PARTIAL DRAINING AND CRUSTAL SUBSIDENCE OF ALAE LAVA LAKE, KILAUEA VOLCANO, HAWAII

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Abstract.—Eruptions of basaltic lava in 1969 filled Alae Crater with a complex lava lake, and subsequent overflows built the southeastern crater rim 24 m higher. The lake partly drained in August 1970, refilled during the next 3 months, and partly drained again in February and March 1971. The solidified crust of the lake subsided 13 m during the 1970 draining and 23 m during the 1971 draining. The volume of draining was about 10^6 m^3 during both events. The August 1970 draining took place when a lava tube, located 2–3 m above the base of the new lava overlying the crater rim, reopened accompanying rapid addition of lava beneath the crust of the lake. The February-March 1971 draining was more complicated; the pre-February lake crust sank into the molten lake because of the weight of new overlying flows. This subsidence displaced underlying molten lava upward and out of the lake through the outlet tube. The elevation of the base of the lake crust after both draining events was controlled in a crudely hydrostatic fashion by the elevation of the outlet tube.

Alae Crater, formerly a 165-m-deep pit crater on the east rift of Kilauea Volcano (fig. 1), underwent a complex sequence of filling, partial draining, and refilling during the 1969–71 Mauna Ulu eruption (Swanson and others, 1971; Swanson and others, 1972). Alae first filled to overflowing on October 10, 1969; subsequent additions of basaltic lava built the surface 24 m higher than the low point on the preeruption rim (fig. 2*A*). A plugged lava tube near the level of the old rim reopened in early August 1970 and quickly drained the upper part of the impounded lava lake, causing the crust to subside and creating an elliptical subsidence bowl that marked the site of the former crater (fig. 1*A*). Minor settling took place in November 1970 as the tube opened still further.

Mauna Ulu continued to feed lava into the crusted lake in Alae for the next few months; this supply was approximately balanced by outflow through the tube. During February 1971, a voluminous surface flow filled the August subsidence bowl to overflowing and built the surrounding levees 5 m higher, to about 29 m above the low point on the preeruption crater rim. The rate of inflow then declined, but a high rate of outflow through the tube continued for several days, again causing a partial draining of the lava lake and the development of a new subsidence bowl (fig. 1*B*). Rates of inflow and outflow once again balanced by early March 1971, by which time crustal subsidence was virtually complete. The crust continued to settle slightly over the next 2 to 3 months owing to mechanical lag effects.

The subsidence events of August 1970 and February–March 1971 each followed an episode of rapid addition of large volumes of lava to the lake. The final elevations of the base of the lake crust at the end of each subsidence were virtually identical and apparently were hydrostatically governed by the elevation of the outlet tube. This participation of the Alae reservoir in the active system of near-surface lava tubes (Swanson and others, 1971; Anderson and others, 1971; Swanson, 1972) is an important and unusual feature of the Mauna Ulu eruption. Analysis of the subsidence events is necessary for an understanding of the interrelations in this complex system.

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DESCRIPTION OF THE AUGUST 1970 DRAINING AND CRUSTAL SUBSIDENCE

Numerous lava flows erupting between February and October 1969 filled Alae Crater to overflowing; overflows continued through December 1969. The resulting crusted lava lake was about 190 m deep and was characterized by numerous highly complicated internal structures (Swanson and others, 1972). The low, southeast part of the crater's former rim was buried 24 m below the surface of the new flows (figs. 2*A* and 4), as determined by precise surveys. A concealed lava tube that had developed by roofing of a surface channel on October 20, 1969, extended about 2.5 km southeastward from the drowned southeastern rim of the crater. This tube, the floor of which was 2 to 3 m above the preeruption rim, channeled a small volume of lava out of the crater between October 20 and

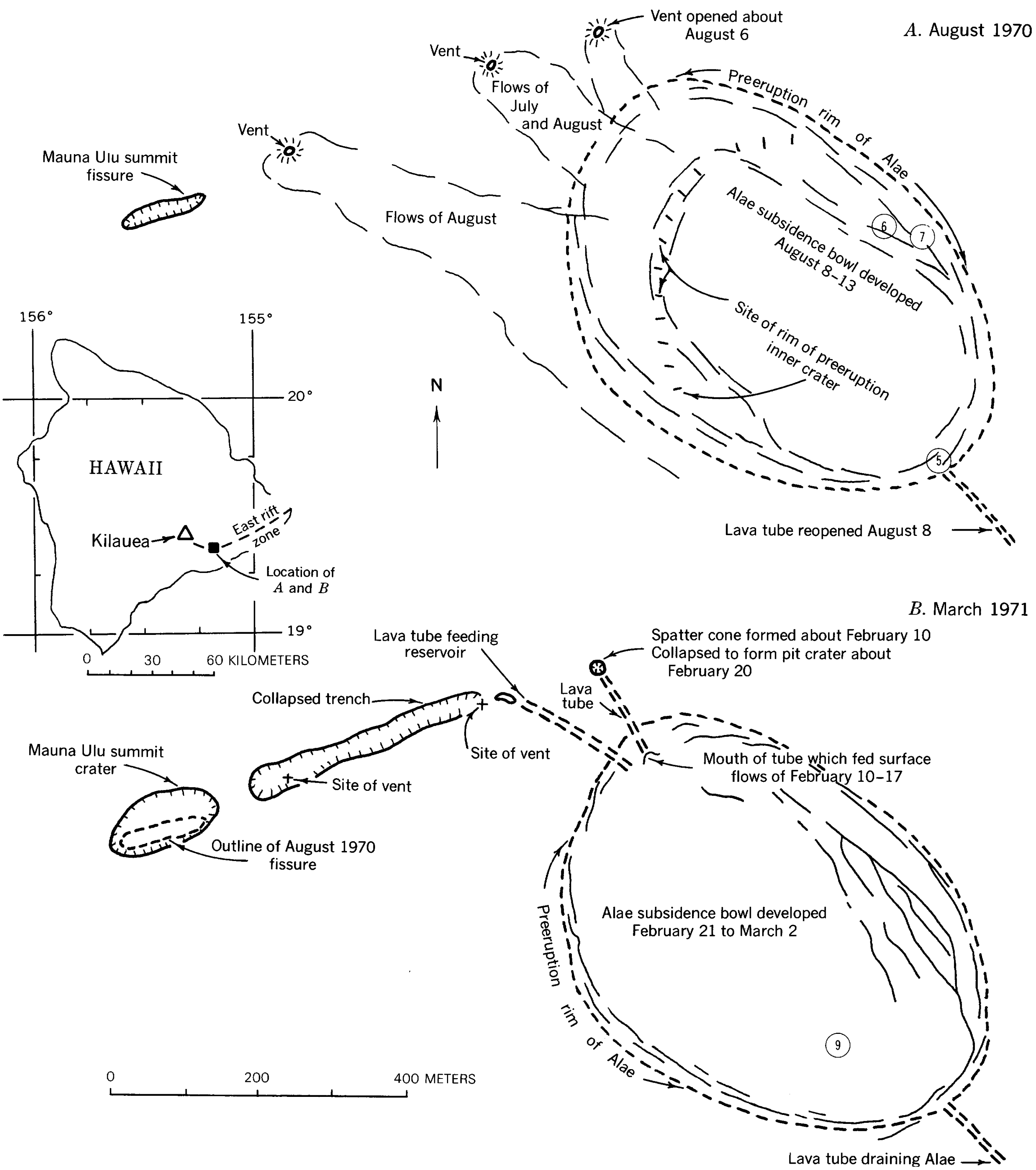


Figure 1.—Sketch maps of Mauna Ulu and Alae Crater. *A*, configuration in late August 1970; *B*, configuration in early March 1971. Inset shows location of area on Kilauea's east rift. Locality of photographs (figs. 5–7, and 9) indicated by circled numbers.

