On the Triggering of Volcanic Eruptions by Earth Tides

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The reported times of major eruptions since 1900 from the world's nonsubmarine volcanoes have been compared at each location with the phase of the various components of the solid earth tide. A correlation, significant to the 5% level, was found between eruption times and the fortnightly component of the tide for the total data set of 680 eruptions. The probability of eruption is greatest at times of maximum tidal amplitude. For individual volcanoes significant peaks in eruption probability occur also at phases other than at the fortnightly tidal maximum. The volcanoes could be subgrouped in terms of petrology, geographic location, local crustal deformation rates, and other geophysical parameters. Subpopulations of andesitic and basaltic eruptions each showed significant concentrations of events at the tidal maximum. In addition, basalt eruptions had an equally well developed concentration at the tidal minimum. In a detailed study of the Japanese region, each volcano that characteristically erupted at or near the fortnightly tidal maximum is located in an area having a negative Bouguer anomaly, a large crustal thickness, and a small rate of horizontal crustal deformation. Conversely, volcanoes in areas characterized by thinner crusts and crustal deformation rates greater than 3.0 cm/yr generally erupt at or near the fortnightly tidal maximum.

Solar and lunar tides produce in the earth's crust quasi-periodic stresses with amplitudes less than 10^3 N/m^2 (10^{-2} bar), a maximum rate of change of 1 N/m^2 sec (10^{-5} bar/sec), and a maximum spatial gradient of 10^{-3} N/m^3 (10^{-8} bar/m). This is the largest short-period oscillatory stress in the earth's crust, and suggestions that it plays a role in triggering slowly accumulating tectonic stress have been frequent [*Morgan et al.*, 1961; *Knopoff*, 1964; *Stacey*, 1964; *Simpson*, 1967; *Shlien*, 1972]. Detailed investigations, however, have been focused almost entirely on the question of triggering earthquakes by earth tides. It is now generally accepted that earthquakes and aftershock sequences occur at times uncorrelated with earth tides, although some particular aftershock sequences appear to be an exception [*Ryall et al.*, 1968].

A second source of tectonic stress variation likely to be affected by periodic tidal stress occurs with volcanic eruptions. In contrast to the earthquake problem, where the rate of stress accumulation and the geographic location of maximum stress concentration are unknown for volcanic activity, its location is usually well defined, and, at least in some cases, crude stress accumulation rates are known. There are some indications that tectonic stress accumulation prior to an eruption occurs at rates that are slow in comparison with the maximum tidal stress rate of 1 N/m^2 sec (10^{-5} bar/sec). Strain observations on Hawaiian volcanoes [*Fiske and Kinoshita*, 1969] infer stress accumulation as low as 0.02 N/m^2 sec. However, for other volcanoes this rate may be much faster. For example, on two New Zealand volcanoes the implied stress accumulation rates from observations of piezomagnetic effects prior to eruptions [*Johnston and Stacey*, 1969*a*, *b*] ranged from 5 to 80 N/m^2 sec.

Previous suggestions of tidal triggering of volcanic eruptions have been vague and usually have followed attempts at identifying cyclic behavior patterns in the repose times between eruptions. In a study of the frequency of eruptions *Eggers and Decker* [1969] proposed that semiannual and annual clustering of worldwide volcanic activity may be related to the tidal accelerations with these periods. *Johnston and Mauk* [1972], in a more detailed study, found a strong correlation between times of eruptions from Mount Stromboli, Italy, and the fortnightly component of the tides. No clear correlation with

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the diurnal, semidiurnal, annual, or semiannual components was detected. An extension of the Johnston and Mauk study to a nearly complete catalog of eruptions from 1900 to 1971 is the subject of this paper.

METHOD OF ANALYSIS

The vertical and horizontal components of tidal acceleration as a function of time and geographical location were computer generated by a modification of the method outlined by *Longman* [1959]. These theoretical estimates of the tide enabled us to plot the tidal time series at each of the world's volcanoes before and during all recorded volcanic eruptions this century. The calculated values at one site were verified by J. C. Harrison (private communication, 1972) using an independent computational method and program [*Harrison*, 1971]. All calculations were in agreement to within 2 μgal. More important, comparison with actual experimental observations of tides from gravimeters [*Melchior*, 1966] also yielded good agreement with tidal amplitude, phase, and period, particularly at periods greater than 1 day, where effects of phase differences from ocean loading are less important. Thus the calculated theoretical tidal accelerations appear to adequately represent the actual earth tides.

