TIDAL EFFECTS ON HAWAIIAN VOLCANISM

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ABSTRACT

This paper summarizes earlier work on possible tidal effects at Kilauea Volcano. From a significant test on 52 historical eruptions of Kilauea, Dzurisin inferred that the likelihood of a fortnightly tidal influence is approximately 90 percent. Reanalysis of early work by Jaggar on the fluctuations of the lava-lake level at Halemaumau shows that semidiurnal oscillations during the highest level of the lava-lake activity are well correlated with solid-Earth tides. This tidal fluctuation of the lake level is attributed to cyclic volume change of the magma reservoir caused by tidal strain. Effective volume of the magma reservoir is estimated to be roughly 800 cubic kilometers from the computed cubical dilatation. The effective magma reservoir beneath Kilauea is suspected to be an assemblage of chambers filled with magma rather than a single large chamber.

INTRODUCTION

Intracrustal stresses caused by lunisolar attraction, though they are small, have been considered by many workers to influence the occurrence of earthquakes and volcanic eruptions. Many attempts have been made to correlate solid-Earth tides with earthquakes (Hoffmann, 1961; Knopoff, 1964; Simpson, 1967; Ryall and others, 1968; Shlien, 1972; Kayano, 1973; Mauk and Kienle, 1973; Klein, 1976).

Some earthquakes or earthquake swarms show significant correlation with tides. For example, earthquakes on several parts of the world rift system are significantly correlated with the semidiurnal tide. This implies an enhancement of stress on parts of tensional spreading axes. From a global viewpoint, however, significant correlations are not found, and this indicates that most earthquakes are not triggered by specific amplitudes of acceleration of Earth-tide components.

As for volcanic eruptions, it seems also intuitively possible that crustal tidal strain could act as a trigger, provided that the volcano is in a nearly critical state. Chamberlin (1918, p. 231) stated that "Pronounced tidal movement might be expected in the necks of volcanoes if they are connected with large reservoirs of lava below, but if there is any response to tidal strains at all, it is scarcely detectable."

Johnston and Mauk (1972) tested for effects of Earth tides on the major eruptions of Stromboli and found a correlation between eruption times and the modulation envelope of the fortnightly tide. However, there was not a good correlation between eruptions and the phase of diurnal tide. Mauk and Johnston (1973) found similar results for the major eruptions of the world's submarine volcanoes since 1900. Hamilton (1973) demonstrated correlations between worldwide volcanic activity and tidal periods, not only for fortnightly periods, but also for periods as long as 18.6 years. Eggers and Decker (1969) made statistical time-series analyses of worldwide volcanic eruptions and suggested a possible relation with the annual component of Earth-tide cycles.

For Hawaiian volcanoes, the pioneering study of tidal effect was by Jaggar (1924), who observed semidiurnal movement of the level of the liquid lava pool at Halemaumau pit crater. Brown (1925) made Fourier analyses of Jaggar's data and found some evidence of tides with periods of 24 h and 12 h 25 min. More recently, Dzurisin (1980) tested the relation between the well-recorded historical eruptions of Kilauea and the phase of fortnightly tidal cycles. From the point of view of forecasting volcanic eruptions of Kilauea, Klein (1984) concluded, on the basis of Dzurisin's analysis, that the fortnightly tidal modulation is a significant eruption predictor, especially for rift-zone eruptions. Shimozuru (1975) made a detailed analysis of Jaggar's (1924) data on fluctuation of the level of Halemaumau lava lake and found a semidiurnal oscillation correlated with Earth tides when the lake was at its highest levels.

In this article I review the previous investigations of tidal effects on the activity of Kilauea Volcano and attempt to use these data to interpret the character of the magma reservoir system beneath the volcano.

EARTH TIDES AND VOLCANIC SYSTEMS

For simplicity, volcanoes are here considered to consist of a major magma reservoir and conduits surrounded by solid rock. A volcanic system's response to solid-Earth tides may be different depending on whether the magma reservoir or conduits are filled with magma or not. Furthermore, tidal strain is a function of latitude, as shown in figure 49.1, and so any tidal effects on volcanic activity should be smaller at high latitudes than low latitudes. These two conditions are principal criteria for the evidence for tidal effects on volcanic activity.