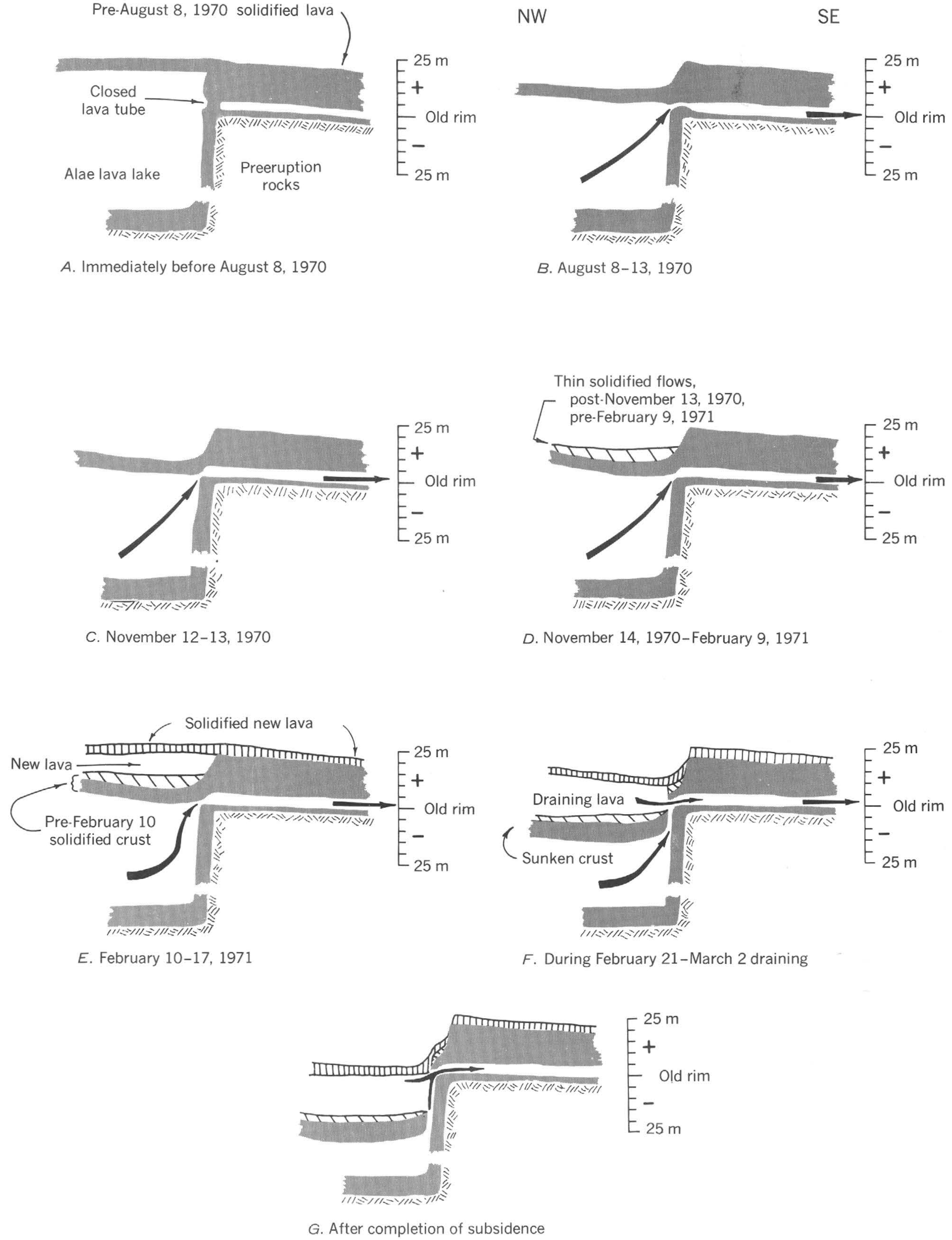


Figure 2.—Schematic cross sections of southeast part of filled Alae Crater, showing sequence of important events between August 1970 and May 1971. Heavy arrows indicate inferred movement of lava.

29, 1969. It subsequently closed, probably by collapse of its walls or blockage of its entrance (fig. 2*A*), and was inactive from October 1969 until August 1970.

Additional lava was added to Alae July 6–9, 13–15, 16–17, and 20–21, 1970, by small flows issuing from a vent 150 m northwest of the crater (fig. 1*A*); none of these flows completely covered the surface crust of the lava lake. Some lava may have been contributed to the molten interior of the lake through a subsurface tube during one or more of these episodes.

A new vent opened about 650 m east-northeast of the summit of Mauna Ulu sometime between August 4 and the early hours of August 7, probably on August 6 (fig. 1*A*). Lava quietly welled out of this vent, flowed in a surface river for 50–100 m, and then disappeared into a tube which carried the lava for several tens of meters before feeding it beneath the crust into the molten part of the lava lake in Alae Crater. Concurrently, other small flows advanced a short distance across the crater floor from the vent 150 m northwest of Alae (Greeley, 1971), and some of this lava may also have entered the molten lake beneath the surface crust. An increase of hydrostatic pressure within the lake accompanied the addition of new lava below the crust, and the crust was probably uplifted as a result. The increased fluid pressure in the lake eventually broke the barrier that sealed the lava tube of October 1969 (fig. 2*B*), and lava poured out of the lake through the tube and emerged about 2.5 km southeast of the crater as a surface flow. The flow was discovered about 0830, August 11, when it had advanced 2–3 km from the lower end of the feeder tube.

Draining of lava through the tube withdrew support for the overlying lake crust, and the crust consequently subsided. Subsidence began late on August 7 or, more likely, early on August 8 but did not become conspicuous until the afternoon of August 8 (Greeley, 1971). We estimated that the surface of the lake had subsided about 10 m when we visited Alae at 1030, August 11 (fig. 2*B*). This estimate is very close to the measured value obtained from later planetable mapping (fig. 3), suggesting that virtually all of the draining and most of the crustal subsidence had been completed by this time. Slight settling of the crust continued until August 13, however, owing perhaps to lag effects resulting from friction, tensile strength of the crust, and other complexities.

All of the subsidence features shown on the topographic and geologic map (fig. 3) were developed by August 11, but the map was not made until November. During this interval, flows that erupted from the vent north of the crater added about 2 m to the entire floor; thus the maximum subsidence in August was about 2 m more than is indicated by the topographic map (fig. 3)–that is, 13 m rather than the indicated 11 m (table 1). Some structures were covered or partly covered by the time the map was made, but their locations and general nature could be determined from aerial photographs taken on August 11. Molten lava flooded many of the structures during and shortly after the mapping, in places completed minutes before lava covered the area.

The August subsidence bowl was elliptical in plan view, conforming to the shape of the filled crater (fig. 1). Its northwestern limb, however, dipped much more gently than the southeastern limb (figs. 3 and 4), and the area of maximum subsidence was located only about 50 m from the entrance to the outlet tube (fig. 4). The constructional slope of the postsubsidence lava fan exaggerates this northwest-southeast asymmetry, but observations made on August 11, before the fan had formed, showed that most of the asymmetry was related to the subsidence itself. Most of the subsidence took place by differential sagging of the lake surface; cumulative vertical displacement along the bordering faults was less than 10 percent of the maximum subsidence amplitude of 13 m (table 1).

Table 1.—*Altitudes, in meters, at various times during the subsidence events*

[Datum is preeruption southeast rim of Alae Crater. Inferred altitude of base of crust refers to the lake crust near the outlet tube]

Lowest point on lake surface	Altitude	Change in altitude	Inferred altitude of base of crust[1]
1. Before August 1970 subsidence. Same as thickness of new flows above preeruption rim.	24		19
		-13	
2. Immediately after August 1970 subsidence.	11		6
		+2	
3. November 11, 1970, after 2 m of new lava had been added (fig. 3 portrays this time).	13		6
		-3	
4. November 14, 1970, after November 12–13 settling.	10		3
		+8	
5. February 9, 1971....	18		3+
		+11	
6. February 17, 1971...	29		27
		-19	
7. March 2, 1971......	10		8
		-4	
8. June 28, 1971 (after final settling).	6		4

[1] For the period through February 9, 1971, the lake crust is that present before the August 1970 subsidence. For the period after February 9, the lake crust is that formed during the interval February 9–17, 1971. See text for details.

