No ring fracture in Mono Basin, California

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ABSTRACT

In Mono Basin, California, USA, a near-circular ring fracture 12 km in diameter was proposed by R.W. Kistler in 1966 to have originated as the protoclastic margin of the Cretaceous Aeolian Buttes pluton, to have been reactivated in the middle Pleistocene, and to have influenced the arcuate trend of the chain of 30 young (62–0.7 ka) rhyolite domes called the Mono Craters. In view of the frequency and recency of explosive eruptions along the Mono chain, and because many geophysicists accepted the ring fracture model, we assembled evidence to test its plausibility. The shear zone interpreted as the margin of the Aeolian Buttes pluton by Kistler is 50–400 m wide but is exposed only along a 7-km-long set of four southwest-erly outcrops that subtend only a 70° sector of the proposed ring. The southeast end of the exposed shear zone is largely within the older June Lake pluton, and at its north-west end, the contact of the Aeolian Buttes pluton with a much older one crosses the shear zone obliquely. Conflicting attitudes of shear structures are hard to reconcile with intrusive protoclasts. Also inconsistent with the margin of the ovoid intrusion proposed by Kistler, unsheared salients of the pluton extend ~1 km north of its postulated circular outline at Williams Butte, where there is no fault or other structure to define the northern half of the hypothetical ring. The shear zone may represent regional Cretaceous transpression rather than the margin of a single intrusion. There is no evidence for the Aeolian Buttes pluton along the aq- ueduct tunnel beneath the Mono chain, nor is there evidence for a fault that could have influenced its vent pattern. The apparently arcuate chain actually consists of three linear segments that reflect Quaternary tectonic influence and not Cretaceous inheritance. A rhyolitic magma reservoir under the central segment of the Mono chain has erupted many times in the late Holocene and as recently as 700 years ago. The ring fracture idea, however, prompted several geophysical investigations that sought a much broader magma body, but none identified a low-density or low-velocity anomaly beneath the purported 12-km-wide ring, which we conclude does not exist.

INTRODUCTION

The Quaternary volcanic field of Mono County, California, USA, has attracted many investigations motivated by interest in magmatic and tectonic processes, geothermal energy, and seismic and volcanic hazards. Spatially and magmatically independent components of the field (Fig. 1) that were active in the late Pleistocene and Holocene include Long Valley caldera, Mammoth Mountain, and its basaltic periphery, the Mono–Inyo chain, and the Mono Lake volcanoes (Bailey, 1989; Hildreth, 2004, 2017; Hildreth and Fierstein, 2016).

Mono–Inyo and Mono Lake are the components of the volcanic field that were most active in the Holocene and are most likely to erupt explosively in our time (Miller, 1985; Sieh and Bursik, 1986; Sampson and Cameron, 1987; Hildreth, 2004; Bursik et al., 2014; Bevilacqua et al., 2018). Because of so many Holocene eruptions and the likelihood of recurrence, it is worth correcting a longstanding misimpression about the structural setting of magmatism in Mono Basin.

The Mono Craters 15-minute quadrangle was mapped by Ronald Kistler (1966a) at a scale of 1:62,500. It includes the eastern range front of the Sierra Nevada, the transition to the Basin and Range Province, several Mesozoic plutons, their multiply deformed metamorphic wall rocks, glacial deposits of several ages, and the recently and potentially active Mono Crater rhyolite volcanoes. Kistler mapped a shear zone in Mesozoic granitoids that he interpreted as a segment of a much broader ring fracture that he postulated to circle beneath the youthful chain of Mono Craters’ rhyolite domes (Fig. 2). The following critique of Kistler’s ring fracture hypothesis does not diminish our admiration for his pioneering geologic investigation of one of the more complex and precipitous terrains of the western USA.

Our re-investigation assembles geologic and geophysical evidence that bears upon the ring fracture hypothesis and Quaternary magmatism. Over the course of three summers, we spent ~30 days examining all outcrops of the shear zone, searching for granitic clasts in Mono Craters ejecta and in tailings from the Mono Craters tunnel, and remapping the geology of the relevant parts of southwestern Mono Basin. We now review the evidence and suppositions behind the ring fracture model, introducing new data and observations concerning (1) the plutons, (2) the outcrops, (3) the tunnel under Mono Craters, and (4) geophysical interpretations of magma storage.

GRANT–PARKER SHEAR ZONE

Kistler (1966a, 1966b) drew attention to a low-relief reentrant in the Sierra Nevada range front directly west of the Mono Craters (Fig. 3). The reentrant is occupied by Pumice Valley, Aeolian Buttes, Grant Lake reservoir, and the moraine-covered valleys of Walker, Parker, and Rush Creeks. It extends 10 km north-south from Williams Butte to Reversed Peak and 12 km east-west from Mono Craters to the Silver Lake Fault at the toe of the main range front (Fig. 3).

Along the southwest side of the reentrant, several separate outcrops of sheared Mesozoic granitic rocks extend as a slightly curvilinear 7-km-long chain of exposures through the glacial deposits (Figs. 2 and 3). For simplicity and location, we refer to the chain as the Grant–Parker shear zone after its main exposures near Grant Lake and Parker Creek. Kistler interpreted the shear zone as the protoclastic margin of a
granitoid pluton, which he named the quartz monzonite of Aeolian Buttes. The pluton is exposed in only a dozen scattered outcrops (Fig. 3), a central one being atop Aeolian Buttes, but most of it is covered by surficial deposits.

The southwest marginal shear zone is 50–400 m wide and was described as variously including mylonite, crushed granitic rock, intensely fractured granitic rock with slickensides and thin bands of mylonite, and granitic augen enclosed in a black flinty matrix. Where the pluton’s outer contact is exposed, at two outcrops along the shear zone (Fig. 3), Kistler mapped shear structures as likewise imposed on contiguous strips of the adjacent older plutons (Fig. 2).

The early names for these plutons were redesignated by Bateman (1992) as the Triassic granite of Lee Vining Canyon and the Cretaceous granite of June Lake (Fig. 3). It was inferred that intrusion of the Aeolian Buttes pluton took place late in the Cretaceous and that granulation and shear during its forceful intrusion imposed a protoclastic structure on its margin (and on contiguous wallrock) when it had largely crystallized but before its complete solidification.