Volcanic activities can be categorized into two types. One type is more or less continuous, such as seismic activity including volcanic tremor, lava-lake activity, and long-lasting eruptive events. The other type is discontinuous, such as sporadic eruptions and short-

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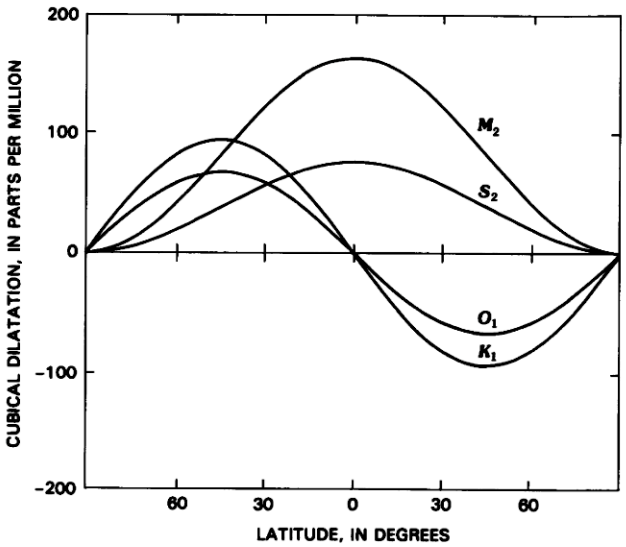

FIGURE 49.1.—Varition of cubical dilatation with latitude due to principal semidiurnal sectorial waves (M_2, S_2) and principal diurnal tesseral waves (K_1, O_1).

term seismic swarms. For the latter type, increasing and decreasing pore pressure caused by the movement of lava and gas resulting from tidal strain may act, together with tidal stress, as the triggering mechanism of volcanic earthquakes. These various modes of activity combined with the above mentioned relations make the problem complex. Most investigations to date have been statistical calculations of the possible relation between solid-Earth tides and volcanic activity.

For a more quantitative approach to this problem, we can learn from the tidal fluctuations of water level in deep wells documented by Pekeris (1940) and Richardson (1956). These investigators observed a high tide in the well at the time when the acceleration from the lunisolar attraction was minimal. Pekeris (1940) estimated that a change of water level of 1 cm in a well of 1-m radius could be brought about by cubical dilatation in a water-bearing hemisphere of only 100-m radius. Replacing water with liquid lava, we can apply this to volcanic episodes.

ROLE OF EARTH TIDES ON ERUPTIONS OF KILAUEA AND MAUNA LOA VOLCANOES—FORTNIGHTLY TIDAL EFFECT

In the light of growing evidence for tidal triggering of volcanic eruptions, Dzurisin (1980) made a statistical study of the onset times of individual eruptions of Kilauea and Mauna Loa in relation to solid-Earth tides. Incorporated in his study were 52 historical eruptions of Kilauea, from 1832 to 1979, and 37 of Mauna Loa, from 1832 to 1972. The beginning of surface lava extrusion was taken as the starting time of each eruption. In light of the results of previous investigations, he concentrated on the influence of the fortnightly tide. Tidal acceleration was computed for the 2-week period centered on each eruption. Examples of the correlation of vertical acceleration of solid-Earth tides and eruptions of Kilauea are shown in figure 49.2. Dzurisin confirmed that eruptions at Kilauea clearly occur preferentially near the fortnightly tidal maxima, with approximately 90 percent likelihood. For Mauna Loa, however, he found that the 37 historical eruptions have been distributed randomly with respect to the fortnightly tide. He inferred that differences in structure or internal plumbing may limit the effectiveness of tidal influences on Mauna Loa. In contrast to the tidal-phase correlation of Kilauea eruptions, Johnston and Mauk (1972) found that eruptions of Stromboli clustered conspicuously about the time of fortnightly tidal minima. This difference in behavior between Kilauea and Stromboli, though they are both basaltic volcanoes, is not understood. Possibly it is related to the difference in tectonic setting.

