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On tidal triggering of earthquakes at Campi Flegrei, Italy

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SUMMARY

The caldera at Campi Flegrei underwent an inflationary episode during 1982–84 that produced a maximum uplift of 1.6 m at Pozzuoli, Italy. The seismicity at Pozzuoli increased enormously during the time of the uplift, but was delayed by several months. Ground deformation during inflation has been previously well modelled with a finite element model of a pressurized magma chamber in an elastic medium that takes into account the effects of increasing pressure and temperature with depth on elasticity. We used the output from this model to estimate the temporal change in the stress field that presumably controls the seismicity during inflation. The result is that the solid-earth tidal stress should modulate heavily the seismogenic inflationary stress, which in turn should result in some tidally triggered earthquakes. This expectation is based on the assumptions that: (a) the inflationary model is valid; (b) tidal and inflationary stresses can be superimposed; (c) the inflation is smooth on the time-scale of periodic tidal stress variations; and, most importantly (d) earthquakes occur when a critical level of stress has been reached. We checked the Pozzuoli catalogue for evidence of tidal triggering with the Schuster test and found none. The Schuster test is sensitive enough to easily detect a diurnal variation of reported seismicity caused by day-to-night changes in noise levels. The lack of tidal triggering suggests that one (or more) of the above assumptions is wrong. After evaluating each assumption, we conclude that the most likely explanation is that the failure threshold for seismicity is time dependent at Pozzuoli. In other words, earthquakes do not necessarily occur when the stress exceeds the yield strength of a fault for a short time only.

Key words: Campi Flegrei, Phlegraean Fields, seismicity, tidal triggering.

INTRODUCTION

Can the Sun and the Moon influence seismicity? The answer to this question has been the topic of considerable research in the geophysical literature, dating back to an early study by Schuster (1897) that used a statistical method by Rayleigh (1880). Recently, the importance of this question was brought to light by the highly publicized prediction of a large destructive earthquake in the New Madrid seismic zone of the central United States on 1990 December 2–3. On this date, a maximum in the tidal 'force vector', resulting from an uncommon positioning of the Sun and Moon, was supposed to trigger the earthquake. The prediction was evaluated by the National Earthquake Prediction Evaluation Council (NEPEC 1990) and rejected. The event never occurred, but the promulgation of the prediction by the mass media raised uncalled-for levels of concern and anxiety among those living in and around the targeted zone.

If earthquakes happened only when stress exceeded some critical value on a fault, then tidal stress could influence seismicity. In this situation, a fault that is pre-stressed tectonically to its yield point and primed for failure, should fail when additional stress is applied and the total stress is raised above the critical value. Thus, the superposition of the sinusoidal tidal stress generated by the Sun and Moon onto the tectonic background stress in the Earth may at times sweep the total stress on a fault above failure, therefore causing the earthquake to occur earlier than if the stress was due to the slow increase in tectonic loading alone. Similarly, if the instantaneous tidal stress was such as to reduce the total stress, the earthquake would be delayed. Earthquakes occurring in this manner are considered to be tidally triggered.

The phenomenon of tidal triggering has been clearly observed in lunar seismicity (Lammlein *et al.* 1974) but has not been conclusively demonstrated in catalogues of global or large-scale seismicity of the Earth (Schuster 1897; Knopoff 1964; Simpson 1967; Shlien & Toksöz 1970; Heaton 1975, 1982; Shudde & Barr 1977; Stothers 1990; and many others). In regional and local catalogues, however, correlations with varying levels of significance between lunar/solar phases and earthquake origin times have been reported by Shlien (1972), Klein (1976), Young & Zürn (1979), Kilston & Knopoff (1983), Palumbo (1986), Ulbrich, Ahorner & Ebel (1987), Shirley (1988), and others. The cases of tidal triggering showing the most significance involve classes of events that are perhaps the most easily affected by small tidal stress, namely earthquakes occurring in volcanic zones (McNutt & Beavan 1981, 1984; Emter *et al.* 1986; Rydelek, Davis & Koyanagi 1988), or in certain aftershock sequences (Berg 1966; Mohler 1980; Ryall, Van Wormer & Jones 1968; Souriau, Souriau & Gagnepain 1982).