Although the 7-km-long alignment of sheared outcrops describes only a 70° segment of the roughly circular outline of the 12-km-wide Aeolian Buttes pluton depicted by Kistler (1966a), he proposed that an unexposed protoclastic margin continues for 360° beneath the June Lake scoria cone, the entire Mono Craters chain, and across the toe of Williams Butte (Fig. 3). He further suggested that there had been renewed movement along the shear zone during Pleistocene range front faulting and that such reactivation had taken place during the interval separating emplacement of the Sherwin Till and the Bishop Tuff, which are now dated, respectively, at 900–800 ka and 767 ± 2 ka. In his discussion, Kistler (1966a, p. 47–49) referred to the inferred quasi-circular margin of the Aeolian Buttes pluton as “the ring fracture zone.” Whether he did or did not intend to suggest a modern magma chamber beneath the whole ring, he did implicate his ring fracture as guiding eruptions of the Mono chain.
Nevertheless, many geophysicists and a few geologists simply accepted the provocative use of the term “ring fracture” and inferred a contemporaneous magma reservoir beneath all or much of the Cretaceous ring rather than just along its Mono Craters margin.

**UNCritical Repetition Promotes Entrenchment**

Various versions of the ring fracture sketch map (Fig. 2) were repeatedly published in volcanological and geophysical articles. These include papers by Loney (1968); Lachenbruch et al. (1976); Bailey et al. (1976, 1989a, 1989b); Bailey (1982); Hermance (1983); Hermance et al. (1984); Hill et al. (1985a, 1985b; 1985c); Rundle and Whitcomb (1986); Achauer et al. (1986); Dawson et al. (1990); and Kelleher and Cameron (1990). The ring fracture sketch map was widely disseminated in Field Guides for the 1989 International Association of Volcanology and Chemistry of the Earth’s Interior (IAVCEI) General Assembly and the 28th International Geological Congress (Bailey et al., 1989a, 1989b) and in Bailey’s (1989) Geologic Map of the Long Valley Caldera and the Mono-Inyo Craters Chain. It thus provides a classic example of a loosely based suggestion becoming entrenched as conventional wisdom through repetition alone prior to additional investigation.

Bailey (1989, Maps A and D) smoothed Kistler’s ring fracture sketch to form a more perfect circle, and he drew its outline through an unsheared granitic outcrop at Rush Creek that had been well inboard of Kistler’s hypothesized margin (Fig. 2). Bailey’s revision left nine of the northernmost vents of the Mono chain outside the ring, but he otherwise repeated the speculation that other vents of the Mono chain had erupted along the unseen “mylonitized border” of the Aeolian Buttes pluton (Bailey, 1989, pages 3 and 7).

Paleozoic metasedimentary strata. The two masses of granitic unit Kae on Williams Butte were assigned to a different pluton by Kistler.

Figure 2. Kistler’s (1966b) original depiction of his hypothetical ring fracture zone (digitized and colored after his fig. 32) is shown. He extrapolated the shear zone, which is exposed only in the southwest sector, to the entire ring, which he interpreted as the protoclastic border of the Aeolian Buttes pluton (red). Squiggles indicate domains that Kistler identified as sheared. Red dashed line across northern sector, inboard of Kistler’s line, is Bailey’s (1989) modified sheared margin, which he drew through the Rush Creek contact and into dacitic Dome 12, thereby leaving nine northern rhyolite domes outside the ring (Fig. 3). For numbering and updated distribution of Mono domes, see Figure 16. Map pattern, dashed lines, and vent stars (incomplete) are Kistler’s, but unit labels have all been updated to conform with present-day understanding and usage: s—surficial deposits, mostly pumice and alluvium; rm—rhyolites of Mono chain; t2—Tioga Till of marine isotope stage (MIS) 2; t6—Tahoe Till of MIS 6; t22—Sherwin Till of MIS 22; mjl—trachyandesite cone and lava flows of June Lake; dac—Pleistocene dacite Dome 12; BT—Bishop Tuff; Kae—Aeolian Buttes pluton; Kjl—June Lake pluton; Trlv—Lee Vining Canyon pluton; Mzmv—Mesozoic metavolcanics rocks; Pzms—Paleozoic metasedimentary strata. The two masses of granitic unit Kae on Williams Butte were assigned to a different pluton by Kistler.
Figure 3. Simplified geologic map shows the study area in the southwest sector of Mono Basin. At right, stars mark vents for 30 rhyolites (42–0.7 ka) and one older dacite that form the Mono Craters chain. In red are all outcrops of Aeolian Buttes pluton (Kae). Small patch labeled “till bench” northeast of Parker Lake was called sheared granite by Kirstler. Uncolored and undivided are the Bishop Tuff ignimbrite, Mono Craters pumice deposits, and extensive glacial and alluvial deposits that combine to conceal the pluton. In solid pink is the Lee Vining Canyon pluton (Trlv), and in patterned pink is the June Lake pluton (Kjl). Metasedimentary rocks of Paleozoic age are designated Pzms, and unassigned Mesozoic granitoids are shown as gr. Silver Lake Fault (SLF) at left (southwest) is the principal Sierra Nevada range front structure. Secondary range front is Lee Vining Fault (LVF) at north-center and Hartley Springs Fault zone (HSFZ) to the southeast. Their continuity is interrupted by the large erosional embayment that is now occupied by Pumice Valley and thick surficial deposits of three principal streams. Peak 9764 is Mount Downs; Peak 8508 has been called Deer Peak. For Kirstler’s (1966a, 1966b) postulated ring structure, see Figure 2.
THE PLUTONS

The sheared margin of the Aeolian Buttes pluton is in contact with two other granitoid bodies—the Lee Vining Canyon and June Lake plutons. Chemical data that distinguish the three are given in Figure 4 and Table S1. As outlined by Kistler (1966a, 1966b), the Aeolian Butte pluton has an assumed area of ~132 km², of which its exposed outcrops total ~1.6 km² or only ~1% of it (Fig. 3). The rest of its low-relief area is covered by Bishop Tuff, till, alluvium, and unconsolidated pumiceous deposits. Everden and Kistler (1970) reported K–Ar ages of 87.7 Ma for biotite and 85.5 Ma for hornblende, placing the cooling of the Aeolian Butte pluton in the Late Cretaceous, which was the final intrusive episode in the Sierra Nevada.