TIDAL OSCILLATION OF HALEMAUMAU LAVA LAKE IN 1919—SEMIDIURNAL TIDAL EFFECT

Jaggar (1947, p. 7) stated that the routine of the Hawaiian Volcano Observatory "had been determined by the necessity for

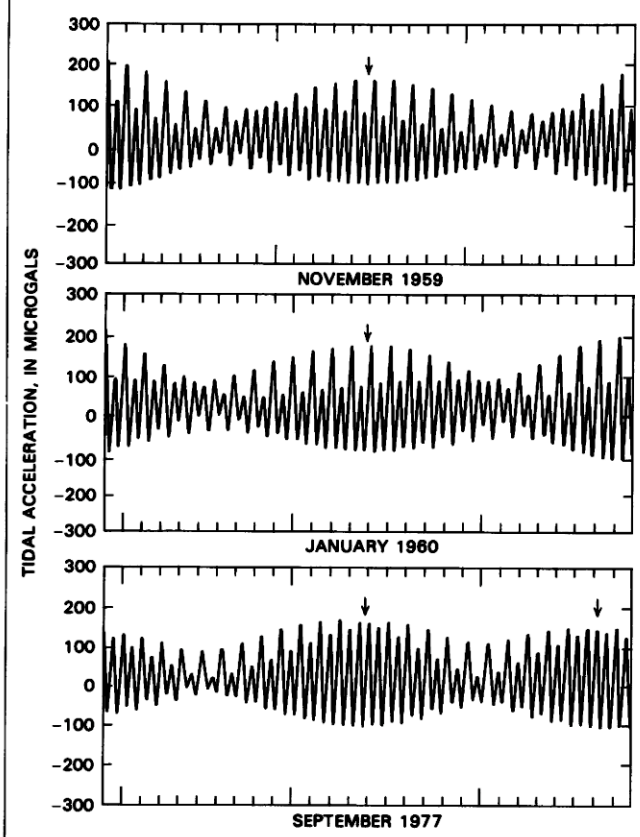

FIGURE 49.2.—Variation of tidal acceleration at Kilauea during time periods in which eruptions occurred. Beginnings of eruptions marked by arrows. After Dzurisin (1980).

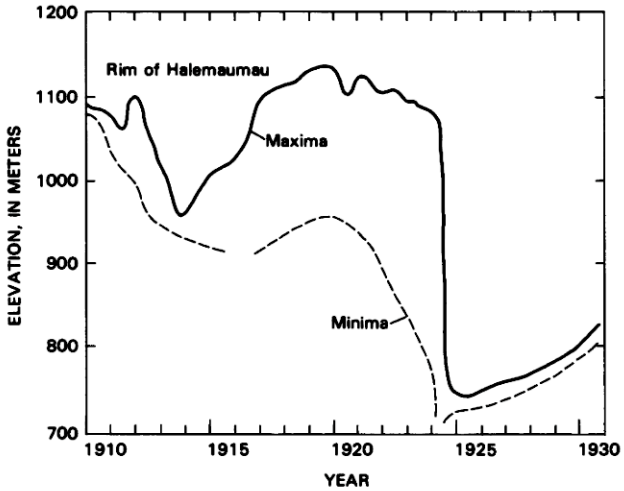

FIGURE 49.3.—Long-term changes in level of Halemaumau lava lake from 1910 to 1930. After Jaggar (1947).

continuous measurement with surveying instruments of the lava pool in Halemaumau pit." The elevation of the surface of the lava lake was measured from 1909 until 1930. Timing of the measurements was arbitrary except during July–August 1919, when the level was highest. A smoothed curve of the level of the lava lake is shown in figure 49.3. The dramatic drop of the level in 1924 was related to magma injection into the east rift zone of Kilauea Volcano and the explosive eruption at Halemaumau.

During the interval of 28 days from July 21 to August 16, 1919, transit measurements of the level of the Halemaumau lava lake were made by Jaggar and his coworkers every 20 minutes. Two points on the edge of the liquid lava lake and two points on the pit floor outside the lava lake were repeatedly measured with reference to a datum station located at the western rim of the crater. The height of the datum station was occasionally checked from the observatory. Brown (1925) made a Fourier analysis of Jaggar's data and found some evidence of tides with periods of the lunar day and lunar half-day, with double amplitudes of about 1 in. His analysis covered the entire measurement interval. However, for a few days near the end of the interval, the liquid lava showed marked oscillations of amplitude 30–60 cm with a period of about 12 h.