The partial success of these studies prompted us to investigate the possibility of tidal triggering at Campi Flegrei (Phlegraean Fields), a volcanic zone near Naples, Italy, about 20 km to the west of Mt Vesuvius. We focus on the ancient caldera at Pozzuoli which underwent an inflationary episode in 1982–1984 that resulted in alarming ground uplift and considerable seismic activity (Fig. 1; see also Lirer, Luongo & Scandone 1987). Elastic models have been developed by others to explain the deformation of the ground during the inflation, and these models can be used to infer the spatial and temporal evolution of the inflationary stress field that presumably controls the seismicity. The fortunate result is that the seismicity at Pozzuoli may be particularly susceptible to tidal effects; at seismically active locations within the caldera, model estimates of the rate of inflationary stress are within the same order of magnitude as that expected from the solid-earth tide.

In fact, the recent inflationary episode at Pozzuoli affords almost laboratory-like conditions to investigate tidal triggering: (1) the steady inflation of the subterranean magma chamber acts to stress the caldera, and deformation of the ground occurs; (2) seismicity, which was practically absent before the inflation, develops in response to this stress; and (3) the tides represent a well-defined source of periodic external stress to modulate the inflationary stress. This contrasts other studies of tidal triggering where the growth of the background tectonic stress was mostly unknown, estimated in general terms, or estimated roughly by time-averaging the stress drop between earthquakes (see, e.g., Stacy 1977). At Pozzuoli, if we assume that the stress from inflation is smoothly varying and can be superimposed with the local tidal stress, and that earthquakes occur at some critical stress, then tidal influences on the seismicity stand an excellent chance of being observed because tidal stress would modulate the seismogenic inflationary stress by significant amounts.

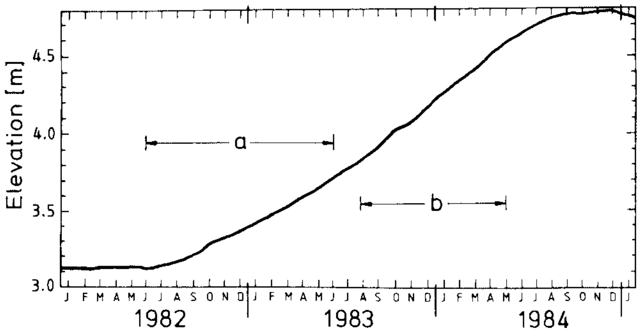

Figure 1. Elevation of the Port of Pozzuoli (from Aster & Meyer 1988). Surface deformation that occurred during (a) is plotted in Fig. 4; seismic activity during (b) is plotted in Fig. 3. Before this inflationary episode, the seismicity at Pozzuoli was less than moderate.

Evidence of tidal triggering would help validate the above assumptions (the third assumption is taken for granted in most studies of tidal triggering) and shed much needed light on the important problem of the mechanism of fault failure. In addition, spatial and temporal changes in the amount of tidal triggering, if and when observed, could be used as an important tool in monitoring the growth of stress and the seismic conditions in this potentially hazardous volcanic zone.

OBSERVATIONS AND CATALOGUE

The volcanic area at Campi Flegrei has a long history of episodic inflations (and deflations) dating back to at least Roman times (Lirer *et al.* 1987). These inflations are caused by the yielding of the crust from the injection of magma at depth. The most recent episode of inflation started in June 1982 and produced 1.6 m of uplift at Pozzuoli in two years (Fig. 1).

A local network monitors the seismicity at Campi Flegrei. Before November 1982, only moderate seismic activity was recorded at Pozzuoli, but following an $M = 3$ earthquake in March 1983, a huge increase in seismicity took place (Lirer *et al.* 1987). The earthquake hypocentres have been estimated by several different methods: single-event location and 3-D velocity inversion (Aster & Meyer 1988), and joint hypocentral determination (JHD; Pujol & Aster 1990). There are systematic differences in the hypocentres from these methods but a certain amount of location uncertainty can be tolerated in this study without affecting our conclusions; accurate hypocentres, however, are important in studies that model the dynamical inflation of the caldera. Pujol & Aster (1990) conclude that in some circumstances a joint location method can produce a sharper image of the seismicity than a 3-D velocity inversion; thus the JHD locations are used here.