Two crudely concentric sets of faults were recognized (figs. 3 and 4). The outer set was defined by small, nearly vertical cracks, generally less than 75 cm wide, that outlined the position of the buried rim of the crater. Most of these boundary faults had less than 5 cm vertical displacement, and many showed no vertical offset. The only substantial vertical displacement (1.3 m) on a fault of this set was at the southeast end of the subsidence bowl, directly above the location of the outlet tube (figs. 2*B*, 3, 4, and 5) and close to the area of maximum subsidence.

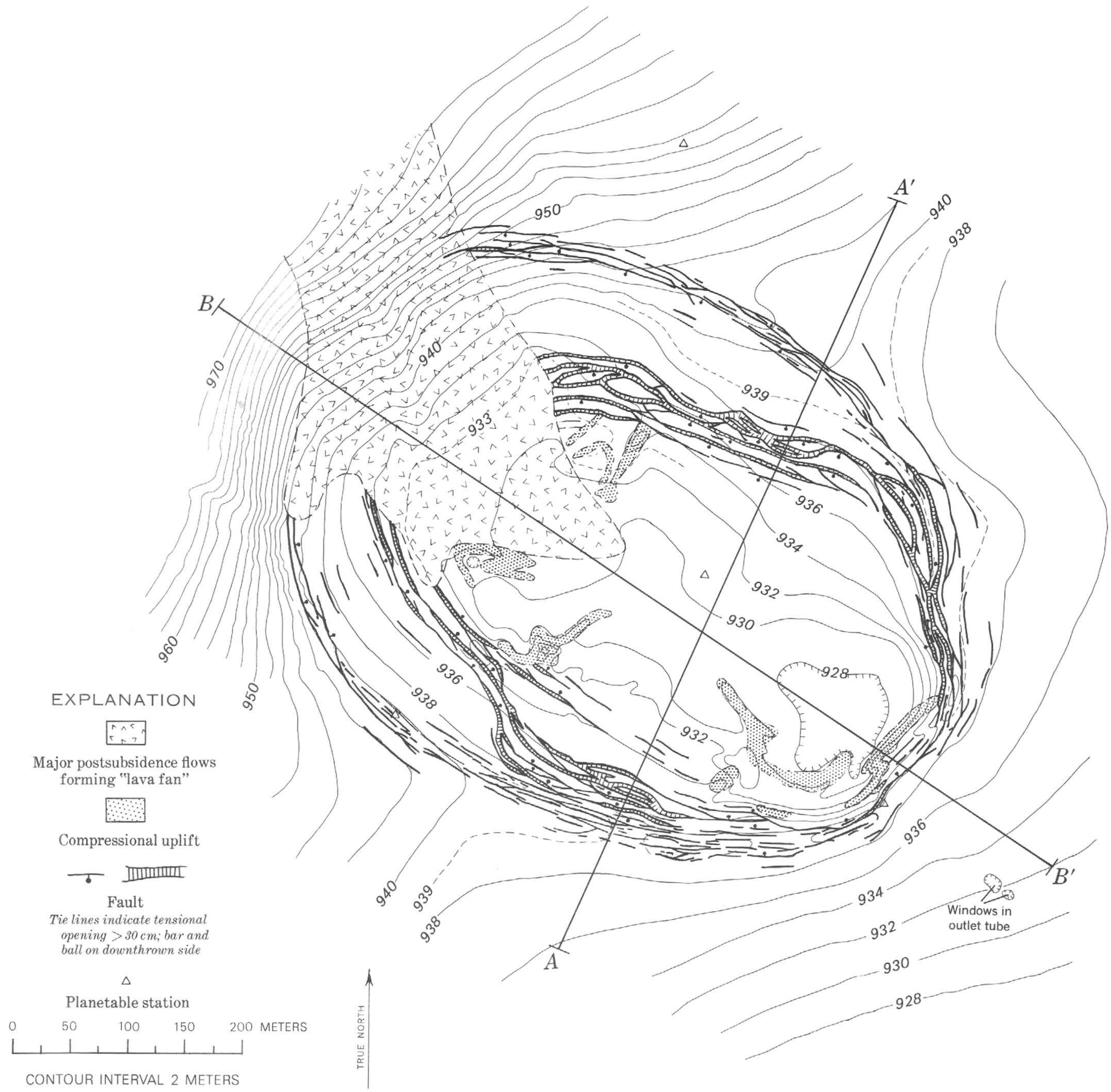


Figure 3.—Geologic map of subsidence bowl in Alae Crater, November 1970. Topography based on planetable mapping by D. W. Peterson, R. T. Okamura, J. B. Judd, and D. A. Swanson. Geology by D. A. Swanson and D. W. Peterson. Elevation in meters above sea level.

The inner set of faults (fig. 3) was defined by large, gaping cracks as much as 8 m wide and averaging 2–4 m. Almost all of these cracks penetrated the zone of partly molten material (plastic crust) between the crust and melt about 5 m below the surface, and viscous lava from this zone oozed upward and largely filled the cracks (figs. 4 and 6), suggesting that the lava was less dense than the overlying crust. Most of the faults probably bottomed out in this zone (fig. 4), and the tensional opening of the faults apparently took place as lava in this viscous layer slowly flowed toward the axis of subsidence, carrying the overlying crust with it.

Vertical displacement on most of the faults of the inner set was small, although offsets as large as 2 m occurred locally. The surfaces of crustal blocks bounded by large faults