While at the Hawaiian Volcano Observatory in 1963 as a member of the Japan-U.S. Cooperative Science Program, I examined Jaggar's data on the level of the Halemaumau lava lake and was very impressed by the detailed measurements. Stimulated by his work, I made an extensive analysis of his data and found that the semidiurnal oscillations during the time of the highest general lake level were in good correlation with the tidal phase (Shimozuru, 1975). This correlation was attributed to squeezing out and drain-back of magma from and to the magma reservoir caused by tidal strain. However, in my previous study there were some uncertain points and a miscalculation. I am therefore revising my analysis of Jaggar's data in order to enhance their scientific value.

DATA

Assuming they approximately reflect the level change of the entire lava lake, I have adopted the hourly mean values of elevation at the edge of the lava lake from the table in Brown (1925, p. 109). For a 7-h period in the middle of the observation interval, no measurements were made; values were interpolated for this missing time. These data are plotted in figure 49.4 together with the variation of gravitational acceleration caused by tidal forces during the corresponding period. The geographical location was taken as latitude 19.42° N., longitude 155.29° W., and elevation 1,800 m above sea level. Though the level of the lava lake shows in detail a ragged rise and fall, there is a general gradual rise until it reaches its highest level about August 15, 1919.

METHOD OF ANALYSIS

The data were treated first by a moving-window analysis as shown in figure 49.5. The starting time was taken as 0300 (Hawaiian standard time) on July 23. A significant semidiurnal spectral component at the later stage of the observation period is seen in figure 49.5. This evidence is more clearly shown by the fast Fourier analysis shown in figure 49.6. Over the whole period, there is no significant peak (fig. 49.6, uppermost curve), however, in the later part (August 10–16), a strong peak appears near to the period of the semidiurnal tidal components M_2, S_2, N_2, and K_2. The period of the dominant peak is slightly longer than that of the semidiurnal tides; this discrepancy may be partly because the analysis covers such a short period. Considering the difficulties of observation and the limitations resulting from the complex dynamics of the lava lake, particularly the horizontal movement of the liquid lava, I conclude that in the later part of the observation period, a semidiurnal period was evident in the lava lake oscillation.

CORRELATION WITH SEMIDIURNAL TIDE

Encouraged by this evidence of correlation, I tried to interpret quantitatively the relation of the semidiurnal fluctuation of the lava-lake level to Earth tides. Using the concept of tidal strain causing magma to squeeze out and drain back from and to the magma reservoir, the cubical dilatation was computed for the period from July 20 to August 19, 1919. The cubical dilatation (Δ) at the surface is, if Lame's constants λ is equal to μ,

$$\Delta = F(r)\,\frac{W}{rg} = \frac{2}{3}\,(2h-6l)\,\frac{W}{rg},$$

where W is the potential due to tide-generating forces, r is the distance from the point under consideration to the center of the Earth, g is the acceleration of gravity, and h and l are Love's numbers (Melchior, 1966). The world-wide means of h and l are 0.610 and 0.085, respectively. When these values are used in the