The nearly continuous seismic activity was confined mostly to depths between 0 and 3 km in a small volume centred on the point of maximum uplift (Fig. 2; Pujol & Aster 1990). Del Pezzo *et al.* (1987) analysed high-quality seismograms that were recorded during the uplift and their results indicate that the bulk of seismicity is consistent with a pattern of tensile stress and has the particular features: mostly normal faulting with minor strike–slip components, dip angles of 30°–60°, constant stress drops of ≈4 bar (Brune model), and small values of source radii (few tens of metres). Del Pezzo *et al.* (1987) believe that the seismicity is the result of the activation of pre-existing structures in the caldera from magmatic activity at depth. Also, because of fairly constant seismic stress drops of about 5 bar, which is well below the yield strength of rocks, Aster & Meyer (1988) suggest appreciable fluid lubrication in a zone that may be extensively prefractured.

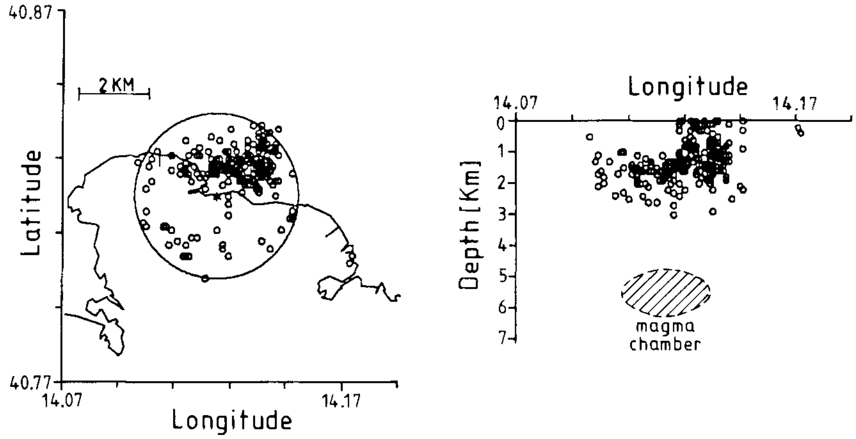

Figure 2. Hypocentres of 228 selected events from the Pozzuoli catalogue, located by the method of joint hypocentral determination (JHD) (from Pujol & Aster 1990). Location and size of the magma chamber from the model of Bianchi *et al.* (1984) are drawn to scale. See inset in Fig. 4 for the location of Pozzuoli, Italy.

The local catalogue from Pozzuoli used in this study starts near the middle of the uplift interval (see Fig. 1), at the end of July 1983, and runs uninterrupted for 279 days, containing slightly over 8000 events. Fig. 3(a) is a plot of the catalogue. Further statistical information about the catalogue, such as *b*-value curve, is found in De Natale & Zollo (1986).