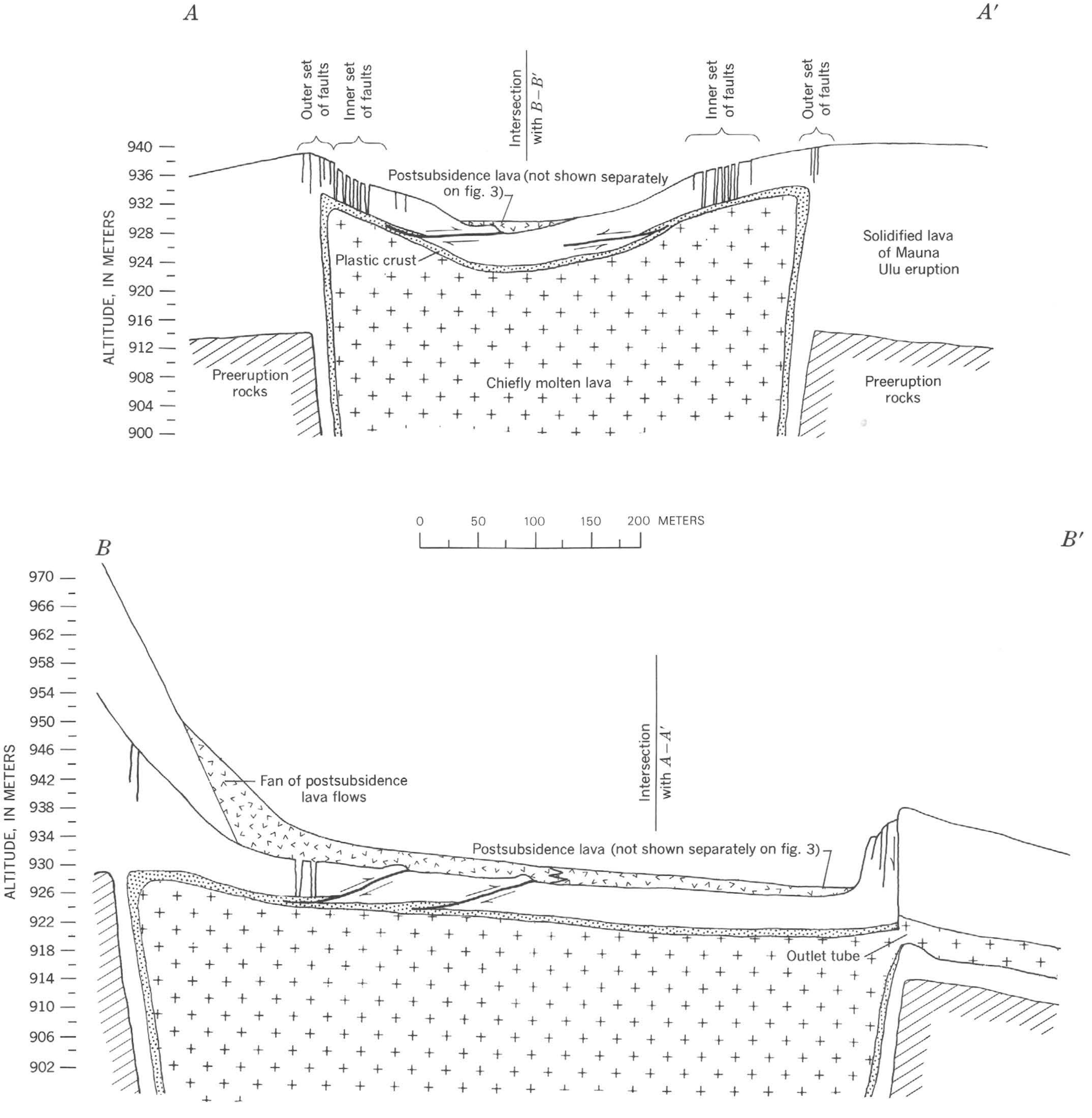


Figure 4.—Schematic cross sections of August 1970 subsidence depression along profile lines shown in figure 3. Lava that oozed upward into open cracks in inner set of faults is not shown. Relations near entrance to outlet tube are generalized; actually this area is jumbled in a highly complex manner owing to postsubsidence rock falls and slumps.

generally dipped inward at the prevailing gradient of the subsidence bowl, but a few were rotated such that dips were flattened or even directed outward. All faults were vertical at the surface.

The inner and outer sets of faults merged toward the southeast end of the crater but formed two separate zones elsewhere (fig. 3). The sets diverged at approximately the location of the buried rim of the inner pit in Alae Crater (fig. 1*A*), and some causal relation seems likely; in detail, however, the correspondence to the rim was far from perfect.

As the two sides of most cracks in both sets could be matched like pieces of a jigsaw puzzle, the azimuth and

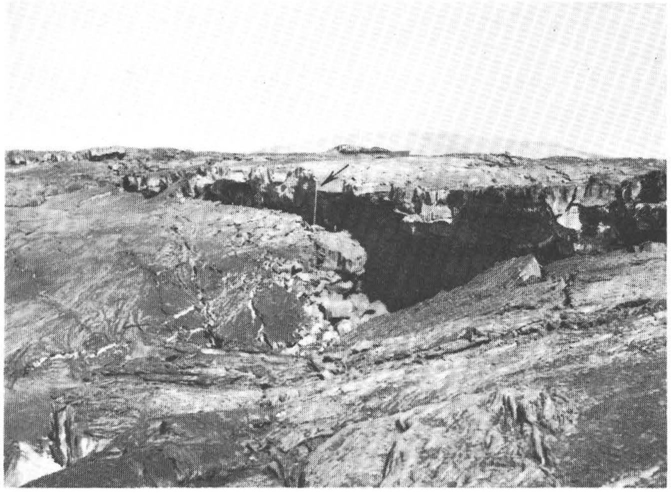


Figure 5.—Vertical displacement on master fault at southeast margin of August 1970 subsidence bowl. Leveling rod (arrow) is 1.5 m long. Note sharply defined trough, a local structure developed immediately adjacent to entrance to outlet tube (hidden in shadow). Photograph taken in mid-November 1970, when lava could be seen flowing in tube from a vantage point in trough. See figure 1 for location.

Figure 6.—Wide crack in inner fault set, east side of subsidence bowl, mid-November 1970. Filled by viscous lava (rough surfaced, dark rock) during August 1970 subsidence; later crustal settling (November 12–13, 1970) caused fault to reopen, cracking lava fill. Leveling rod 1.5 m long spans new crack. See figure 1 for location.

magnitude of the horizontal component of fault displacement could be easily measured (fig. 7). The azimuths of opening were locally quite variable, probably because of slight rotation of blocks or the guiding of stress by preexisting cooling joints; overall, however, they describe an axis of subsidence, not a point source (fig. 8), as do the vertical displacements (fig. 3).

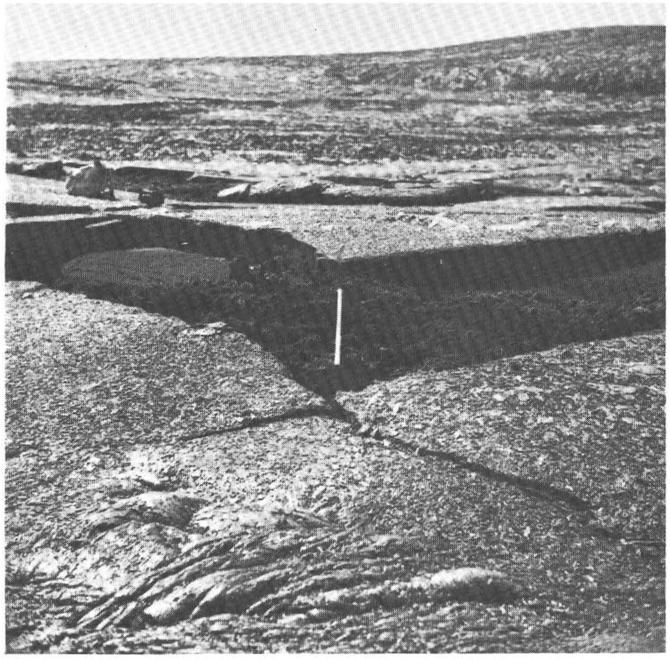


Figure 7.—Tension fault, east side of subsidence bowl, mid-November 1970. Opposite walls can be matched, indicating azimuth and amount of opening. Leveling rod is 1.5 m long. See figure 1 for location.

If minor elastic effects are disregarded, the total amount of extensional opening along a profile perpendicular to the subsidence contours indicates the amount of maximum basinward displacement of the crust within the fault zone (fig. 8). The measured displacement across the two fault zones was about 15 m on the northeastern flank of the subsided area, and about 14 m on the southwestern flank. Horizontal displacement was less than 1 m at the southeast end of the area, where vertical displacement greatly dominated, and was estimated from direct observations and photographs to be several meters at the northwest end, which was covered by new lava before measurements could be made.

The distribution of compressional ridges and domes that formed between the axis of subsidence and the inner set of tensional faults (fig. 8) defined quite closely the line of inflection between tensional and compressional stresses (Yerkes and Castle, 1969; Hamilton and Meehan, 1971, fig. 6). The compressional structures were rarely greater than 5 m high, and many were buried by younger lava before they could be mapped in detail; their approximate locations (fig. 8) are based on aerial photographs taken on August 11. No uplifts formed along the northeastern slope of the subsidence bowl. Elsewhere they were crudely concentric to the subsidence basin, except for the boxwork pattern developed by the northwestern structures. Many, if not all, of the uplifts probably formed by buckling at the toe of the upper plate of thrust faults (fig. 4), a process actually watched during the February 1971 subsidence (fig. 9*A*).

The magnitude of thrusting during the August 1970 subsidence can be easily calculated. The surface distance between

