of the dome suggest that flow direction (and fold orientations) were controlled by the geometry of the vent rather than by preflow topography.

A series of structures southwest of Obsidian Dome share a similar alignment with those on the dome surface. Several explosion craters and faults define a N25°E trending zone that runs southward across Glass Creek from the base of the southwest flow front of the dome. The craters range in depth from about 10 to 50 m. Comparable structures appear to be lacking to the northeast of the dome where it flowed into a paleo-stream valley (D. E. Sampson, unpublished manuscript, 1985).

South Glass Creek Dome has at least two parallel pairs of 5–10 m deep, N25°E trending fractures cutting its elevated central vent area. These fractures align with a partly buried tephra cone to the NNE of the dome and with two explosion craters and a series of longer ground cracks trending 2.2 km to the SSW toward Deadman Creek. Although the dome is elongated to the southeast where it flowed down an 18° gradient into Long Valley caldera, a recently identified small dome (D. E. Sampson, unpublished manuscript, 1985) and a slight protuberance on the southwest margin of the flow may overlie an extension of the conduit in this direction. Orientations of most of the compressional folds on this dome reflect flow directions controlled by preflow topography.

South Deadman Dome is subcircular in shape, reflecting the gentle underlying topography. A large portion of its southern half is covered by smooth, relatively flat surfaces enclosed by two pair of ridges that appear to have spread laterally away from a central N25°E trending axis. The northern half of the dome lacks the smooth areas but has an elongated elevated portion with fractures whose preferred orientation is N17°E. Other fractures define an ENE trend in the vent area. As at Obsidian Dome, a series of explosion craters are found beyond the southwest margin of the dome, along a trend of N25°E. A second group of shallower phreatic pits is found about 1 km to the southwest along the same trend. Ground cracks and faults around these shallower craters are oriented approximately N15°W.

The southernmost vents of the latest eruptive episode are the three Inyo Craters. These range in depth from approximately 100 to 20 m progressing from south to north, with the most northerly crater lying on top of Deer Mountain, a 100,000-year-old rhyolite dome [*Bailey et al.*, 1976]. The craters sit within a 400-m-wide graben that extends about 1 km south and 500 m north of Deer Mountain. The faults making up the graben trend N05°E south of the craters and N22°E north of the craters. In addition to these faults the N15°W oriented zone mentioned above containing numerous ground cracks, small craters, and hummocks extends away from the central Inyo Crater.

South of the Inyo Craters is a series of faults and ground cracks interpreted here as a continuation of the Inyo volcanic trend. The faults can be placed into at least two paired sets whose average trend is N07°W, parallel to that of the overall dome alignment. The graben containing the Inyo Craters runs south for about 1 km, at which point a second set of faults forms a 1.6-km-wide graben, coaxial with the first, that extends another 4 km south to Mammoth Mountain. This southern graben includes the so-called "earthquake fault" on the east and a second group of faults and cracks on the west [*Benioff and Gutenburg*, 1939]. The faults making up both graben have vertical displacements of over 30 m on the west and locally up to 3 m on the east. Individual crack segments have N75°E to N85°W opening directions and are up to 10 m deep. Additional phreatic pits dated at 500 ± 200 years [*Miller*, 1985] occur within the southern graben on the flank of Mammoth Mountain (Figure 1).

DIKE GEOMETRY INFERRED FROM THE STRUCTURAL DATA

Various types of structural evidence have been cited that indicate the orientation of magmatic conduits beneath the Inyo Domes. Although the overall trend of the domes and the graben that contain them is N07°W, the three largest extrusions appear to have emerged from zones of deformation oriented N15°E to N25°E. These zones are arranged in a left-stepping, en echelon pattern and are marked by ground cracks, faults, explosion craters, and structures on the dome surfaces. The Inyo Craters and each of the vents for the three largest domes are located at the northeast ends of these zones. Ground cracks and explosion pits are found as far as 2 km southwestward from the vents but are much less common to the northeast. These observations can be explained by assuming that the Inyo dike divided into segments, rotated, and rose obliquely as it neared the surface.

The spacings of paired ground cracks and the depths of explosion craters can be used to constrain the depths to the tops of dikes along the Inyo trend. Rising dikes produce tensional stresses at the surface resulting in paired sets of ground cracks parallel to the dike trend and separated by a spacing roughly equal to 2–3 times the depth to the top of the dike [*Pollard et al.*, 1983]. The closest spaced crack pairs may thus be used to infer the depth to the top of a buried dike. If the two nested graben that run from Mammoth Mountain to the Inyo Craters formed over a dike that fed the most recent eruptive activity, then the 1.6-km width of the outer, southern graben suggests a dike top 500–800 m below the surface, whereas the 400-m-wide graben immediately surrounding the three craters indicates a depth of 130–200 m.