The June Lake pluton extends ~15 km northwest from the wall of Long Valley caldera past June Lake to Rush Creek. It is exposed over an area of ~33 km², but an isolated outcrop atop Peak 8508 (2593 m), 5 km east of June Lake, suggests that an additional area roughly half as large is concealed by surficial deposits and Bishop Tuff (Fig. 3). The June Lake pluton shares the shear zone with the Aeolian Buttes pluton where Rush Creek enters Grant Lake reservoir. Everden and Kistler (1970) reported K–Ar ages of 87.9 Ma for biotite and 97.1 Ma for hornblende, placing cooling of this pluton, too, in the Late Cretaceous.

The Lee Vining Canyon pluton shares the shear zone with the younger Aeolian Buttes pluton for ~2 km along a 300-m-high ridge (Ridge 8841) just north of Parker Creek near Parker Lake (Fig. 3). Zircons from the Lee Vining Canyon gave U-Pb ages of ca. 210–220 Ma (Chen and Moore, 1982; Barth et al., 2011), so crystallization took place in the late Triassic, which was long before intrusion of the June Lake and Aeolian Buttes plutons during the Cretaceous.

The Aeolian Buttes is medium grained, equigranular, with abundant biotite and hornblende and 63–71 wt% SiO₂. The slightly older June Lake is porphyritic, contains far more biotite than hornblende, and 69–73 wt% SiO₂. The Late Triassic Lee Vining Canyon is equigranular, the finest grained, whitest, and most felsic of the three, containing sparse biotite, little or no hornblende, and 73–76 wt% SiO₂. All three exhibit modest ranges in texture and mineral proportions, but there is seldom difficulty in distinguishing them.

THE SHEARED OUTCROPS

The sheared outcrops near Grant Lake and Parker Creek include: (1) a commonly anastomosing foliation (mylonitic zones with sigma and phi porphyroclasts and pressure shadows on granitic fragments) that strikes NW–SE and dips steeply or vertically; (2) sparse, greenish-gray, fine-grained veins that appear to have originally been pseudotachylite and are closely associated with mylonitic zones; and (3) slickenlines on block surfaces, most of which are subhorizontal but some with contrasting orientations. Some slickenlines may have formed during brittle deformation that postdated the main shear zone, as some offset the shear bands and veins or have various trends inconsistent with the main shear sense. Many outcrops have multiple generations of fabrics. Descriptions below of the outcrops and measured attitudes identify a continuous shear zone, but a detailed structural analysis of the Grant-Parker shear zone has been deferred to a future paper.

Ridge Southeast of Grant Lake

Kistler (1966a, 1966b) mapped the shear zone as extending ~1.5 km southeastward from the south side of the Grant Lake peninsula (Figs. 2 and 3) and exposed as far as a right-lateral moraine north of Reversed Peak. He portrayed the shear as having affected both sides of the contact between the Aeolian Buttes pluton and a granite later assigned to the June Lake pluton (Bateman, 1992). Bailey’s (1989) map, however, portrays the shear zone only within the Aeolian Buttes pluton, whereas—like Kistler—we observe it in both. We examined the shear zone in well-exposed areas: adjacent to Grant Lake and on Peak 7870 at the upper (eastern) end of its exposure.
Along the southwest-facing scarp of the granitic peninsula (Fig. 5) southeast of Grant Lake, the Aeolian Buttes pluton is massive and nonfoliated, its mafic enclaves are equant, and several leucogranitic dikes (5–30 cm thick) are subhorizontal, planar, and nonshaped. Joints spaced 20–200 cm are near-vertical and nonsheared, though some blocks have slickensides. On the northeast-facing slope of the peninsula, slickensided fractures and mylonite seams 1–3 mm thick are scattered sparsely, but much of that slope (Fig. 5) is massive Aeolian Buttes pluton.

Starting ~100 m east of the Grant lake shoreline on the southwest-facing wall (Fig. 5), sparse black, wavy seams interpreted as mylonite (Fig. 6) become conspicuous; most are 1–50 mm thick, near-vertical, and strike ~290°. The thickest seams contain slivers and equant fragments (1–15 mm across) of the host granite; some were aligned by shear within the black, fine-grained mylonite matrix. Some thin, branching veins may have originated as pseudotachylyte (Fig. 6). Discontinuous slickensides in massive granite are widespread in all segments of the shear zone, but they are commonly variably oriented (Fig. 7). Leucogranitic dikes that crosscut the shear features are undeformed.

At the upper (eastern) end of the prominent shear-zone scarp (Fig. 5), the south-facing wall of Peak 7970 (600 m east of the Grant Lake shoreline) is penetratively shear porphyritic granite of June Lake (Fig. 8). A steep slope, 200 ft (60 m) high, that leads up to the base of that wall consists likewise of the granite of June Lake but is not foliated there. Across the summit of Peak 7970, the shear zone is ~120 m wide. Notably, the slopes, knolls, and benches 100 m northeast of the summit of Peak 7970 are outside the shear zone and include the contact (Fig. 5) between the June Lake and Aeolian Buttes plutons.

Within the shear zone, packages of mylonite are commonly 40–60 cm wide, near-vertical, strike 270°–300°, and consist of wavy anastomosing veins of black mylonite 1–5 mm thick. Some shear-zone domains are a meter thick and enclose swarms of granitic slivers and fragments (3–30 cm long); some are milled and elongate and others subangular and apparently rotated randomly (Fig. 9). Shear sense indicators are ambiguous; whereas most features suggest subhorizontal shear, there is locally a vertical component. On and near Peak 7970, the shear zone is within the June Lake pluton, but 500 m W–NW near the east shore of Grant Lake, it is within the Aeolian Buttes pluton (Fig. 5), as it is on Knoll 8240+ just west of Grant Lake.

**Knoll 8240+ West of Grant Lake**

A granitic knoll west of Grant Lake, 400 × 650 m across with ~75 m of relief (Fig. 10), consists largely of Aeolian Buttes pluton. Kistler mapped the entire knoll as sheared, and Bailey (1989) drew the shear zone only in its southwestern half. We examined all outcrops and find that only the southeast quarter of the knoll is sheared. Previous mapping assigned the entire knoll to the Aeolian Buttes pluton; however, the summit plateau and northern exposures are not.