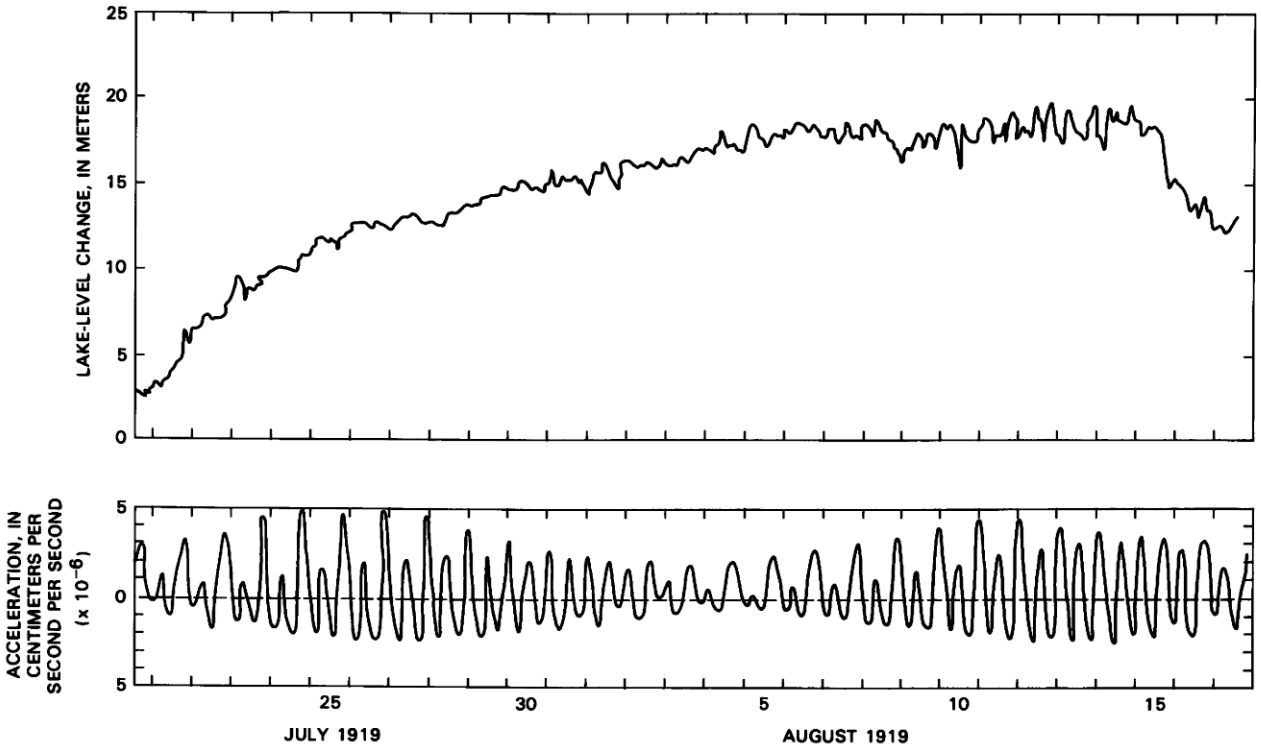

FIGURE 49.4.—Hourly means of level of Halemaumau lava lake and gravitational acceleration due to tide-generating forces during part of 1919. Lake-level data from Brown (1925).

equation, $F(r)$ is 0.47. However, the value of $F(r)$ may be different from the world-wide mean at a hot spot. Cubical dilatation divided by $F(r)$ was computed for the period from August 10–16, 1919, when semidiurnal oscillation of the lava-lake level was dominant. Results are plotted in figure 49.7.

The long-period variation in the original lake-level data was eliminated by Pertzev's method (Pertzev, 1957). The semidiurnal fluctuation of the lake level built up gradually and was mostly pronounced during August 12–14; when the lava lake was at its highest general level. It is interesting to find that the high tide of the lava lake occurs during the time when lunisolar attraction is at a minimum and the low tide occurs when it is at a maximum. A similar relation was also shown by tiltmeter records during the 1968 Halemaumau lava-lake activity (Kinoshita and others, 1969). That eruption started in 1967, and semidiurnal oscillations began to appear in the tilt records during February–March, 1968 (phase 28).

This evidence indicates that magma is transported between the magma reservoir and the lava lake because of semidiurnal dilatational strain. The phase lag of magma transport between the magma reservoir and the lava lake was estimated at 7 minutes, a quantity of time negligible for the present study (Shimozuru, 1975). Phase lag of the oceanic tide is approximately 7 hours at the Island of Hawaii; hence ocean loading had no apparent correlation with the lava-lake fluctuation.