Six hundred and eighty nonsubmarine volcanic eruptions between 1900 and 1971 were used in this study. Submarine eruptions were not included because of uncertainties associated with the time of eruption; solfatara events were likewise not included. The volcanoes have a worldwide distribution, and the eruptive products display wide petrological variation. Eruption times were taken from the *Catalog of Active Volcanoes of the World, Bulletin Volcanologique*, and the *Smithsonian Institution Short-Lived Phenomena Reports*. Only a few eruption times were reported with a precision finer than a day, making tenuous any correlation with the diurnal or semidiurnal components. Thus attention was focused on the relationship of eruptions with the fortnightly tide.

For each eruption site, vertical and horizontal tidal accelerations were calculated. Computations were made at 2-hour increments for 30 days, beginning 10 days prior to the reported eruption date. The series of calculated accelerations were then plotted, yielding a visual record of the tides. In terms of the fortnightly cycle, each day represents a 25.5° phase segment (360°/14.7 days). Thus the eruption times can be specified in degrees of phase lag or lead from a fortnightly tidal maximum. Use of such a phase-based analysis rather than a time-based analysis permitted a uniform comparison of the data, regardless of the asymmetry of the tidal envelope configuration. The variable nature of the tides is displayed in Figure 1. Although most of the observed records are typically like plots *a*, *b*, or *c*, plots *d–h* show some of the variety of patterns that develop. Varying degrees of constructive and destructive interference of the principal components and proximity to nodal

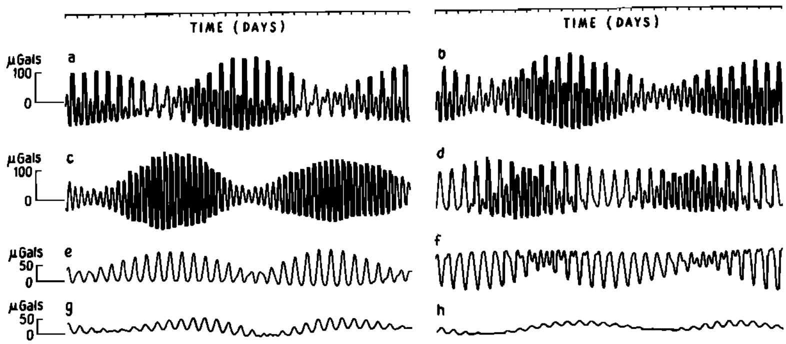

Fig. 1. Calculated vertical tidal accelerations at (*a*) Ngauruhoe, 39°S, 175°E, October 27 to November 25, 1968; (*b*) Mauna Loa, 19°28.5′N, 155°36.5′W, December 27, 1948, to January 25, 1949; (*c*) Yake Dake, 36°13′N, 137°35′E, August 23 to September 21, 1913; (*d*) Akita Kamaga Take, 39°45′N, 140°40′E, September 8 to October 7, 1970; (*e*) Krakatau, 06°06′S, 105°25′E, October 29 to November 27, 1938; (*f*) Masaya, 11°57′N, 86°09′W, March 26 to April 24, 1970; (*g*) Irazu, 09°59′N, 83°′51′W, September 17 to October 16, 1917; and (*h*) Lewotobi Lakilaki, 08°32′S, 122°46′E, September 18 to October 17, 1907.