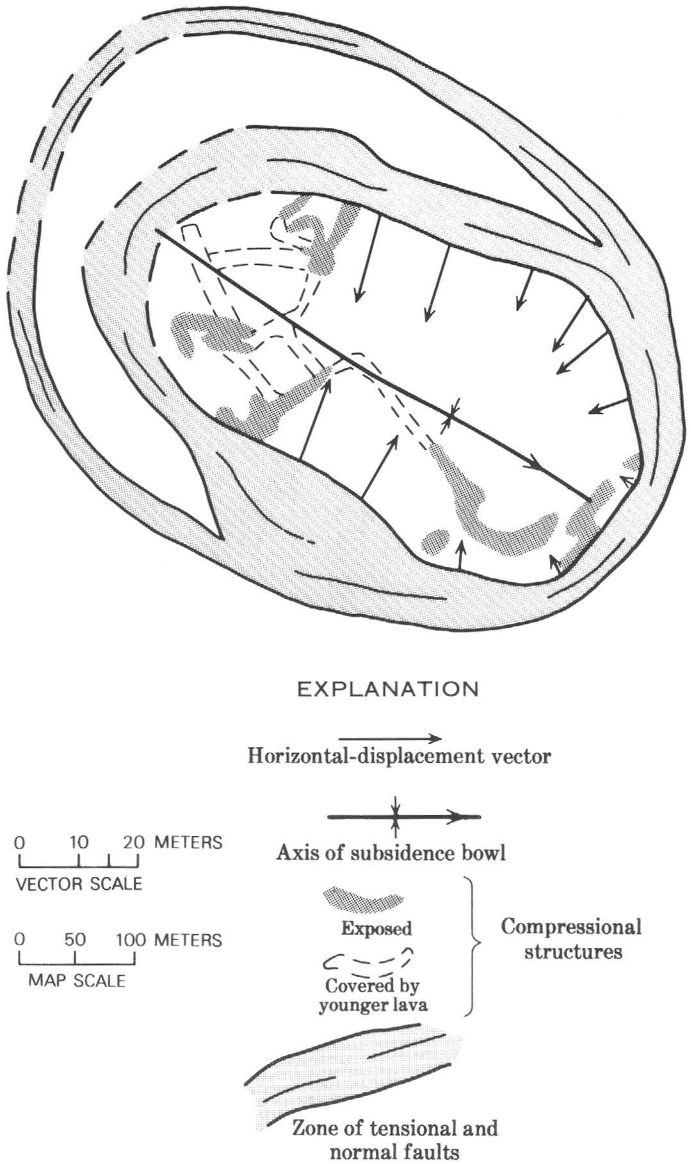
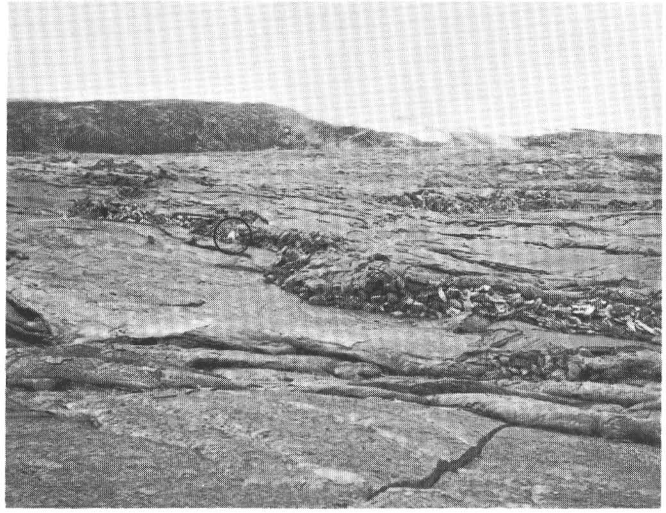
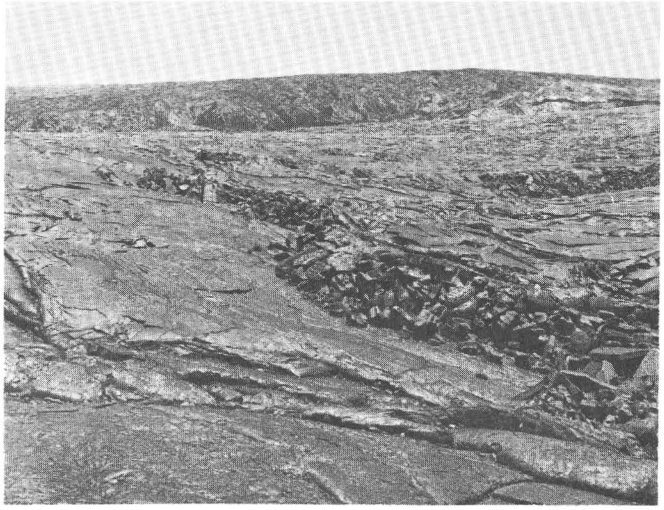


Figure 8.—Generalized structural map of August 1970 subsidence depression, showing horizontal displacement at line of inflection between tensional and compressional strain. Dashed lines indicate structures mapped from aerial photographs taken in mid-August and covered by new lava before geologic map (fig. 3) was made.



A



B

Figure 9.—Thrusting and subsidence of lake crust.

A. Actively forming compressional ridge at buckled toe of thrust fault, February 26, 1971. Thrust is moving 1.2 cm/hour toward crouching man (circled). Note how thrust has apparently advanced across what is now the axis of subsidence (near right edge of photograph). Cliff in background consists of 1969–71 lava flows that accreted on preeruption rim of crater, building rim several tens of meters higher. Thickest fume cloud in upper right issues from active inlet tube and hides part of slope of Mauna Ulu. See figure 1 for location.

B. Approximately same view as *A*, June 28, 1971. Note greatly steepened slopes of subsidence bowl, reflecting 6 m of subsidence after photograph *A* was taken and 4 m since March 2.

two points on opposite sides of the lake increased when subsidence occurred, as illustrated in figure 10*A*. If no thrusting is assumed, the difference between x_h (original distance) and x_s (distance after subsidence) should equal the total cumulative opening of the tensional faults (F) less the effect due to compressional buckling and uplift (P), giving $x_h = x_s - F + P$ (fig. 10*A*). However, measurements of the August fault openings and compressional structures (including the required correction for their partial burial) revealed an important discrepancy. A northeast-southwest profile of the actual subsidence bowl showed that $x_s - x_h = 3$ m. The value of P was determined to be a maximum of 13 m. The measured value of F totalled 29 m. According to the equation, however, $F = (x_s - x_h) + P = 3 + 13 = 16$ m. The tension faults had actually opened 13 m farther than they should have if they alone were to account for the increased surface distance across the subsided lake surface.