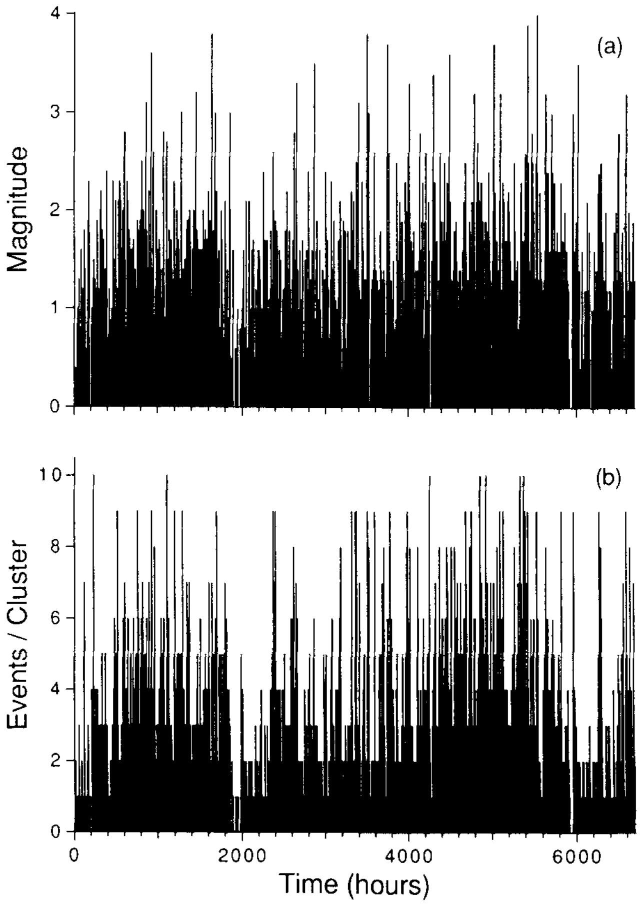

Figure 3. (a) Plot of the Pozzuoli catalogue. Starting date is 1983 July 28 (see Fig. 1). Before November 1982, the seismic activity was less than moderate. (b) Plot of the clusters used in this study. The clusters are formed by binning events in 1 hr windows.

MODELLING THE POZZUOLI INFLATION: STRESS ESTIMATES

Tidal stress in the earth can be computed from tidal theory by using a seismologically constrained elastic earth model. But tidal stress is only one ingredient in the phenomena of tidal triggering; to investigate the phenomena quantitatively, we also require some knowledge about the tectonic stress that produces the seismicity. By having estimates of both the tidal and the seismogenic stress, an assessment can then be made to determine whether the former could significantly affect the latter, and hence the seismicity. We prefer this approach to that of testing earthquake catalogues against an assortment of lunar and/or solar positional parameters, such that a physical explanation is necessarily lacking when a significant correlation is found (e.g., Shirley 1988).

In the case of Pozzuoli, modelling the inflation of the caldera, and hence the inflationary stress field, has proven to be a formidable task. Key data in the problem come from geodetic surveys that measure ground deformation and from additional data consisting of seismograms and borehole temperature profiles of the caldera. The deformation data shown in Fig. 4(a)—horizontal and vertical ground displacements—have been used in various models to infer the placement and overpressure of the subterranean magma chamber as well as the material properties of the caldera (Corrado *et al.* 1976; Berrino *et al.* 1984; Bianchi *et al.* 1984, 1987; Bonafede, Dragoni & Quareni 1986; Dragoni & Magnanensi 1989; Quareni 1990). Among these efforts, one point is agreed upon: any simple elastic model (e.g., Mogi 1958) using homogeneous elastic properties cannot explain the large uplift of 1.6 m at Pozzuoli because of the following considerations. If the seismically preferred burial-depth of about 5 km for the magma chamber ($\approx$1 km in diameter) is used, and if average elastic properties of the crust are assumed, then a tremendous cavity pressure (150 kbar) is required. If much lower, reasonable magma pressures are assumed (e.g., 100–300 bar), then an overly shallow