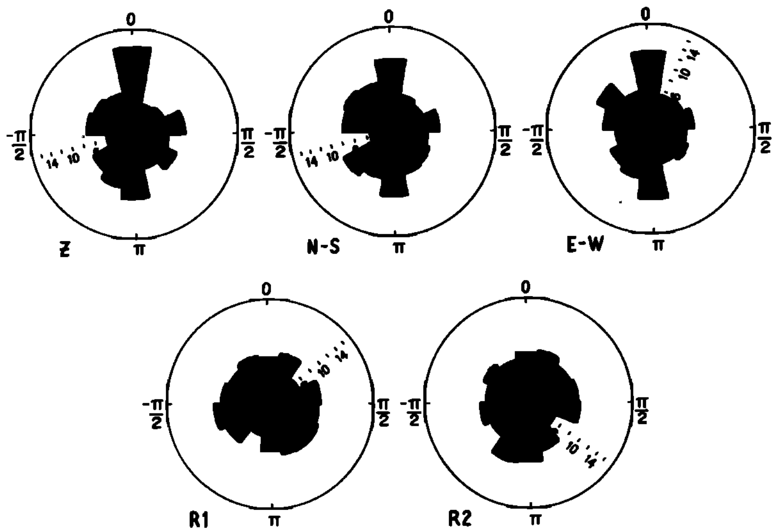

Fig. 2. Lambert equal area polar histograms showing the percentage of total worldwide major volcanic eruptions (680 events) from 1900 to 1971 for each 25.5° phase increment of the fortnightly tidal cycle. The distributions for the three tidal components are shown together with two distributions (R_1 and R_2) generated by using an equivalent number of eruptions in a random number generator. Zero phase corresponds to the fortnightly tidal maximum.

areas are the primary causes of the variations. On the vast majority of the records the fortnightly tidal maximums could be determined visually for both vertical and horizontal components. The remaining few were complicated either by displaying broad maximums invariant for a period greater than a day or by displaying a high degree of mixed-frequency interference. These records therefore were not included in the analysis. No minimum acceleration amplitude of the fortnightly tide was assumed to be necessary for triggering.

Since major events from almost any volcano occur at time intervals that are large in comparison with tidal variations, standard time series correlation techniques can hardly be applied to test the significance of correlation between eruption times and tidal phase. A significance test to handle similar situations was developed by Schuster in 1897 and later extended by *Shlien* [1972] to test the situation where peaks in eruption times occur at two opposite tidal phases. This test was used in this analysis. In addition, a crude independent test for significance was used that involved the generation of a completely random data level. To define this level, a random number generator was used to generate an equivalent number of events randomly distributed over the fortnightly cycle. A percentage distribution level was then determined that enclosed the entire random collection.

The data were all plotted on Lambert's equal area polar diagrams as a percentage of total events per day (i.e., in a 25.5° phase increment) for the seven days lagging and leading the fortnightly tidal maximum.

RESULTS

The distribution of the entire data collection for both vertical and horizontal components is given in Figure 2. In addition, two plots of an equivalent number of randomly generated events are given for comparison. The percentage level of the data distributed uniformly over each of the 14 days of the fortnightly cycle is 7.1%/day. In both random distributions, all of the events lie within the 7.9% annulus. The actual volcanic data, however, have definite concentrations of events about the fortnightly tidal maximum and and minimum with peaks near 14.2%. Although this pattern is present on all three components, it is best developed on the vertical component. *Shlien*'s [1972] test on these peaks indicates a statistical significance to the 5% level. This prominent concentration of eruptions at the fortnightly tidal maximum indicates that volcanic eruptions are correlated with the phase of the fortnightly tide.

Johnston and Mauk [1972] found that eruptions of Stromboli, a basaltic volcano, clustered conspicuously about the fortnightly tidal minimum. On the other hand, every reported eruption of Paricutin, an andesitic volcano, occurred within 2 days of the fortnightly tidal maximum. This divergence of eruptive behavior promoted a study of the possibility that petrologically dissimilar volcanoes react differently to tidal accelerations. Based on petrologic analyses reported in the *Catalog of Active Volcanoes of the World*, eruptions were grouped into andesitic and basaltic subpopulations. Petrologic descriptions seldom permitted more refined discriminations. The subpopulation distributions are shown in Figure 3. Even though the clear divergence suggested by Stromboli and Paricutin is not substantiated in the extreme, there remains an apparent diversity in the eruption distributions. The andesitic eruptions show prominent and statistically significant concentrations of events at the fortnightly tidal maximum. This peak emerges from an otherwise random background. Similarly, the distribution of the basaltic events has a peak of activity at the tidal maximum but, in addition, has an equally well developed concentration at the tidal minimum. The significance of these distributions will be discussed later.