The southeast side consists of three separate, well-exposed outcrops at the base, middle, and top of the slope (Fig. 10). Much of the lowest outcrop is chaotically fractured; slickensides are oriented variously but are commonly subhorizontal. Strongly sheared domains consist of abundant nonplanar undulating black mylonite bands 1–40 mm thick (Fig. 11) that are near-vertical and strike 280°–340° (mostly 300°–315°). Undefomed granitic domains are as thin as 10 mm and as thick as several meters. The exposure affected by shearing is at least 50 m

**Figure 5.** The shear zone and Reversed Peak are shown as viewed toward southeast across Grant Lake from sheared Knoll 8240+ (seen in Fig. 10). Glacially excavated along the shear zone, the steep, right-facing scarp at left center (downhill from Peak 7970) is largely sheared granite of June Lake (KJL). The shear zone there is ~120 m wide; to its left runs the contact with Aeolian Buttes pluton (Kae), which forms most of the peninsula and cliffs to the left. Dashed line is plutonic contact; dotted line delimits shear zone. Reversed Peak consists of unsheared granite KJL. At far right are steep diagonal contacts of Paleozoic metasedimentary rocks (ms) and of Triassic Lee Vining Canyon pluton (Trlv) with Cretaceous granite of June Lake. Canyon of Rush Creek enters Grant Lake from the right. For scale, distance between Reversed Peak and Peak 7970 is 1.36 km.

**Figure 6.** Mylonitic bands that may have originated as pseudotachylyte are shown. Branching veins are in deformed granitoid of Aeolian Buttes pluton on peninsula east of Grant Lake (Fig. 5).
across. Slickensided surfaces may reflect jostling or rotation of blocks within the wide shear zone.

The middle outcrop is nonsheared equigranular Aeolian Buttes with only sparse slickensided surfaces and no mylonite. The upper outcrop and knoll-top plateau are likewise little deformed but do exhibit uncommon slickensides and rare steep bands of mylonite ≤ 1 mm thick. The upper granite merges with irregular masses and dikes of nonsheared diorite. Cliffs and benches at the far north end of the knoll consist of fine-grained, equigranular granite with less than 5% dark minerals that is horizontally jointed and slabby but nonsheared; it is unlike any Aeolian Buttes outcrop but is instead similar to the granite of Lee Vining Canyon. Kistler’s (1966b) map does identify a small window (through surficial deposits) ≈ 800 m west of the knoll as the Lee Vining Canyon pluton and portrays it as nonsheared.

**Granitic Windows Southeast of Parker Creek**

Kistler (1966b) mapped a small window of sheared Aeolian Buttes granite exposed through moraines ≈ 1.6 km E–NE of Parker Lake (Figs. 2 and 3). Bailey (1989) recognized that there are two low-relief windows, roughly 200 m apart, and he portrayed them both as sheared. The two are respectively ≈ 650 m and ≈ 750 m northwest of Knoll 8240+.

The southwest window is pervasively foliated, but it has only a few black mylonite seams, which are typically near-vertical and only 1–2 mm thick. The streaky foliation is defined by alternating darker and lighter gray laminae, which are near-vertical and strike variously between 210° and 260°. The darker laminae are 1–3 mm thick, and the lighter ones (apparently less deformed granite with quartz and feldspar crystals intact) are 2–5 mm thick. The NE-striking foliation and mylonite seams here contrast with the generally NW strike of the foliation in the other parts of the shear zone NW and SE of Grant Lake. Prominent near-vertical joints strike NW nearly perpendicular to the foliation.

The northeast window is more mafic and is neither foliated nor sheared, though a few block faces show weak, wavy slickensides. The granitic knoll includes irregular masses of nonfoliated diorite 10–100 cm across that appear to be intruded by the granite. Several outcrops of the diorite, each 3–10 m across, extend downhill from the knoll for ≈ 200 m ESE.

**Bench on Right Bank of Parker Creek**

A small bench at elevation 8280 ft, just above the right bank of Parker Creek 1.3 km northeast of Parker Lake, was mapped by Kistler (1966b) as a sheared outcrop of the Aeolian Buttes pluton, and Bailey (1989) agreed. We found no true outcrop on the bench, which consists of Tioga Till (marine isotope stage [MIS] 2). Blocks on the bench, which are as much as 1–4 m across but not in place, are massive, nonsheared granite (74.3% SiO₂) that is indistinguishable from glacial debris along Parker Creek that was derived from outcrops of the Lee Vining Canyon pluton above Parker Lake.

**Ridge 8841 (2695 m) Northwest of Parker Creek**

The northernmost exposures of the shear zone are on a north-elongate ridge just northwest of Parker Creek (Figs. 3 and 10). Kistler (1966b) mapped the contact between the Aeolian Buttes and Lee Vining Canyon plutons as striking north, high along the east slope of the hill, thus placing
the eastern third of the hill in the Aeolian Buttes pluton and two thirds of it in the Lee Vining Canyon. He mapped the entire exposure of the Aeolian Buttes pluton as sheared as well as a contiguous strip of the Lee Vining Canyon pluton 100–300 m wide. Bailey (1989) reproduced Kistler’s contact but depicted the shear zone only in the Aeolian Buttes pluton. Our mapping reveals the plutonic contact to be very different from previous depictions and the distribution of shear to be irregular and far less prevalent (Fig. 12).

Although Kistler (1966b) depicted the summit ridge and its entire southern and western slopes as the Lee Vining Canyon pluton, it appears that he interpreted a slightly more felsic phase of the Aeolian Buttes as the Lee Vining Canyon (Fig. 12). The south nose and southwest side of the ridge both consist of coarse-grained Aeolian Buttes granite. On the other hand, although depicted by Kistler as Aeolian Buttes granite, much of the northeast slope of the ridge consists of the Lee Vining Canyon granite, as does the cliffy north nose of the ridge. These exposures are largely nonsheared, except for rare near-vertical mylonite seams that strike 325° to 340°, and sparse slickensided vertical fractures. The contact between the Aeolian Buttes and Lee Vining plutons runs close to the ridgetop and bends sharply northeastward down the east slope (Fig. 12), oblique to the trend of the shear zone, and it has little resemblance to the contact depicted on previous maps (Fig. 2). Local shear structures are distributed widely but sparsely and are concentrated mainly in the Aeolian Buttes granite on the east and southeast slopes of the ridge and weakly within the Lee Vining pluton at the northeast end. Their distribution is inconsistent with a systematic protoclastic margin, as is the overall map pattern, which shows the Aeolian Buttes to have intruded and separated part of the Lee Vining from its principal outcrop belt on the Sierran range front a few kilometers west.