As dikes approach the surface through water-saturated volcanic rocks, the rapid influx of magmatic heat may cause phreatic explosions that leave craters over the highest portions of the dike, with alignments that crudely parallel the dike trend. The southern Inyo Crater is about 80 m deep, the middle crater is about 60 m deep, and the shallowest crater lies on top of the 170-m-high edifice of Deer Mountain. This zone of craters and ground cracks only extends about 100 m northeast from Deer Mountain. Even if we assume that considerable slumping back into all of the craters occurred, the observed depths are consistent with the idea of a dike or dike segment whose upper surface slopes upward to the north.

Additional evidence supports the model of a sloping dike. Southwest of Obsidian Dome a 400-m-wide graben containing 50-m-deep explosion craters emerges from under the dome and runs in the same direction as an elongated depression on

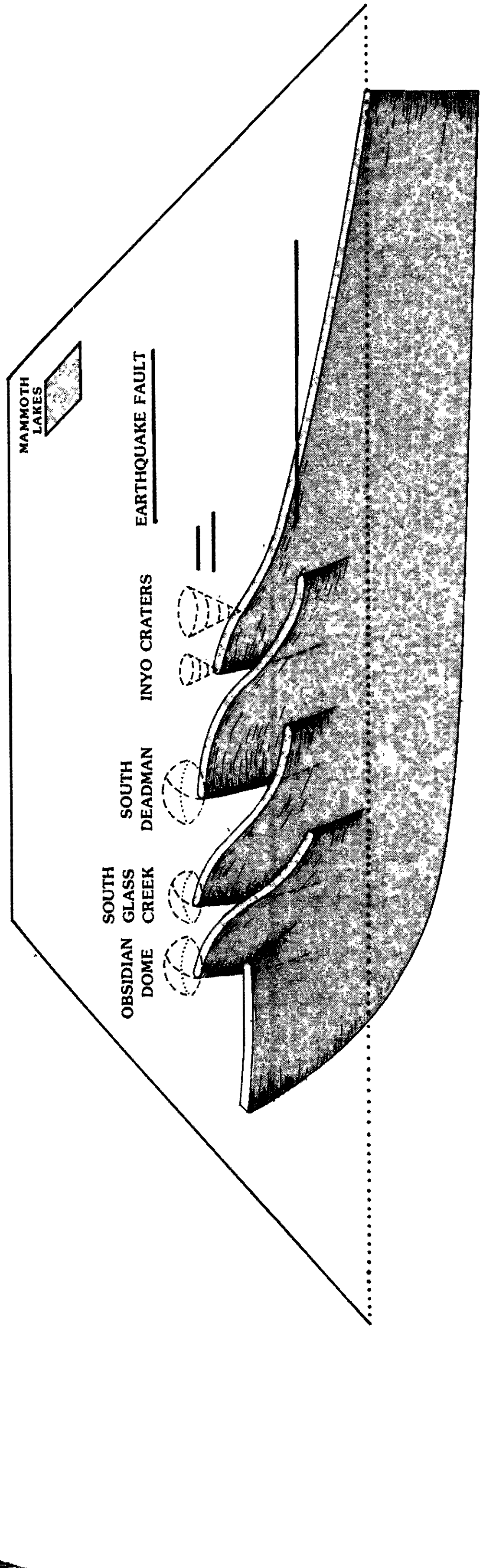

Fig. 3. Schematic diagram of dike rising beneath the Inyo Domes showing near-surface segmentation and rotation. Largest domes, craters, and ground cracks located approximately. Note that individual dike segments rise to the northeast (toward magmatic vents) and that spacing of major paired faults decreases as dike rises toward the surface. North is to the left.

the dome surface. At Glass Creek Dome, ground cracks with a minimum spacing of 250 m extend for several kilometers to the southwest, again paralleling the structural trend seen on the dome. Although regularly spaced ground cracks were not observed to the southwest of South Deadman Dome, detailed stratigraphic studies show that the pyroclastic eruptions immediately preceding the emplacement of the dome came from a crater at the dome's southwest margin [*Miller*, 1985], whereas the source for the lava was a few hundred meters to the north.