To explore the possibility that the tectonic setting of the volcanoes may also affect the triggering of eruptions by earth tides, the 680 eruptions of the data set were separated into 13 geographic regions: South America, Mexico and Central America, the West Indies, Alaska, Katmai and the Aleutians, Kamchatka and the Kurile Islands, Japan, Melanesia and Micronesia, New Zealand, Indonesia, the West Indian Ocean, the Mediterranean, Iceland and the mid-Atlantic ridge. The polar plots for each of these regions are shown in Figure 4. Regions having less than ten usable events, such as the Iceland–mid-Atlantic ridge region, were not included on the map. Regional subpopulations were treated collectively and not separated on petrologic character. The plots show clearly that the response of volcanoes to the fortnightly tidal stresses is regionally dependent. Although clustering of eruptions at the fortnightly tidal maximum is observable on nearly every plot, this concentration is particularly well developed in Melanesia-Micronesia (21%), the West Indian Ocean (17%), Kamchatka and the Kurile Islands (16%), and South America (16%). Similar eruption concentrations at the fortnightly tidal minimum are significant in Melanesia-Micronesia (16%) and Hawaii (15%). In addition, some regions have events concentrated at phases other than the maximum or minimum. The following areas show phase leads: New Zealand (19%) 3 days

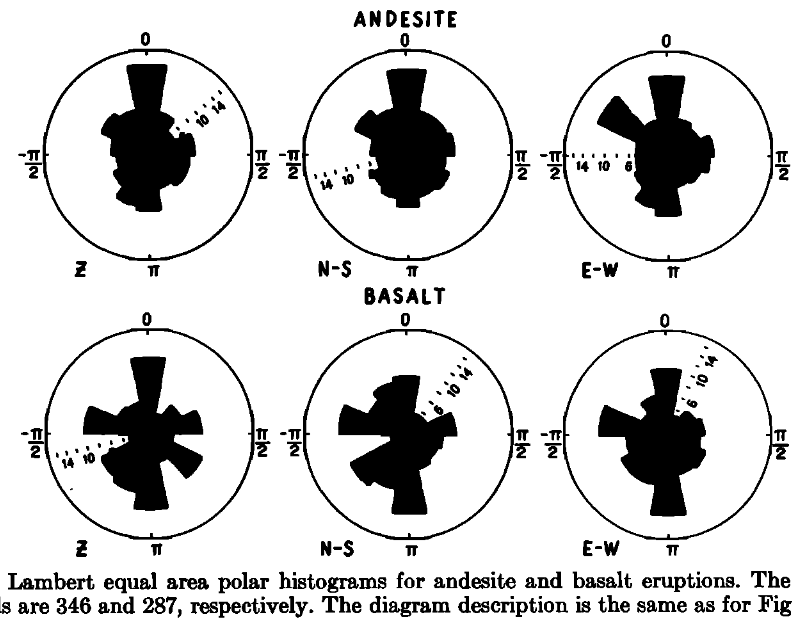

Fig. 3. Lambert equal area polar histograms for andesite and basalt eruptions. The eruption totals are 346 and 287, respectively. The diagram description is the same as for Figure 2.