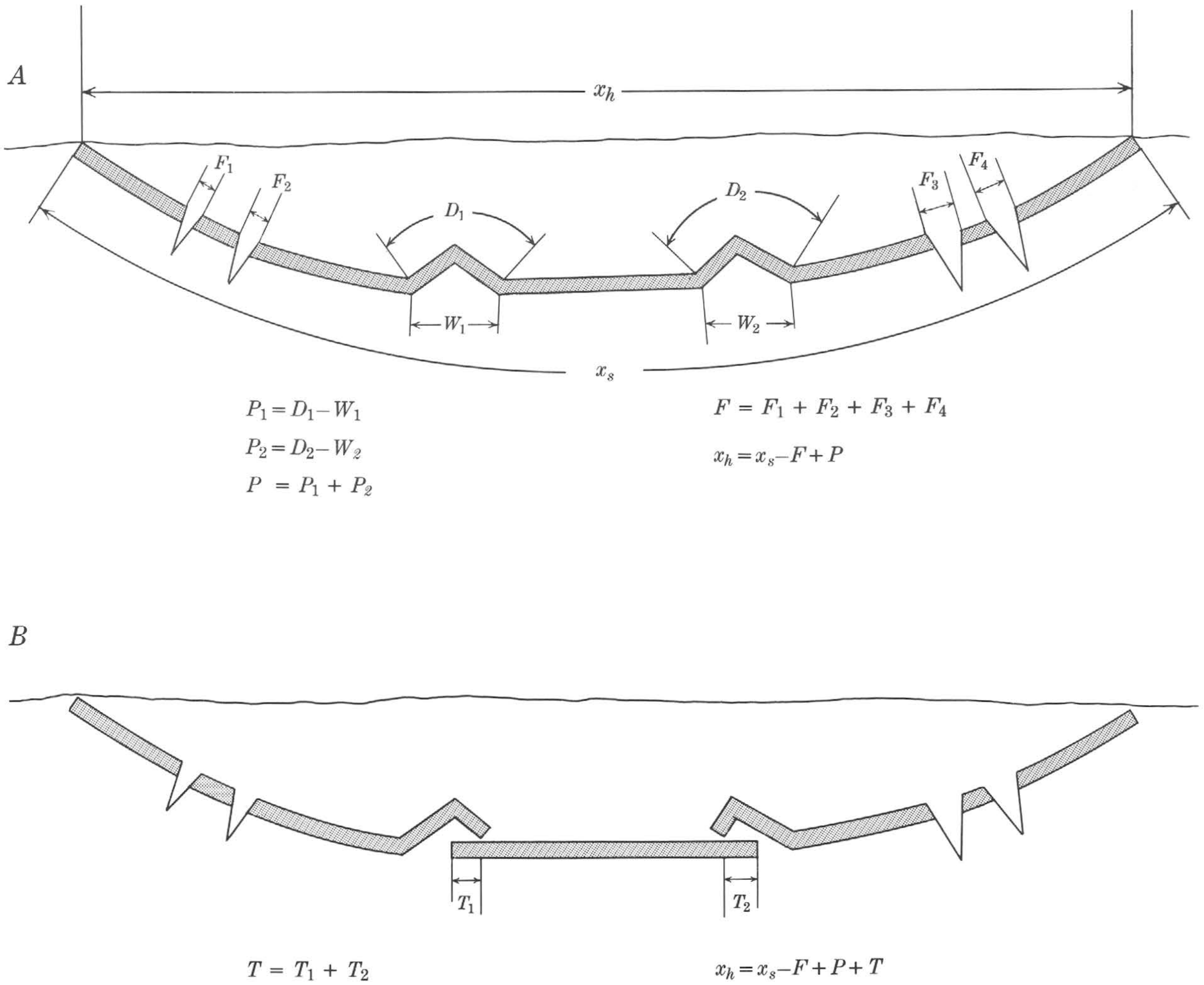


Figure 10.—**Diagrams illustrating method of calculating magnitude of thrusting.**
A. **Relations between presubsidence surface distance across lake (x_h), postsubsidence distance (x_s), total tensional opening of faults (F), and effect of buckling of compressional uplifts (P). Elastic strain is neglected.**
B. **Similar to *A*, except that effect of thrust faults (T) is included.**

The explanation for the discrepancy between predicted and observed surface deformation was discovered during the February 1971 subsidence, when plates of crust were observed being thrust over one another (fig. 9*A*), creating compressional structures of the type formed in August 1970. Hence the relation between x_h and x_s is properly expressed by the equation $x_h = x_s - F + P + T$, where T is the horizontal component of thrusting, as shown in figure 10*B*. According to this interpretation, displacement caused by thrusting amounted to about 13 m during the August subsidence. The thrusting probably took place at the base of the crust or in the layer of viscous, partly crystalline material underlying the crust, and the thrusting was doubtless caused by gravity acting on the sloping sides of the subsidence depression.

Renewed settling occurred during the night of November 12–13, and a partial resurvey revealed that the southeastern part of the depression had lowered about 3 m (fig. 2*C*; table 1). The topography shown in figure 3 is that existing prior to the settling. Several of the larger tensional faults along the east and southeast slope of the depression were reactivated during the settling. The total amount of new fault opening was slightly more than 1 m and was recognized by cracking of the solidified viscous lava fill in several of the August faults (fig. 6) and by pulling away of the inner wall of a large fault from its rooted, viscous lava fill. Lack of evidence for such processes before November 12 suggests little, if any, subsidence between August 13 and November 12.

MECHANISM OF THE AUGUST 1970 DRAINING AND CRUSTAL SUBSIDENCE

The subsidence was caused by a disparity in the rates of flowage of lava into and out of the lake. Direct observations indicate that inflow continued during the subsidence at an estimated rate of about 1.3×10^4 m^3/hour. The average rate of outflow is roughly calculated to have been about 3.4×10^4 m^3/hour; this average rate assumes the rate of inflow cited above, a subsidence volume of 10^6 m^3 (determined by computer from the topographic map), and a duration of draining of 2 days (noon August 8–noon August 10). The calculated average rate of outflow is probably valid to a factor of 2 and is consistent with lower rate estimates for lava flowing in tubes at times when no draining is taking place (Hawaiian Volcano Observatory, unpub. data, 1970–71).

The preeruption southeast rim of Alae Crater was buried beneath about 24 m of new lava prior to the August draining (fig. 2*A*; table 1). The maximum amplitude of the August subsidence was 13 m; hence the floor of the subsidence bowl was about 11 m higher than the old southeast rim (fig. 2*B*). The thickness of the lava-lake crust which formed the floor of the subsidence depression can be estimated as follows. This crust began to form on October 20, 1969, and was probably about 3 m thick when it was uplifted several meters by subcrustal injection of lava on December 30, 1969 (Swanson and others, 1972), on the basis of the rate of crustal growth determined by Peck and others (1966) and Shaw and others (1968). Injection of the December 30 lava probably disturbed the thermal regime sufficiently to make calculation of subsequent crustal growth unreliable. An upper limiting value, if no thermal disturbance is assumed, gives a total, but unreasonably large, crustal thickness of about 7 m by August 1970. If a crustal thickness of 5 m is assumed, then the base of the crust after the August subsidence was about 6 m higher than the lowest point on the buried southeast rim (fig. 2*B*; table 1).

Observations of the October 20, 1969, surface channel that developed into the outlet tube show that the floor of this tube was 2 to 3 m above the low point on the preeruption southeast rim and 3 to 4 m lower than the base of the subsided crust of the lake (fig. 2*B*).

Knowledge of the relative elevations of the critical features is essential for an interpretation of the subsidence. Hydrostatic pressure in the lake increased sufficiently during the subcrustal addition of lava in early August to reopen the plugged, preexisting lava tube. Lava stored within the lake rapidly drained through the tube at an average rate of about 3.4×10^4 m^3/hour, about 2.5 times the rate of inflow. The upper surface of the molten lava lake (base of crust) consequently dropped to about the level of the top of the lava tube, which probably was several meters above the tube floor. Draining continued at a reduced rate until the outflow in the tube just balanced the inflow of about 1.3×10^4 m^3/hour, at which time the level of molten lava stabilized. The solid crust subsided as its support was withdrawn, and it became detached from the walls, but owing to mechanical lag effects slight amounts of local settling continued for several days beyond the time at which inflow balanced outflow.

The crustal settling of about 3 m on November 12–13 (fig. 2*C*; table 1) is consistent with this interpretation, if the entrance of the outlet tube in early August remained partly blocked to a height of about 3 m above its floor (fig. 2*B*). If this blockage had been removed in November, the lake would have drained and the crust would have settled until the equilibrium state was again reached (fig. 2*C*). An alternative explanation is that the crust settled in November to the level that the surface of molten lava had already reached during the August draining. This explanation implies that a tabular void about 3 m thick existed between the crust and lava surface during the August–November interval, and does not involve draining of excess lava from the lake in November. Either alternative is preferred to one of a relatively sudden decrease in rate of inflow on November 12, which is not indicated by either direct observations of the inflow tube or tilt and seismic records.

The final elevation of the liquid surface of the lava lake was controlled in a basically hydrostatic fashion by the elevation of the entrance to the outlet tube. But details of the subsidence show marked departure from ideal hydrostatic behavior. For example, the crust of the lake should have subsided pistonlike, with no differential settling, if the subsidence were purely hydrostatic. The complex structures on the crust indicate, in fact, considerable mechanical complication. Such structures (fig. 3) include the elongate asymmetric trough that parallels the dominant flow direction, the overall southward slope of the lake surface, and the depression near the exit tube.

Lava behaves more nearly like a Bingham than a Newtonian fluid (Shaw and others, 1968); hence, the laws of hydrostatic fluid behavior did not strictly apply as the lava traveled through the reservoir and drained through the outlet tube. Furthermore, the internal complexity of Alae lava lake (Swanson and others, 1972)–layers of melt sandwiched between partly melted layers of crust–indicates that the lake was not a simple pool of fluid. As a result, the circulation pattern of throughgoing lava in the lake was probably complicated. Lateral gradients in temperature and crystallinity governed local variations in viscosity which, in turn, influenced paths of most rapid flowage. In addition, the effective tensile strength of the crust itself probably was highly variable from place to place, owing to differences in thickness, vesicularity, and adhesion to the walls of the crater; thus the response of the crust to stress changes was nonuniform. Factors such as these must have played a significant part in producing the irregular surface of the downdropped crust throughout the entire subsidence event. Indeed, when all these complications are considered, it is remarkable that the draining and resulting crustal subsidence were as strongly hydrostatically controlled as they were.