The discrepancy between the Inyo Dome alignment and the orientations of local structures around the domes can be explained by assuming that the youngest domes and craters were fed by a dike whose overall trend was controlled at depth by a maximum compression direction of N07°W. As this dike reached the surface, the maximum principal compressive stress direction underwent a 20°–30° clockwise rotation. Possible reasons for this rotation include an upwardly increasing influence of right-lateral shear stresses along the Sierra frontal faults or an encounter with fracture patterns inherited from the formation of Long Valley caldera. In order to realign itself with the near-surface stress state, the rising dike divided into 2- to 3-km-long segments or "fingers" [*Pollard et al.*, 1975] that rotated individually to N15°E to N25°E orientations (Figure 3). The asymmetrical distribution of ground cracks around the domes and the position of vents at the northeast ends of the deformation zones suggest that the dike segments approached the surface obliquely, rising to the north. The southward increase in the spacing of cracks and faults along the Inyo trend indicates that the entire dike also rose as it propagated laterally northward.

Studies of basaltic dike geometry and emplacement mechanisms [*Delaney and Pollard*, 1981; *Pollard et al.*, 1982] show that rather than being exceptional, segmentation, rotation, and oblique flow of the types proposed above are common aspects of dike propagation near the earth's surface. Exposures of rhyolite and rhyodacite dikes in areas such as Summer Coon Volcano in the San Juan Volcanic field of Colorado [*Lipman*, 1968] clearly demonstrate the same geometric relationships.

A southward projection of the ground cracks and faults along the Inyo trend points to a possible source for the dike north of the eastern margin of Mammoth Mountain. If one projects the dike trend inferred from the recent south moat seismic activity [*Cockerham and Savage*, 1983; *Savage and Cockerham*, 1984] to the west, it intersects the Inyo trend northeast of Mammoth Mountain in this same vicinity. Although this may be a fortuitous correlation, it would probably be prudent to monitor carefully this area for deformational evidence of future intrusive and incipient extrusive activity.

DIKES BENEATH THE OLDER INYO DOMES

Although there is less structural evidence that can be related to the older Inyo Domes, the above model allows some inference to be made about the geometry of the earlier conduits. It is unlikely [*Shaw*, 1965] that a silicic dike could have retained molten magma for the several hundred to several thousand year intervals between eruptive phases suggested by age dates [*Wood*, 1977; *Miller*, 1985]. However, the state of stress that favored the emplacement of a single dike could have persisted long enough to influence the formation of additional dikes. In addition, rising dikes create joints ahead of their tips that result in parallel zones of fractures around the intrusion (P. T. Delaney et al., unpublished manuscript, 1985). Renewed injection of magma could occur along one of these zones of weakness adjacent to an earlier dike, resulting in the observed parallel alignments of vents of different ages.

Segmentation and rotation of dikes could also occur repeatedly in a given area. If a new dike were to be intruded adjacent to an earlier one, subsequent segmentation and rotation might cause portions of the later dike to intersect locally and remobilize cooled magma within the first. Such a process might result in mixed textures like those observed in the three largest Inyo Domes [*Sampson et al.*, 1983; D. E. Sampson, unpublished manuscript, 1985]. However, this process would require the younger intrusions to have higher melting temperatures than the earlier emplaced dikes, which is opposite to the conditions calculated for the Inyo Domes (D. E. Sampson, personal communication, 1984).

DIKE ROTATION AND ERUPTION PREDICTION

Future intrusions of dikes in the Mammoth Lakes area will most likely be accompanied by characteristic seismic activity and ground deformation, the interpretation of which would allow estimation of impending hazards. Such intrusions may also cause the formation and growth of new ground cracks. Analysis of the geometry of these cracks can provide an additional tool for predicting sites and timings of eruptions.

A closer look at the structural data along the Inyo trend reveals evidence that the rotation of dike segments may have occurred at very shallow depth, possibly within a few hundred meters of the surface. Normal faults separated by over a kilometer form a broad N10°W trending graben containing the Inyo Craters and South Deadman Dome (Figure 1). The narrower graden enclosing the Inyo Craters trends N07°W south of Deer Mountain but appears to swing to a bearing of N25°E for its northernmost 100 m, suggesting that rotation of the dike occurred only under this northeastern part of the deformed zone. Crack spacings and crater depths cited earlier indicate that the unrotated dike top may have been within 200 m of the surface beneath the craters, plunging deeper to the south. Similar rotations appear to have occurred along the portions of the dike that fed the three large domes to the north. Crack spacings in these areas are also consistent with dike segments that shallow northward.