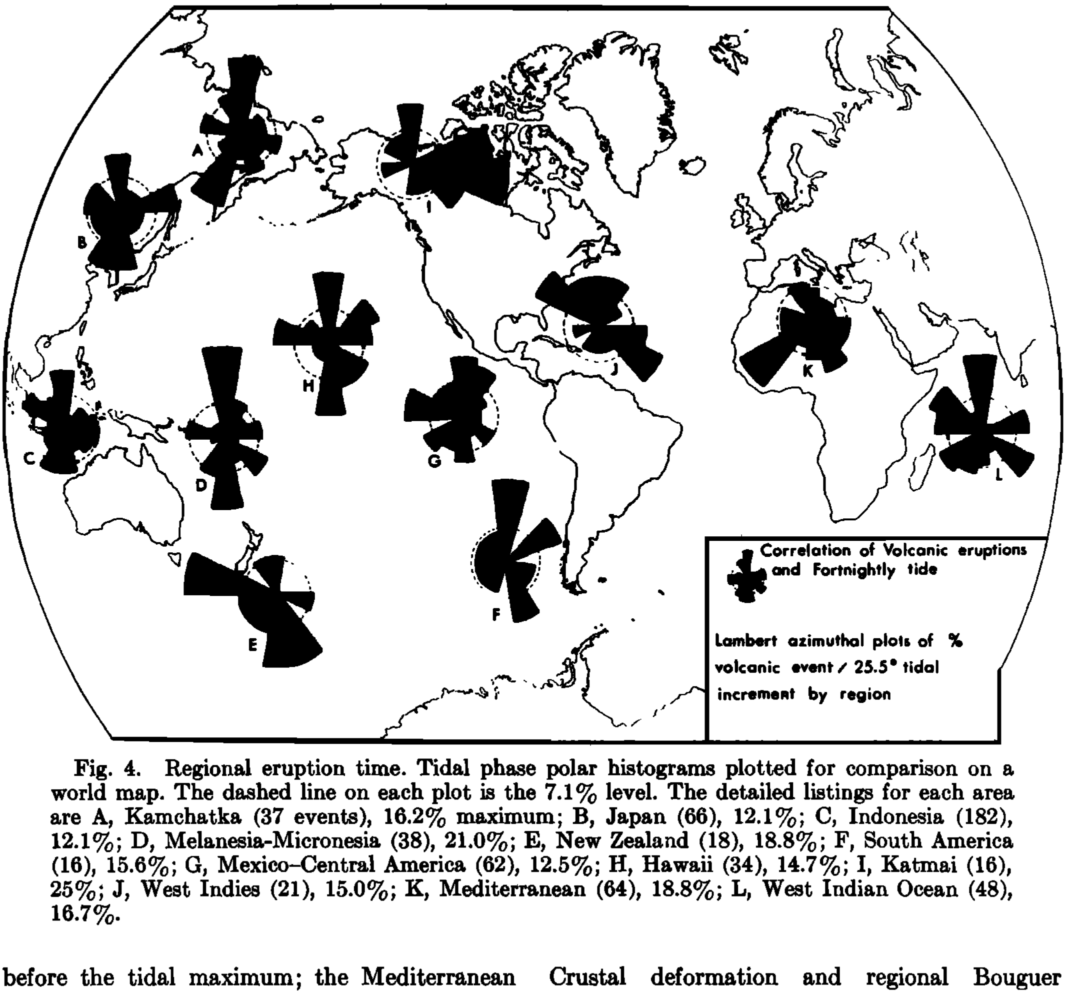

Fig. 4. Regional eruption time. Tidal phase polar histograms plotted for comparison on a world map. The dashed line on each plot is the 7.1% level. The detailed listings for each area are A, Kamchatka (37 events), 16.2% maximum; B, Japan (66), 12.1%; C, Indonesia (182), 12.1%; D, Melanesia-Micronesia (38), 21.0%; E, New Zealand (18), 18.8%; F, South America (16), 15.6%; G, Mexico–Central America (62), 12.5%; H, Hawaii (34), 14.7%; I, Katmai (16), 25%; J, West Indies (21), 15.0%; K, Mediterranean (64), 18.8%; L, West Indian Ocean (48), 16.7%.

before the tidal maximum; the Mediterranean (19%) 5 days before the tidal maximum; and the West Indies (15%) and the West Indian Ocean (15%) 2 days before the tidal maximum. Phase lag concentrations are significant for Katmai and the Aleutians (25%) 4 days after the tidal maximum and the West Indies (15%) and the West Indian Ocean (15%) 5 days after the tidal maximum.

To investigate the relationship of other geophysical parameters, attention was focused on the Japanese region. The selection of Japan for a detailed analysis was based on two criteria: (1) the numerous Japanese eruptions (Table 1) are relatively homogeneous petrologically for the majority of the volcanoes but displayed a complex distribution over the fortnightly cycle, and (2) other geological and geophysical data are readily available for comparison. The locations of the 18 studied volcanoes are shown in Figure 5. Crustal deformation and regional Bouguer anomaly maps for the area have been plotted by *Harada* [1967] and *Hagiwara* [1967], respectively. Without exception, volcanoes displaying random eruptive patterns or clustering about the fortnightly tidal minimum were in regions characterized by negative Bouguer anomalies, crustal thickness exceeding 28 km, and horizontal crustal deformation rates near 1.5 cm/yr (crustal deformation rates were derived by measuring the total deformation in a 60-year period and dividing by time to get an average rate of deformation). Conversely, volcanoes that consistently erupted within a day or two of the fortnightly tidal maximum were in regions having thin crusts, positive Bouguer anomalies, and horizontal deformation rates greater than 3.0 cm/yr. Although crustal thickness and Bouguer anomaly contours are often not in agreement as suggested by *Steinhart and Woollard* [1961], for Japan they