**Gorge of Lower Rush Creek**

Where Rush Creek is joined by Walker Creek in Pumice Valley (Fig. 3), it has incised a 15-m-deep gorge that exposes the northern contact of the Aeolian Buttes pluton (Fig. 13). On both walls of the stream gorge, the pluton intrudes bedded Paleozoic metasedimentary rocks that strike nearly east-west and dip close to vertical. The contact strikes 280°–300° and is also nearly vertical on both walls except at stream level on the southeast wall, where the granite contact bends slightly beneath and truncates the bedding. The granite is almost completely nonfoliated and nonsheared. An exception to the absence of shear is a toppled granite block (1 × 3 m across) at the southwestern end of the left-bank cliff (Fig. 13) that has slickensides and a set of wavy, black mylonite seams ~2 m long. The loose block has tilted, so the original attitude of its shear set is unknown.

The granitic outcrops have no systematic joint set but are cut by numerous fractures—
horizontal, vertical, and inclined—that are spaced 1–3 m apart near the top but are more widely spaced on the lower walls. The location is clearly the northern contact of the Aeolian Buttes pluton, but there is practically no shear here and no evidence for a protoclastic margin.

Bailey (1989) drew the proposed ring fracture through this Rush Creek outcrop, depicting it as sheared on both sides of the gorge, thus placing his north margin of the ring ∼1 km south of Kistler’s original suggestion (Fig. 2). Kistler did not depict the outcrop as sheared. Uncertainty in locating such a ring is not surprising because, apart from this gorge outcrop, the entire northern sector from Walker Lake to Mono Craters (Fig. 3) is concealed by thick, surficial deposits.

**WILLIAMS BUTTE**

Kistler (1966a, 1966b) drew the NW side of his ring as a postulated down-to-the-southeast fault that he depicted as striking N55°E across the southeast toe of Williams Butte (Fig. 2). This requires a 70° swing of the ring between Ridge 8841 (previously discussed) and Williams Butte, a 5-km-long segment completely concealed by glacial deposits. We recognize no fault at the foot of Williams Butte, and none was drawn on maps of the area by Putnam (1949), Gilbert et al. (1968), Christensen et al. (1969), Bailey (1989), or Bursik and Sieh (1989). The steep south face of Williams Butte is more likely an erosional feature attributable in part to the early Pleistocene Sherwin Glaciation; till deposits of this glaciation are exposed atop Aeolian Buttes, in the tunnel beneath the Mono Craters, and just west of Williams Butte.

Williams Butte is today enveloped on three sides by glacial and alluvial deposits, while its steep east face reflects the range front Lee Vining Fault that forms the west scarp of Mono Basin (Fig. 3). The upper part of Williams Butte consists largely of Paleozoic metasedimentary rocks, but these are intruded by three discrete granitic masses (Fig. 3). The large granitic outcrop on the north flank is porphyritic and not part of any of the plutons discussed here. The two granitic masses on the south flank, however, are indistinguishable from the Aeolian Buttes pluton and from each other. The western one was assigned to the Aeolian Buttes pluton by Bateeman (1992), and our evidence is strong that both should be. That the two granite masses extend, respectively, 1100 m and 800 m outside (north of) Kistler’s (1966a, 1966b) ring (Fig. 2) conflicts with the protoclastic-margin hypothesis as well as with his simple ovoid pluton.

**ALTERNATIVE EXPLANATION OF GRANT–PARKER SHEAR ZONE**

The Grant-Parker shear zone curves from a strike of ∼315° near Grant Lake to ∼345° near Parker Creek. In the Sierra Nevada, the Gem Lake shear zone (Fig. 14) runs roughly parallel but 7 km directly west of the Grant-Parker shear zone, and it likewise curves around from 340° to 320° to 360° to 300°. It is interpreted as a syn-batholithic dextral transpressional shear zone that was active between 91 Ma and 80 Ma during emplacement of the youngest Cretaceous plutons (Greene and Schweickert, 1995). Likewise, the...
Rosy Finch Shear Zone (Fig. 14), which curves variably between 310° and 360° for ~80 km southeast of Mammoth Mountain, was identified as dextral transpressional and was active between 88 Ma and 80 Ma during emplacement of several Late Cretaceous plutons that it cuts or borders (Tikoff and de Saint Blanquat, 1997). Both shear zones were reported by the authors cited to have near-vertical foliations and to expose mylonite, orthogneiss, and cataclasite that reflect synmagmatic transpression, which produced brittle and ductile deformation during upper-crustal emplacement. Together, they are components of a set of Late Cretaceous shear zones that may extend as far as 300 km along the Sierran Crest. Cretaceous plutons associated with the Gem Lake and Rosy Finch shear zones are strikingly elongate and generally extend northward, as do the contemporaneous or younger June Lake pluton and the far older Lee Vining Canyon pluton. Development of coeval shear zones may have guided emplacement of the elongate plutons including the June Lake pluton. Poor exposure of the Aeolian Buttes pluton has allowed speculation that it may be equant in plan, but if its concealed eastern margin is no farther east than West Portal (Jacques, 1940), looking for angular fracture in Mono Basin, California

Figure 13. Isolated knoll of Aeolian Buttes pluton incised by lower Rush Creek, midway between Williams Butte and Mono Craters chain, is shown. View is westward from right bank rim to left bank cliff, which is 15–20 m high. Vertical contact at right, between Aeolian Buttes pluton (gr) and steeply foliated, orange-brown metasedimentary rocks (ms), crosses gange and strikes ~300°. Granite is fractured and strongly jointed but massive and non-sheared. Prominent vertical joint at center shows no shear features but cuts a biotite-rich granitic dike near stream level. At left, one-third of the granitic exposure is a whiter, fine-grained phase with only ~5% biotite, contrasting with the main gray phase, which is medium-grained and has 15%–20% biotite and hornblende; both phases are equigranular with 64–65 wt% SiO₂. Knoll ~100 m long is surrounded by fluvial gravels composed of dominantly glacial outwash. Universal Transverse Mercator (UTM) grid location: NAD27 317250E 4198100N.