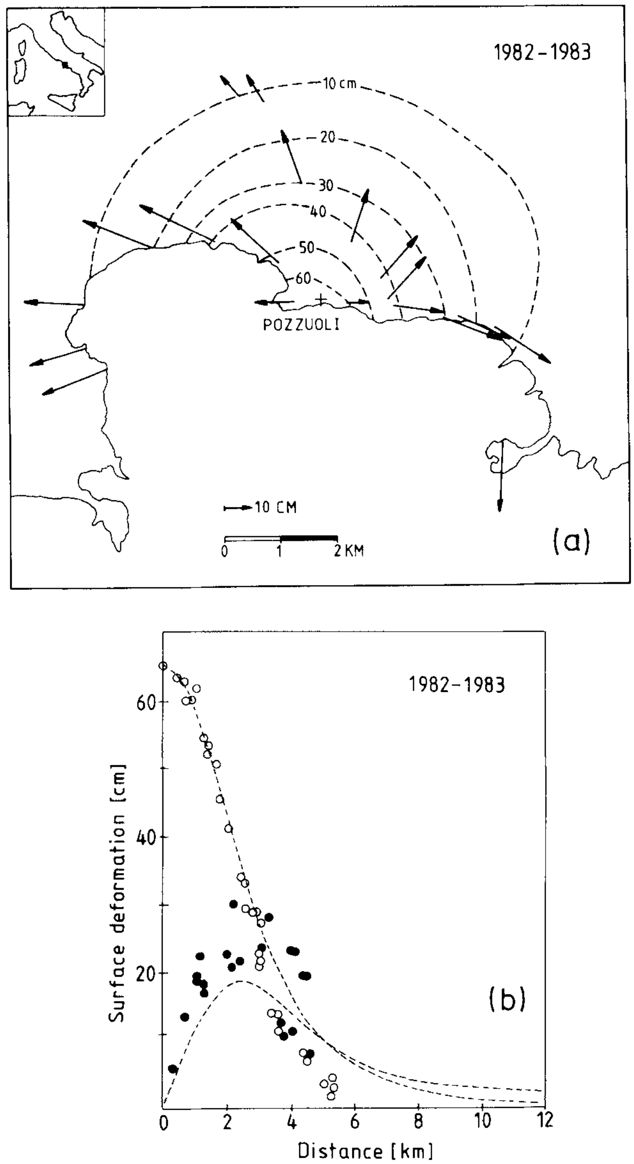

Figure 4. (a) Ground deformation at Pozzuoli from June 1982 to June 1983. (b) Horizontal and vertical displacements are the solid and open circles, respectively, and the dashed lines show the fit of model VI-b of Bianchi *et al.* (1984). (The abscissa is distance from the epicentre of the magma chamber.)

burial-depth is indicated or a very low elastic rigidity about two orders of magnitude below normal is required over a large spatial extent in the model. These requirements are either unjustified on physical grounds or inconsistent with the seismic data mentioned above. Moreover, the assumption of uniform elasticity at Pozzuoli is hardly defendable considering the geologic heterogeneities and high thermal gradients observed (Bianchi *et al.* 1987).

Several more appropriate models have been developed for Pozzuoli. Bianchi *et al.* (1984, 1987) use a numerical finite element model that takes into account the effects of increasing temperature and pressure with depth on elastic properties. In their model, the rock in the caldera is considered to be homogeneous and perfectly elastic under normal surface conditions, but the net result is non-uniform elasticity when depth-dependent temperature and pressure effects are included. Bianchi *et al.* (1984) show that temperature effects on the elastic parameters from the high geothermal gradient at Pozzuoli can result in surface deformations up to three times larger than when normal elasticity is used.

Bonefede *et al.* (1986) developed an analytic model with volcano-tectonic features in mind, in which the magma chamber is situated in a half-space having the rheological properties of a Maxwell solid. The solution to the model equations reveals that because of viscous effects, substantial displacements may be obtained with a relatively small increase in pressure in the magma chamber (e.g., 100 bar); this is especially helpful in explaining a large uplift, such as that observed at Pozzuoli. A viscoelastic solid, however, may not allow the stress build-up necessary for earthquakes, especially for low estimates of viscosity, so the Bianchi model seems more appropriate.

The above model by Bianchi *et al.* (1984, 1987) is consistent with the data from all independent sources at Pozzuoli: (a) measurements of surface deformation; (b) seismic constraints on the depth of the magma chamber; (c) effects of temperature and pressure on elasticity with increasing depth; and of less importance, (d) constraints on the shape of the magma chamber from models of thermal cooling. The good fit of this model to the deformation data is seen in Fig. 4(b) where the surface displacements measured from June 1982 to June 1983 and the model predictions are plotted. The fit was made by assuming an overpressure of 300 bar in an oblate spheroidal magma chamber at a depth of 5.4 km (see Fig. 2).

We were unable to obtain details of the Bianchi model (specifically model VI-b) that were necessary to numerically determine the inflationary stress, so the following was done instead. At different depths along a vertical section through the magma chamber, we measured the lengths of the arrows used to indicate total displacement in Fig. 3(b) of Bianchi *et al.* (1984). These lengths were then scaled so that the surface uplift in the figure matched the observed uplift of 0.65 m during June 1982 to June 1983 (see Fig. 4b). Next, radial and vertical strains were estimated by forming differences in these lengths and then dividing by the measurement baseline in the figure; the strains were then converted to stress via the elastic parameters in the model and by assuming linear elasticity and a cylindrically symmetric stress field. The radial component of the stresses obtained in this manner corresponds to the normal (or tensile) stress on any vertical plane slicing through the centre of the magma chamber and is probably good to within 20 per cent, considering the sources of error in our reduction of the displacement arrows in Bianchi's figure. More precise estimates of the inflationary stress are probably not worth the effort, considering the statistical nature of the test used for tidal triggering (see the Appendix).