EFFECTIVE VOLUME OF MAGMA RESERVOIR BENEATH KILAUEA INFERRED FROM TIDAL EFFECT

Using the concepts developed above, we can estimate the effective volume of the magma reservoir during Jaggar's observation period from the following formula:

$$V = dh \cdot A/\Delta,$$

where dh is the change of the lake level, A is the area of the lava lake during the measuring interval, and Δ is the cubical dilatation. Difficulties arise in estimating the area of the lava lake. Jaggar's sketch map for July 10, 1919 (Jaggar, 1947), is shown in figure 49.8. The lava lake consisted of the main pool in the east and two other pools at the north and southwest. The total area of the lake was estimated at 21.13×10^3 m^2 by tracing the shoreline of the white and lined areas in Jaggar's map (see fig. 49.8). From the difference between the minima and maxima of the lake level (dh) during the period August 12–14, we can calculate the volume of magma that

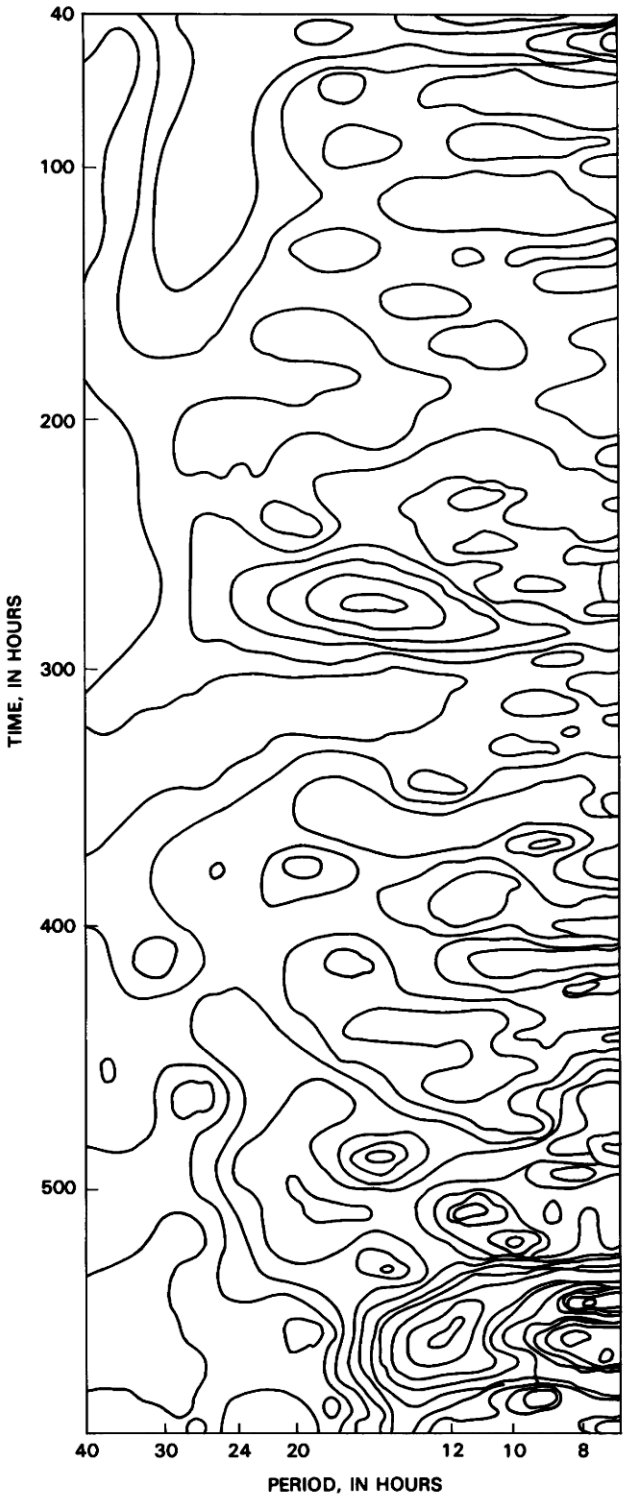

FIGURE 49.5.—Running spectra of fluctuation of height of Halemaumau lava lake during the period from July 21 to August 16, 1919, based on Jaggar's data (Brown, 1925).

squeezed out from the magma reservoir and drained back into it because of semidiurnal tidal strain. If we use the value 0.5 for $F(r)$, then the effective volume of the magma reservoir is roughly 800 km^3. On the other hand, Wright (1984, p. 3238) estimated a volume of 11 km^3 for Kilauea's shallow magma reservoir on the basis of geodetic data. The effective volume of magma reservoir estimated here is two orders of magnitude larger than that estimated from geodetic data. The reason for this large discrepancy is not clear, however, the calculated volume based on tidal strain may involve not only the shallow magma reservoir, but also involve the entire volume including conduits and plumbing system at the rift zone.