MONO CRATERS TUNNEL

Kistler (1966a) alluded to a large fault zone beneath the axis of the Mono chain, attributing the observation to Putnam (1949), who had examined the tunnel (Fig. 15) during its 1934–1939 construction. Kistler (1966a, p. E47) added that a “rough circle of faults is completed by the arcuate trace of the fault system that no doubt lies beneath the line of the Mono Craters eruptive centers,” thus imputing that such inferred arcuate faults should coincide with his postulated protoclastic margin of the Aeolian Buttes pluton. Putnam (1949), however, had not referred to a fault but instead to vent tuff, brecciated obsidian, and a swarm of very thin obsidian dikes beneath two of the Mono domes (Domes 25 and 26; Fig. 16).

In Mono Basin, the tunnel entrance is at West Portal, 2 km west of the South Coulee. Heading #1 extends 6.83 km southeast from West Portal, passing under distal South Coulee, under three or four smaller Mono domes (Domes 23–26; Fig. 16), and thence well beyond the Mono chain (Wyckoff, 1938; Gresswell, 1940; Jacques, 1940). The first 5.3 km of the tunnel was driven predominantly through Bishop Tuff and only locally encountered glacial deposits and unidentified granitic bedrock beneath it. Beyond 5.3 km, just east of the Mono chain, the tunnel passed through glacial and alluvial debris into metamorphic bedrock. The eastmost granitoid penetrated along Heading #1 was only 1.5 km from West Portal.

At 4.4 km from West Portal and for ~100 m farther, the tunnel passed through “badly broken formation,” which was interpreted as a neck (Jacques, 1940), a vent along a fissure or fault (Gresswell, 1940), or vent tuff (Putnam, 1949). No fault displacement of the Bishop Tuff at this site or elsewhere beneath the Mono chain is indicated in the cross-sections along the tunnel published by each of those three authors. A line of dikes and conduits is necessarily present beneath the Mono chain, but there is simply no evidence that a significant fault exists there nor that the margin of the Aeolian Buttes pluton coincides with the chain of conduits.

We searched tailings from West Portal and from Shafts 1 and 3 and Test Hole 2J, all three of which accessed the tunnel from above (Figs. 15 and 16; Jacques, 1940), looking for angular
granitic clasts that might help locate the extent of plutonic rocks beneath the Mono chain (neglecting rounded cobbles likely to have been excavated from till or alluvium). An enormous tailings pile at West Portal consists mostly of clasts of metasedimentary rocks and Bishop Tuff but also includes <1% granitoids; among these, fine-grained leucogranites dominate. Clasts thought to be similar to Aeolian Buttes lithologies are sparsely present, but the two analyzed (71–72 wt% SiO₂) are compositionally unlike that pluton and instead similar to the June Lake pluton. Tailings at West Portal thus appear to lack material excavated from the Aeolian Buttes pluton.
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Figure 15. Profile shows segment of Mono Craters tunnel beneath the Mono rhyolite chain from West Portal to Shaft 1. Adapted from Jacques (1940) and Putnam (1949). Elevations are in feet; vertical exaggeration is 2x. Tunnel was driven in 1934–1939, for what is now the Los Angeles Department of Water and Power, to transfer Mono Basin streamflow to the Owens River in Long Valley caldera. With a gradient of 0.0005, tunnel is concrete-lined, almost 10 ft in diameter, and 59,812 ft long (11.33 mi; 18.23 km), of which this profile depicts the first 27,700 ft (5.25 mi; 8.44 km). Red line is tunnel level. Unexposed granitic rocks (gr)—unidentified but not Aeolian Buttes pluton—were penetrated only in the first 6200 ft (1.2 mi) of the tunnel. Bishop Tuff (BT) ignimbrite (767 ka) and as much as 100 m of subjacent Sherwin Till (t) overlie low-relief erosion surface of early Pleistocene age cut on Paleozoic metasedimentary rocks (Pzms) and Mesozoic granitoids. For map location of tunnel and domes and coulees of Mono chain, see Figure 16.

Around Test Hole 2J, there is no tailings pile, but rare scattered clasts of leucogranite and porphyritic granite are present. A still-rarer equigranular type of clast that we thought resembles the Aeolian Buttes pluton is compositionally far different, containing 75 wt% SiO$_2$. Shaft 3 also lacks tailings, but there are scattered clasts of porphyritic granite and leucogranite and a few that resemble the Aeolian Buttes pluton. Because they are rounded cobbles, however, they are less likely to be excavated tailings than Mono Craters ejecta entrained from till.

Near Shaft 1, ~2 km southeast of the Mono chain, a 400-m-long pile of tailings consists dominantly of metasedimentary clasts, except that toward its west end the pile is rich in clasts of coarse-grained mafic plutonic rocks. Just east of the east end of the tailings, sparsely scattered granitic boulders include leucogranite as well as rare Aeolian Buttes granites (equigranular, medium-grained, color index (CI) ~15, 65 wt% SiO$_2$). Because the boulders are at the abandoned site of a multi-year, tunnel-construction village, they are likely to have been brought in. There is thus no evidence that the Aeolian Buttes pluton was penetrated by the tunnel. The eastern contact of the pluton has not been located and is probably west of West Portal (Figs. 3 and 16).

A late Pleistocene scoria cone near June Lake may have erupted through an unexposed part of the June Lake pluton (Fig. 3) rather than along the shear zone (Fig. 2). Cone ejecta were searched for granitic xenoliths, but none were found.

ARCUATE TREND OF THE MONO CHAIN

The Mono Craters array is a crescentic chain of 30 virtually contiguous domes and coulees, all but one of which are phenocryst-poor, high-silica rhyolite. The arcuate trend, however, can be resolved into three segments (Fig. 16)—a central array of 13 vents that trends north-south,
a northern array of 12 vents that trends N30°W (330°), and a short southern line of four vents that trends S45°W (225°). At an angle of ~55°, the southern line intersects the range front fault zone, which strikes ~350° and influences alignment of Wilson Butte and the Inyo domes (Fig. 17).

Bursik and Sieh (1989) inferred a lessening of range front faulting along the Sierran reentrant facing the Mono chain (Fig. 3) during its eruptive lifetime, which is now known to have started ca. 62 ka (Vazquez and Lidzbarski, 2012). It was proposed that numerous dikes that fed the Mono chain provided strain relief, thus accommodating local extension and compensating for a late Pleistocene-to-Holocene “slip gap” along the adjacent range front fault system. Diverging from the north-south central alignment, the more westerly trends of vent arrays at the north and south ends of the arcuate chain (Fig. 16) seem to require additional processes or influences.