The proposed shallow rotation of dikes provides a potential basis for predicting sites of future eruptions. Ground cracks have been observed to form above and parallel to rising basaltic dikes in Iceland and Hawaii [*Pollard et al.*, 1983] and could similarly be expected to develop over any rising dike of silicic magma in the Mammoth Lakes area. If rotation and segmentation occurred at relatively shallow depths, then any observed changes in ground crack orientation from initial linear trends to subsequent en echelon patterns could indicate the near-surface approach of a dike. Spacings of paired cracks could be monitored to calculate the depth to the top of the dike. However, in pumice-covered areas like those around the Inyo Domes such crack pairs may be difficult to identify. Progressive changes in crack orientations may be more reliable precursors.

It is difficult to estimate the amount of warning such crack changes could provide, as no detailed observations of their development before silicic fissure-type eruptions have been reported. However, studies of deformation accompanying the growth of the dacite lava dome at Mount St. Helens may be instructive. Acceleration of ground tilt and movement along thrust faults around the base of the dome were used to successfully predict several eruptions between 1980 and 1982 [*Swanson et al.*, 1983; *Chadwick et al.*, 1983]. According to these interpretations, surface deformation (including formation of ground cracks) was driven by intrusions of magma from depths of 1–2 km into the conduit beneath the dome. This intrusion could usually be detected a few weeks before an eruption. Comparable lead times might be expected for surface deformation over a rising silicic dike in the Mammoth Lakes area.

The occurrence of new, parallel ground cracks and faults cannot be used in isolation as a definitive predictive tool in an area where tectonic extension is likely to precede and accompany the shallow rise of magma. Regional extension that controls the orientation of dikes at depth will also be reflected in the attitudes of ground cracks and faults caused by concurrent seismic activity. An episode of crack formation and widening could reflect either the rise of a new dike, ongoing tectonic extension, or a combination of the two. Cracks caused by extension alone should have consistent orientations and should lack systematic spacings. Cracks caused by dike rise should occur in paired sets whose spacings decrease with time. However, successful distinction of tectonic from magmatic ground cracks requires the use of seismic, tilt, or other geophysical data sets.

Dike rise in other nearby areas, such as along the south moat of Long Valley caldera, or beneath the Mono Craters, might also be preceded by a systematic change in crack orientation, with the actual sense of rotation depending on the local state of stress. In order to be able to make and interpret such observations, additional analyses of the state of stress and increased monitoring of ground deformation should be conducted throughout the Long Valley/Mono Craters area. In addition, the CSDP holes currently being drilled along the Inyo trend are planned to intersect buried silicic dikes. These holes will help constrain dike orientations and their relationships to surface structures on and around the Inyo Domes.

CONCLUSIONS

The N07°W trend of the Inyo Domes, Inyo Craters, earthquake fault, and other nearby structures probably reflects the orientation of a dike that propagated perpendicular to the minimum principal compressive stress direction. Fractures, folds, and other structures on and adjacent to the domes suggest that the shallow conduits feeding the individual magmatic vents were oriented N15°E to N25°E. The vents for the youngest Inyo Domes and Inyo Craters all lie at the northeast ends of NNE–SSW oriented deformation zones up to 2 km long that are marked by ground cracks, normal faults, and explosion craters. These zones are interpreted as overlying dike segments that fed the domes. Segmentation and rotation allowed the dike to reorient itself to different principal stress directions near the surface. The asymmetrical distribution of the vents at the northeast ends of these zones may reflect the SSW plunge of individual dike segments. Ground crack spacings and the depths of craters combine with this plunge to suggest that the dike that fed the Inyo Domes may have risen from the area immediately east of Mammoth Mountain. The older Inyo Domes may have been fed by a different dike or set of dikes that then partly influenced the location of the subsequent, most recent intrusion. Analysis of the changing orientation and spacings of ground cracks and faults in the Mammoth Lakes area may help predict the timing and sites of future eruptions.

Note added in proof. In November 1984, drill hole RDO-3A of the Inyo Drilling Program intersected a 10-m-wide rhyolite dike at a depth of 650 m between Obsidian Dome and South Glass Creek Dome, identical in composition to the 550-year-old extrusions. The position of the dike is offset to the west from a line connecting the vent areas of the two domes and slightly east of the graben that emerges from beneath Obsidian Dome. This location is consistent with the prediction made in this paper that the domes were fed by a segmented dike having an en echelon structure with clockwise rotation of the segments. Future drill holes in the vicinity of RDO-3A may help document the variation of this rotation and the associated stress field with depth.

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