The shape of the magma reservoir beneath Kilauea Volcano is probably complex. Using tilt patterns associated with eruptions, Decker (1968) and Shimozuru (1981) prepared an electric-analog model, a kind of relaxation oscillator. I interpreted the complicated inflation pattern of Kilauea to result from an assembly of a main magma reservoir and several surrounding small reservoirs. The equivalent electric analog is the composite parallel and serial connection of components in a single oscillator. This proposed model of the magma reservoir system is reasonable for interpreting tidal fluctuation of the lava-lake level that appears at the highest general level of the lake and also for explaining the wandering of the uplift center at the summit region of Kilauea (Decker and Kinoshita, 1971, p. 58).

CONCLUSION

Dzurisin (1980) confirmed that the beginning of surface lava extrusion during 52 historical eruptions of Kilauea occurred preferentially near the fortnightly tidal maxima with approximately 90

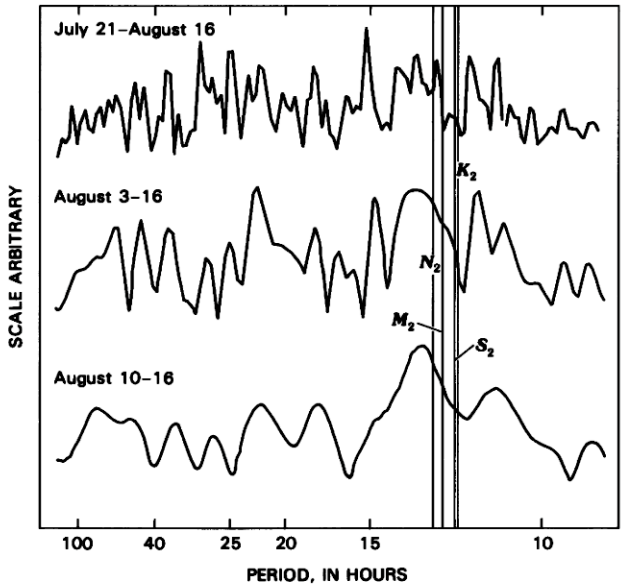

FIGURE 49.6.—Fast Fourier analysis of observed fluctuation in height of Halemaumau lava lake based on Jaggar's (1947) data. Spectra are shown for three different intervals in July–August 1919. Semidiurnal tidal components: M_2, S_2, N_2, K_2.