Closest to Mono Lake, the northern array of 12 vents trends ~330° and directly overlies the abrupt southwest structural corner of Mono Basin as defined on the gravity map (Fig. 18). The Mono Lake part of the basin was convincingly shown by Gilbert et al. (1968) to be a shallow warp that dips gently southwest toward its termination against the Sierran range front escarpment. The lake basin thus has the configuration of a weakly sagging trapdoor with flexures, and perhaps minor concealed faults, on three sides.

The steepest gravity gradient runs parallel to but 2–3 km east of the toe of the exposed escarpment (Pakiser, 1976). This separation could reflect the observed belt of coarse deltaic gravels, as advocated by Gilbert et al. (1968) and/or a concealed set of step faults lakeward of the principal escarpment. The abrupt corner in the gravity contour map (Fig. 18), coinciding with the northwestern dome segment, thus appears to be squarely where the down-warped southeastern margin of the Mono Lake depression joins its steep, N-NW–striking faulted termination. The northwest-trending array of rhyolite vents is aligned along the rim of the steep, depression-bounding gravity gradient. The concealed rim structure may have influenced propagation of rhyolite dikes northwestward and away from the main magma reservoir (Achauer et al., 1986) under the central, north-trending part of the Mono Craters chain.

At the opposite (south) end of the Mono chain, a line of four rhyolite vents younger than 16 ka (Domes 27–30) diverges southwest (225°) from the north-south central array of the Mono Craters. From the end of the contiguous Mono chain at Dome 30, however, a nearly linear alignment of Holocene vents then extends southwest (170–175°) for 13.5 km (Fig. 17). These include

Figure 17. Image depicts magmatic linkage represented by southwest-trending segment of Mono chain and south-trending Inyo chain, which roughly parallels range front fault system. Mono domes and Wilson Butte are high-silica rhyolite, whereas Inyo domes are lower-silica rhyolite, and some are mixed hybrids. For Inyo chain: Obsidian flow (OF), Glass Creek flow (GC), and Deadman Creek flow (DC) erupted from a common southward-propagating dike in 1350 CE; units rcd, rcw, and rnd are undated Holocene extrusions described in Hildreth and Fierstein (2016). Wilson Butte erupted ca. 1.7 ka (Bevilacqua et al., 2018). Mono domes 25–30, all fayalite-bearing, are thought to have erupted in the interval 5–16 ka (Marcaida et al., 2019).

Figure 18. Gravity map of Mono Basin as contoured by Pakiser (1976) is shown. Contour interval is 4 mGal. Shoreline of Mono Lake is outlined in blue. In lake, P—Paoha Island; N—Negit Island. Mono Craters dome chain is in yellow; its northwest array of 12 rhyolite vents (Fig. 16) trends 330° along the steep gravity gradient northwest of the contoured corner.
two phreatic craters within 1 km south of Dome 30, Wilson Butte (1.7 ka) at 3.3 km south, the three dike-linked Inyo extrusions of 1350 CE at 6–11 km south, and finally the phreatic Inyo Craters (also 1350 CE) as far as 13.5 km south. Three additional small silicic domes (Fig. 17) distributed along the south-trending Inyo array are undated but certainly also Holocene. The four southwest-trending Mono domes are older—early Holocene or as old as ca. 16 ka (Dalrymple, 1967; Hu et al., 1994; Bevilacqua et al., 2018).

The Inyo alignment thus runs parallel but on a echelon to the main central Mono alignment, both trending within 5°–10° of north-south. The trend of the Inyo chain, which is exclusively Holocene, is probably influenced by the contiguous multistrand Hartley Springs Fault array (Figs. 3 and 17). The several vents of 1350 CE were linked by a south-propagating dike (Mastin, 1991), which was shown by drilling to be ~7 m thick (Eichelberger et al., 1985). Likewise, the 13 vents of the main central Mono chain are plausibly linked by a longer-lived, south-trend ing array of rhyolite dikes (Bursik and Sieh, 1989). It seems likely that the southwest-trend ing array of four high-silica-rhyolite domes, numbers 27–30, reflected onset of a diagonal crossover from the persistent Mono magma reservoir toward the extending fault system. Dome 30 is within 1.5 km of an exposed strand of the Hartley Springs Fault array (Fig. 17), and a fault largely concealed by surficial deposits strikes south from Dome 30 through two phreatic craters toward Wilson Butte (Fig. 17). Eruption of Mono high-silica rhyolite at Wilson Butte along the Inyo range front alignment is evidence that the plumbing linkage was complete by 1.7 ka. The six other Holocene Inyo lavas altogether contain mixed contributions of at least three additional magmas, but all appear to include a Mono high-silica-rhyolite component (Sampson and Cameron, 1987; Vogel et al., 1989; Varga et al., 1990; Hildreth, 2004).

In summary, the apparently arcuate vent array of the Mono chain reflects local tectonic influences at its north and south ends (Figs. 17 and 18), which produced deviations from the north-south central segment, where Holocene magma has principally been stored. The vent pattern of the chain has no relation to the Cretaceous structure—ring fracture or otherwise.

**IMPLASIBILITY OF A RING FRACTURE**

Kistler (1966a, p. E47) cited a “rough circle of faults [that] is completed by the arcuate trace of the fault system that no doubt lies beneath the line of the Mono Craters.” He wrote that the circle “encloses a topographic low that is the embayment in the east zone of Sierran frontal faults” and that inside the circle all exposed bedrock (though sparse) is the Aeolian Buttes pluton. Kistler further advanced the idea that the pluton had been “displaced as a single block” during the faulting that had produced the present range front escarpment. Accordingly, “renewed (Quaternary) dislocation took place along the contact of the pluton, which had already been sheared during its (Cretaceous) forceful emplacement and produced the fractures that are superimposed on the mylonite zone.” Kistler introduced the term “ring fracture zone” in the context of advancing his idea of brittle reactivation of the contact in the early Quaternary.