TABLE 1. Summary of Characteristic Eruption Patterns of Japanese Volcanoes with Respect to the Fortnightly Tidal Component

Volcano No.	Name	Eruption Patterns
1	Suwanose Zima	Eruptions at phase lag of 2 to 3 days.
2	Sakura Zima	Eruptions at phase lead of 4 to 6 days.
3	Kirisima	Eruptions about fortnightly minimum.
4	Aso	Eruptions randomly distributed.
5	Yake Dake	Eruptions essentially random but broad concentrations about fortnightly minimum.
6	Kasatu Sirane	Same as for Yake Dake.
7	Niigata Yake Yama	Only eruption at fortnightly tidal minimum.
8	Bandai	Eruptions at phase lead of 1 to 2 days.
9	Adatara	Eruptions at phase lag of 4 to 5 days.
10	Azuma	Only eruption at fortnightly minimum.
11	Akita Komage Take	Eruptions about fortnightly maximum.
12	Kurikoma	Same as for Akita Komage Take.
13	Komage Take	Eruptions essentially random but broad concentration at phase lag of 2 to 3 days.
14	Usu	Eruptions random.
15	Tarumai	Eruptions essentially random but broad concentrations at phase lag of 4 to 6 days.
16	Tokati	Only eruption at phase lag of 4 days.
17	O-Sima (basalt)	Eruptions concentrated about tidal maximum.
18	Miyake Zima (basalt)	Only eruption at tidal minimum.

are sufficiently similar to attribute the Bouguer contours to crustal thickness.

CONCLUSIONS

A positive correlation has been found between the worldwide distribution of volcanic eruption times and the fortnightly tidal harmonic. A subdivision of the world's volcanoes into two petrologic types indicates that volcanoes in these two subgroups have eruptions that occur at different phases of the tide. This result, however, appears to be more a function of the region in which the volcano occurs, which presumably also determines the petrology, than the petrology itself.

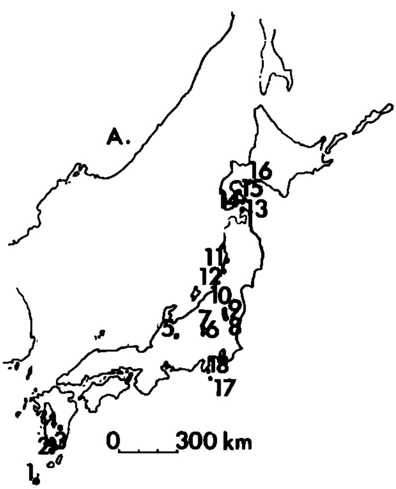

Fig. 5. Map of Japan showing the location of 18 studied volcanoes.

A detailed analysis of one particular region shows that the relationship of volcanic eruptions with respect to the tides is influenced by geophysical parameters such as gravity anomalies and crustal deformation rates in different parts of the region. This and the previous petrological result can only have necessarily vague explanations owing to the almost complete lack of understanding of the volcano mechanism. They are, however, not unexpected if *Ringwood*'s [1969] petrologic argument that andesitic and basaltic magmas originate at different depths, have different viscosities and, when cool, produce rocks of differing strengths is accepted. The somewhat unique phase relation to the tides for particular volcanoes is most likely a result of complex magma emplacements such as that proposed for Hawaii by *Fiske and Kinoshita* [1969] using *Mogi*'s [1958] model and surface deformation measurements.

Systematic regional tectonic deformation must also be important in eruptions, since magma migration is controlled by the direction of least compressive stress. The study of Japan revealed that volcanoes in regions characterized by horizontal deformation rates greater than 3.0 cm/yr characteristically had smaller phase lags than petrologically similar volcanoes in regions having lower horizontal deformation rates. Existing active faults and/or dike systems above the magma reservoir would grossly alter the confining pressure. In this case the tidal triggering of an eruption would become very dependent on the direction of the tidal vector. The problem of exact determination of the triggering mechanism must therefore wait for more careful and detailed study of preeruptive volcano habits.

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