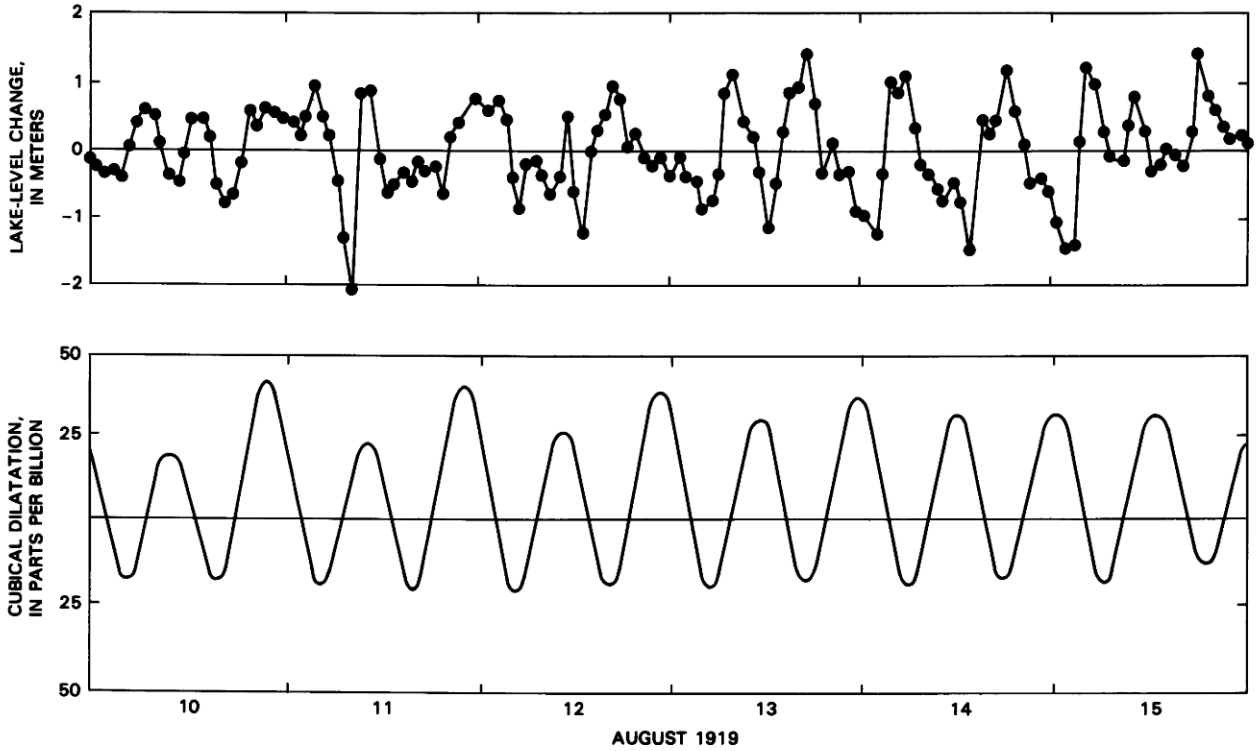

FIGURE 49.7.—Plot of hourly mean of level of Halemaumau lava lake, after filtration of long-term variation, during period August 10–15, 1919, and cubical dilatation ($\Delta/F(r)$) for corresponding interval. Lake-level data from Brown (1925).

percent likelihood. For Mauna Loa, however, he found that 37 historical eruptions began randomly with respect to the fortnightly Earth tide. In earlier work, I analyzed Jaggar's data on the fluctuation of the lava-lake level at Halemaumau in 1919 and found that semidiurnal tidal fluctuations during the highest general lake level correlate well with solid-Earth tides. Using the concept of squeezing out and draining back of magma from and to the magma reservoir caused by tidal strain, I have calculated the concerned volume of magma bodies at roughly 800 km^3 in August 1919. The magma reservoir system at Kilauea is suspected to be an assembly of a main magma reservoir and surrounding smaller reservoirs.

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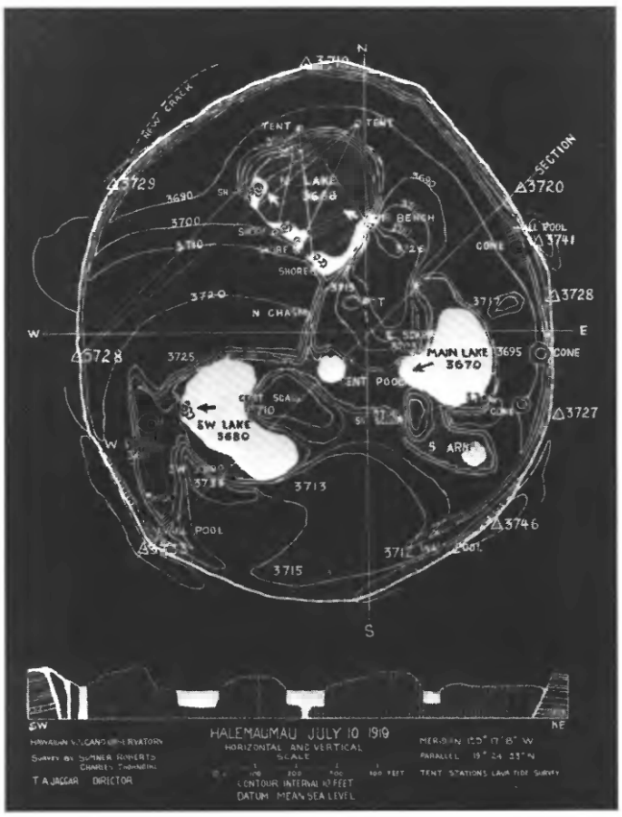

FIGURE 49.8.—Topography and lava pools in Halemaumau pit crater on July 10, 1919. Map originally published in Geological Society of America Memoir 21, (Jaggar, 1947, pl. 79a).

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