DESCRIPTION OF THE FEBRUARY–MARCH 1971 DRAINING AND CRUSTAL SUBSIDENCE

Lava was more or less continually introduced into Alae Crater through the inlet tube and withdrawn through the outlet tube for several months following the August 1970 subsidence, yet, with the exception of the November 12–13 event, no deformation affected the surface crust of the lava lake. Apparently a balance was struck between the rates of inflow and outflow, about 1.3×10^4 m^3/hour. Between November 1970 and early February 1971, thin surface flows from Mauna Ulu intermittently entered Alae Crater and eventually inundated the entire floor of the subsidence depression, covering the area of maximum subsidence with about 8 m of solidified lava (fig. 2*D*; table 1).

On February 10, 1971, a large volume of lava began to pour onto the lake surface from a tube fed by a fissure about 150 m north of the crater (fig. 1*B*), filling the remainder of the subsidence bowl (about 8×10^5 m^3 in volume) to overflowing within about a day (fig. 2*E*). Lava probably entered the molten lake beneath its surface crust as well, via the preexisting inlet tube. The surface activity continued until February 17, and accretion from overflow of the lake built the southeast rim about 5 m higher, to about 20 m above the preeruption rim (fig. 2*E*; table 1). A flight over the area on February 20 revealed that lava was pouring out of the crater through the outlet tube active since August 1970, but there was no noticeable subsidence of the lake crust. Strong fumes from the old inlet tube in Alae suggested that lava was still entering the lake beneath the surface.

The lake crust had already subsided a maximum of 8 m by February 23, when the crater was visited on the ground. We presume that the subsidence began somewhat earlier, probably on February 21. By February 26, the crust had lowered 17 m, and most of the surface structures related to the subsidence had already formed. Deformation was largely complete by March 2, when the subsidence bowl was about 19 m deep (table 1; fig. 2*F*). Slow settling of the crust continued over the next several months, amounting to an additional 4 m by June 28 (figs. 2*G* and 9*B*). Periodic observations between March 2 and June 28 suggest that the settling ended in May.

The structures produced by the February subsidence were generally similar to those of the August 1970 event, but details were different. The subsidence depression, defined by small faults along its circumference (figs. 11 and 12), was again elliptical in plan view. The southeast end was the deepest, and the northwest end showed barely any subsidence; as a result, the entire floor was inclined toward the southeast at an average gradient of about 1:25. The depression was also asymmetric in a northeast-southwest direction (fig. 12), so that the axis of greatest subsidence was located 20 to 30 m northeast of that formed in August. This asymmetry was reflected by the location of the major faults, which were much larger and more numerous along the northeast slope than anywhere else (figs. 11 and 12). These major faults differed from the otherwise similar August faults by their greater vertical displacements, which averaged 0.5 to 1 m, and by their shallower "roots", generally about 2 m beneath the surface (compare figs. 2*B* and 2*F*).

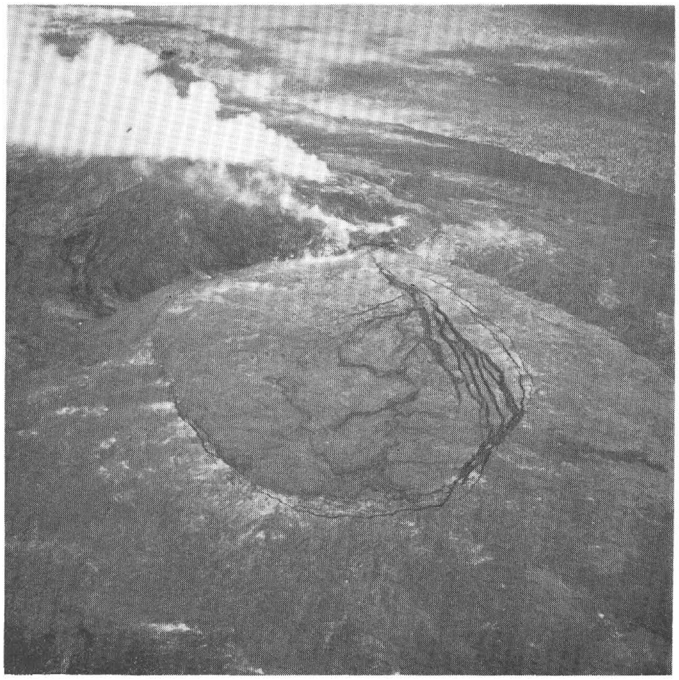


Figure 11.—View looking northwest over February–March 1971 subsidence bowl on March 1, 1971. Sinuous compressional ridges are concentrated near but mostly northeast of axis of subsidence. Tensional faults surround subsidence bowl and define buried rim of Alae Crater. Large faults, with vertical displacement of several tens of centimeters, occur within eastern part of bowl. Largest fume cloud issues from vent at east end of collapsed trench (fig. 1*B*) on flank of Mauna Ulu; smaller cloud near subsidence bowl comes from window in active inlet tube.

Many sinuous compressional ridges and irregular uplifts formed during the February 21–March 2 subsidence (figs. 9, 11, and 12). They tend to outline two crude lobes extending toward the southwest from the northeast flank (figs. 11 and 12). Most of the compressional structures were northeast of the axis of subsidence, as were the tension faults; this coexistence suggests that the compressional structures developed to help accommodate the extension along the northeast limb of the subsidence bowl.

Most of the compressional uplifts probably formed by buckling at the toes of actively moving thrust faults; one such uplift was actually observed in the process of formation on February 26. The upper plate of a thrust, marked by a ridge about 1 m high, advanced at a rate of 1.2 cm/hour over the lower plate (fig. 9*A*). The ridge was buckling and oversteepening as thrusting continued. Large blocks occasionally rolled off the oversteepened slope, only to be slowly pushed ahead or even overridden by the advancing upper plate. The upper plate advanced 3.3 m within the next 4 days (to March 2) but only 10 cm over the next 21 days; movement probably stopped shortly after March 2, although settling continued slowly for 2 months longer (fig. 9*B*). The plane of thrusting was largely within the semisolid, plastic layer immediately

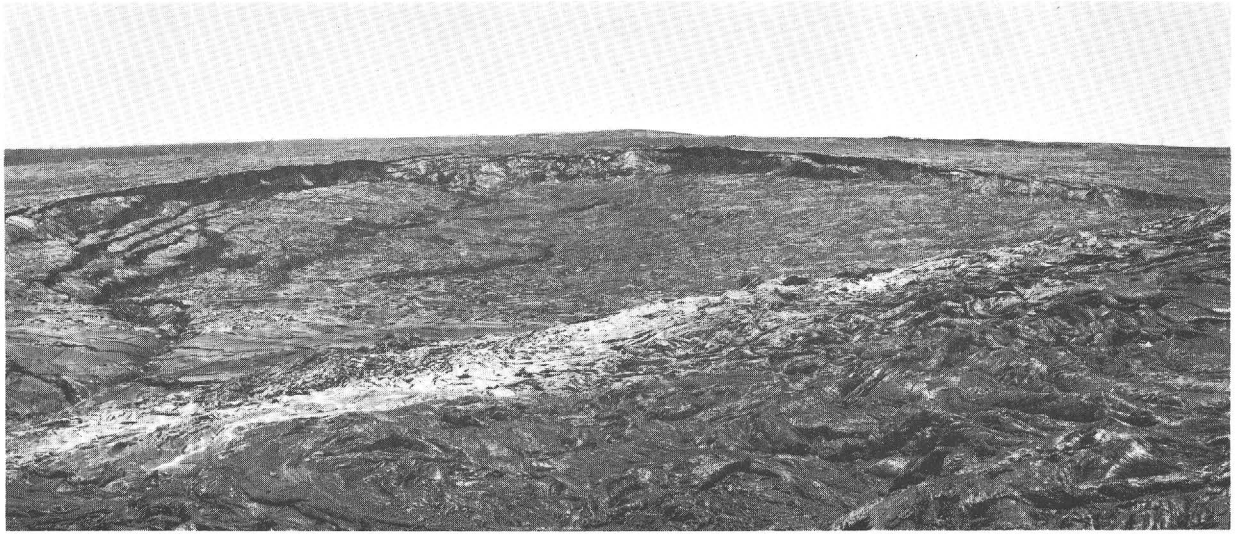


Figure 12.—View looking southeast over February–March 1971 subsidence bowl on June 28, 1971, from southeast flank of Mauna Ulu. Note asymmetry of depression, concentration of large faults on northeast flank, and two lobate compressional ridges near center of photograph. Maximum amplitude of subsidence, near southeast end of depression, is 23 m. Preeruption crater rim is buried 29 m beneath lava flows at southeast end of depression.

below the solid crust, although the toe of the thrust rode over the ground surface. In places, this plastic layer—deeply scored, striated, and crisscrossed by narrow tension cracks—could be seen through cracks in the upper plate. The thrust faults may have bounded large lobes of crust that slid basinward, as suggested by the pattern of compressional structures (figs. 11 and 12).