Kistler never mentioned the possibility of a magma body enclosed within and beneath the ring, but many geophysicists later inferred it. He did speculate that the reactivated protoclastic border of the pluton “localized the extrusion of the rhyolite domes of the Mono Craters” as well as older dacitic Dome 12 and the June Lake mafic scoria cone (Fig. 2).

Problems with the ring fracture model itself include the following:
1. Lack of fault displacement of the Bishop Tuff in the tunnel beneath the axis of the Mono chain (Fig. 16).
2. The unexposed eastern contact of the Aeolian Buttes pluton with its wall rocks is not well located but must be west of West Portal (Fig. 3) and not beneath the Mono chain.
3. The sheared margin of the pluton is exposed in only four outcrops that subextend only a 70° sector along the southwest side of the hypothetical ring. In no other sector is the margin known to be protoclastic, mylonitic, or otherwise sheared.
4. The north side of the ring (Fig. 2) was attributed to a down-to-the-southwest fault (striking N55°E) along the toe of Williams Butte, and the hypothetical fault was drawn to connect with the north end of the Mono chain. Neither we nor any other investigators have considered the southeast slope of Williams Butte to be a fault rather than glacially erosional.
5. Unsheared salients of the Aeolian Buttes pluton (Figs. 2 and 3) extend into Williams Butte, ~1 km north of the ring, casting further doubt on the reality of a protoclastic margin.
6. The Rush Creek window (Figs. 2, 3, and 13), inside Kistler’s original ring but along the revised ring drawn by Bailey (1989), exposes the northern contact of the Aeolian Buttes pluton against metasedimentary rocks, but the granite is not foliated.
7. The suggestion that the June Lake scoria cone erupted through the shear zone has not been disproven but is unlikely. The porphyritic June Lake pluton crops out to the southwest, west, northwest, east, southeast, and within 200 m south of the cone. It would require an unexposed southerly salient of the Aeolian Buttes pluton to bring its margin under the scoria cone, which is in conflict with the presumed circular outline of the hypothetical protoclastic ring.

8. The shear zone is within the June Lake pluton southeast of Grant Lake, within the Aeolian Buttes pluton northwest of the lake, and impinges from the Aeolian Buttes across a complex contact with the Lee Vining Canyon pluton only north of Parker Creek (Fig. 12).

9. Based on fissure vents and vent alignments that released the Mono chain rhyolites, Bursik and Sieh (1989; their fig. 6) inferred extension-induced feeder dikes of various orientations that do not consistently reflect the influence of a hypothetically sheared, systematically arcuate pluton margin.

10. One can only be skeptical of the idea that the roughly cylindrical margin of a 12-km-wide Cretaceous pluton could be remobilized during the Pleistocene “as a single block” within the regional stress field that has promoted Basin and Range extension in Mono Basin since the late Pliocene. Undeformed dikes—variously leucogranite, aplite, biotite-rich granite, or diorite—are present at most outcrops of the shear zone, either crosscutting the shear fabrics or in proximity to them, which proves that the shear took place in the Cretaceous and not the Quaternary.

**LACK OF EVIDENCE FOR MAGMA BENEATH THE RING**

Although many geophysicists reprinted the circular outline of the ring fracture proposed by Kistler (1966a, 1966b) and promoted by Bailey (1989), there is no geophysical evidence for magma beneath the conjectured ring except under part of the Mono chain itself.

1. The gravity and seismic surveys of Paker et al. (1960) and Pakiser (1976) extended far into Pumice Valley and the Grant Lake area, well within the ring, and found no upper-crustal low-density or low-velocity anomalies there.
2. At Aeolian Buttes, in a 124-m-deep drill hole nearly central to the ring and just 5 km west of the Mono domes, Lachenbruch et al. (1976) measured heat flow at 91 mW/m², a normal value for this part of the Basin and Range Province.
3. Seismic refraction profiles (Hill et al., 1985b), north-south and east-west across Pumice Valley, specifically targeting Kistler’s ring fracture, found no evidence for a magma reservoir in the upper 7–10 km. Beneath the low-velocity veneer of pumice and Bishop Tuff, P-wave velocities are in the normal range for granitic basement.
Hildreth et al.

(4) Based on 94 teleseismic events recorded at 16 stations surrounding Mono Craters, Achauer et al. (1986) interpreted P-wave velocities up to 7% slow to indicate an anomalous body, arguably partially molten, centered directly beneath the central reach of the Mono chain. Its top was interpreted to be at a depth of 8–10 km, and it was thought to extend into the middle crust to ~20 km. They found no anomaly west of the Mono chain, and they dismissed the “notion of a larger mid-crustal chamber centered beneath Pumice Valley and within the Mono Craters ring fracture zone.”

(5) With an expanded array, Dawson et al. (1990) undertook another teleseismic P-wave investigation, confirming the low-velocity anomaly directly beneath the Mono chain, extending it from 10 km to a depth of 28 km, and identifying no anomaly to the west within Kistler’s circle.

(6) Employing a dense array of GPS stations around the Mono Craters for several years, Marshall et al. (1997) interpreted their data as permissive of intrusion of a north-south dike directly beneath the Mono chain, but no anomalous displacement was noted farther west.

(7) A magnetotelluric survey centered on Pumice Valley (Hermance et al., 1984) found no downward decrease in resistivity and dismissed the idea of magma beneath Kistler’s ring.

(8) An advanced 3-D electrical resistivity model was based on 62 broadband magnetotelluric stations surrounding the Mono Chain (Peacock et al., 2015). Two conductive anomalies imaged at the SE and NE margins of the Mono chain extend from depths of ~10 km to >30 km and were interpreted as cylindrical transcrustal shear zones in the nearby Sierra Nevada. There is no evidence for a fault or even an arcuate pluton margin that might define the northern half of the ring. There is no evidence for a ring fracture or even the Aeolian Buttes pluton itself beneath the Mono Craters chain. The high-silica-ryholite Mono domes and coulees have probably been fed from a magma reservoir beneath the central N–S segment of the chain. Deviations of the NW and SW distal segments of the chain reflect Quaternary tectonic influence and not control by a Cretaceous structure. There is no geophysical evidence for magma beneath the Pumice Valley site of the Aeolian Buttes pluton today.

Our debunking of the ring fracture hypothesis illustrates how a poorly documented but convenient and interesting notion can be propagated and entrenched without closer scrutiny. Unexamined narratives are widespread and enduring in politics but need not last long in science.

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