MECHANISM OF THE FEBRUARY–MARCH 1971 DRAINING AND CRUSTAL SUBSIDENCE

The basic process of draining and crustal subsidence was hydrostatically controlled and virtually the same during the February–March 1971 and August 1970 events: Net lava outflow through a tube exceeded inflow, causing the crust of the lake to subside to a final elevation governed by the outlet tube; the elevation of the base of the crust was the same after each event. The two events, however, were characterized by three significant differences: (1) Immediately prior to the 1971 subsidence, the upper part of the reservoir consisted of new lava whose surface crust was considerably thinner than the crust of the reservoir in early August. (2) The pre-February 10 crust was a solid layer sandwiched between two layers of molten lava above the elevation of the outlet tube; no such layer existed in August (compare figs. 2*A* and 2*E*). (3) This solid layer sank into the underlying lava, thus displacing an equal volume of lava upward and out through the outlet tube. Deductions on the behavior of the solid layer are important to understanding the mechanism of the February–March 1971 subsidence.

The pre-February 10 solid layer must have subsided a total of at least 13 to 16 m, after it was torn from the walls of the crater, to account for the final elevation of the surface of the lake, as determined in the following way. The thin flows added to the floor between November 13 and February 9 had a maximum solidified thickness of 8 m. If the solid layer had sunk just 8 m, however, it would have blocked the outlet tube (fig. 2*E*). Hence, it had to sink an additional 3 to 6 m, as shown in fig. 2*F*, to allow the overlying February 10–17 lava to drain. Finally, observations of the new crust that formed on the February 10–17 lava showed it to be about 2 m thick by the end of the event. Thus the submerged solid layer must have sunk at least as much as the total of these increments, or 13 to 16 m. This sinking implies that the crust had a specific gravity equal to or slightly higher than that of the liquid lava. As measured ranges of specific gravities of solidified basalt and glassy melt samples overlap (Hawaiian Volcano Observatory, unpub. data, 1971), this implication is reasonable, and the upward injection of lava into many of the tension cracks likewise suggests that the lava was less dense than the solid crust.

The solid layer consisted not only of the lake crust that had subsided in August, but also of the series of thin solidified flows, totaling about 10 m in thickness, that had been added between August and February 9 (figs. 2*D*, 2*E*, and table 1). When the lake refilled with the February 10–17 lava, this solid layer formed a barrier between the overlying new lava and the outlet tube (fig. 2*E*). During part of November and December 1970, a hole in the southeast wall of the subsidence bowl was open (fig. 5), and lava in the tube could be seen; this hole had been closed by slump debris when the February filling began, however. Thus we suspect that the barrier was complete in February and that little, if any, of the overlying lava drained immediately into the tube.

The timing and amount of sinking of the lake crust, and the overall behavior of the submerged solid layer during the subsidence, are interrelated. The basin refilled in about 20 hours, 1500 February 10 to 1100 February 11, and the added weight of the new lava, about 16×10^8 kg, on the underlying pre-February 10 solid layer must have greatly strained the fragile attachment of this layer to the solid walls. We do not know whether this attachment held until February 21, the day subsidence began and 4 days after surface inflow ceased, or whether it broke loose soon after the basin was filled or at some intermediate time. Regardless of the exact time, lava overlying this solid layer did not begin to drain through the outlet tube until February 21, indicating that the submerged solid layer remained an effective barrier for 4 days after surface inflow stopped.

If the solid layer had been detached during the surface inflow, it would have sunk whole or piecemeal as long as lava beneath it was able to escape through the outlet tube. However, the solid layer would have blocked the tube after it subsided 1 to 3 m, causing the system to become static. This metastable blockage could have existed indefinitely if the solid layer were of equal or only slightly higher specific gravity than the molten lava, or if the layer were hung up on the inward sloping walls of the crater.

For the period immediately preceding and including February 21, then, one of the following situations obtained:

1. The submerged solid layer blocked the outlet tube. In this situation, addition of lava from the inlet tube (which aerial observations suggest was still carrying lava) would have increased hydrostatic pressure in the lake beneath the solid layer, eventually breaking the layer and allowing communication between the outlet tube and the liquid lava on either side of the solid layer. The solid layer would then have sunk as lava drained out the tube.
2. The submerged solid layer remained attached to the walls above the level of the outlet, leaving the underlying liquid lava free to flow out the tube. In this situation, the hydrostatic pressure in the lake almost certainly would not have increased, because the inflow rate would have had to increase manyfold to exceed the capacity of the outlet tube. More likely, in fact, inflow dwindled after surface flowage stopped. In any case, the weight of overlying lava eventually caused the solid layer to tear away from the walls, allowing this lava to drain through the tube, the process being delayed until February 21 because of rate-related mechanical parameters, perhaps including some partial melting. The solid layer would have had to crack near the outlet tube for the underlying lava to be displaced upward and out the tube as the solid layer sank.

We cannot decide between these possibilities, nor can we state whether the solid layer sank piecemeal or as a whole. The general southeastward slope of the floor of the subsidence bowl suggests, however, that the solid layer was "hinged" and sank as a trap door, with maximum sinking adjacent to the outlet tube.

SUMMARY

1. The August 1970 partial draining of a lava lake in and above Alae Crater occurred when increased hydrostatic pressure accompanying renewed inflow forced a sealed, inactive tube to reopen. Outflow through the reopened tube was rapid, exceeding flow into the reservoir by a factor of about 2.5, and the crust of the lake subsided. When the crust lowered to a level governed by the elevation of the tube, the rate of outflow decreased; net draining ceased when the outflow balanced the inflow. Local crustal settling continued for several more days because of mechanical lag effects.
2. Peripheral tensional faults and central compressional ridges were developed by basinward sliding of blocks and lobes of solid crust over the partly molten, semisolid substratum under the influence of gravity. The amounts of tensional and compressional deformation were balanced if the extension of the surface due to subsidence is considered.
3. A small episode of crustal settling took place November 12–13, probably as a result of further opening of the outlet tube or lowering of the crust to the top of the molten lake; no accompanying reduction in inflow rate was recognized.
4. The August subsidence bowl was refilled in February 1971, and the subsequent draining and crustal subsidence were hydrostatically controlled and basically analogous to the August event. Shallower faults developed during the February subsidence owing to the thinner crust. Additional complexities in the reservoir plumbing system were created by the sinking of the pre-February crust and consequent displacement of an equal volume of underlying molten lava. Most crustal subsidence was complete within 2 weeks, but slight settling continued for 2 to 3 months as the crust slowly adjusted mechanically.
5. The observed relations between draining of molten lava, subsidence of the surface crust, and rates of inflow and outflow help confirm and refine the active role that the Alae lava reservoir played in the shallow conduit system feeding flows that descended the south flank of Kilauea from August 1970 to May 1971.

A new chapter was added to Alae's history in early 1972. Lava from a new eruption at Mauna Ulu first reached the 1971 subsidence bowl on February 7, and by February 12 the bowl was filled. Lava spilled over the southeast rim and fed a surface flow, but no lava entered the outlet tube that had drained Alae in 1970 and 1971. The flow into Alae ended about February 16, and the crust subsided only 1 to 2 m, probably solely because of cooling. Lack of lava in the outlet tube and lack of significant subsidence together support the conclusion that tube activity and crustal subsidence are directly related.

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