In this study, we chose normal stress to evaluate the possibility of tidal triggering because Sartoris *et al.* (1990) have shown in a homogeneous half-space model that the deviatoric normal stress dominates the shear stress at all locations in the caldera, except in the immediate vicinity of the magma chamber, and especially at shallow depths where the bulk of the hypocentres are located. Thus, if tidal modulation of the normal stress in the Bianchi model is feasible, then it may be extended to other components of the stress tensor, at least at shallow seismic depths.

The results of our calculations were a deviatoric normal stress of 6.91 bar at the surface, 11.3 bar at a depth of 1.75 km, and 1.25 bar at a depth of 3.5 km; the depth of 1.75 km is close to the average hypocentral depth of 1.23 km of the seismicity at Pozzuoli (Pujol & Aster 1990). (Obtaining a stress estimate at exactly the average seismic depth was precluded by the resolution in Bianchi's figure.) The fact that the deepest point has the lowest stress is a direct consequence of the low rigidity in the model below 2 km, reflecting the effect of temperature at depth on the elastic properties in the model. In short, the model has a local 'soft spot' (i.e., low rigidity) just above the magma chamber.

The uplift shown in Fig. 1 suggests that the rate of inflation was remarkably constant during the time interval June 1982–June 1983 used above to estimate the inflationary stress. Therefore, average inflationary stress rates can be computed by simply dividing the above stress estimates by 1 yr; this results in rates of 18.9, 31.0, and 3.4 mbar day^{-1}, respectively. At face value, these rates are roughly the same order of magnitude as those produced by the solid-earth tides at the latitude of Pozzuoli: 30 mbar in the course of 12 hr or the equivalent of 60 mbar day^{-1} is not unusual (see Fig. 9a). Therefore, tidal stress has the potential to strongly modulate the inflationary stress in the Bianchi model and throughout the entire range of depths of hypocentres.

Another estimate, albeit crude, of the rate of inflationary stress can be inferred from the chronology of the seismicity at Pozzuoli. The ground uplift began in June 1982 and the almost continuous seismic activity started later in March 1983 (see Fig. 1). Del Pezzo *et al.* (1987) found the seismic stress drops to be fairly constant at about 5 bar. If the onset of the anomalous seismicity marks the point at which the accumulated stress from the inflation is being released seismically, then 5 bar divided by the 9 month delay time translates into 18.5 mbar day^{-1}. This seismic estimate of the stress rate is certainly biased low because the earthquakes, from a consideration of the release of seismic energy, are not 100 per cent effective in destressing the caldera. Nevertheless, it is reassuring to obtain an independent stress rate in good agreement with our previous estimate from an elastic model that fits the deformation data.

SUPERPOSITION OF INFLATIONARY AND TIDAL STRESS

The value of the tidal stress quoted in the above section was calculated from a radially symmetric elastic earth model, containing no small-scale variations in crustal properties such as found in the models of the caldera at Pozzuoli. In the presence of such heterogeneity, it would therefore be incorrect to superimpose the inflationary and tidal stress fields by simply adding them together at face value. The main problem, which is as formidable as modelling the inflation itself, is how tidal stress at distance is distributed within the relatively small-scale, heterogeneous structure of the caldera. On the basis of the static limit in linear elastic theory, we surmise that the solution to this problem will involve some linear combination of the elastic parameters in the model and the tidal strains at distance. If the finite element model of Bianchi *et al.* (1984) was available to us, a solution could be obtained by displacing the boundary points of the model by amounts predicted from tidal theory. To obtain a simple solution for the purposes of tidal triggering, however, we speculate that the tidal effect in the model can be written as a superposition of the tidal and inflationary stress, but with a certain scaling of the former. A constant scaling factor seems justified in view of the fact that the seismicity is tightly confined within the caldera (Fig. 2), but this would not be the case for widespread seismicity that spanned major heterogeneities in the model. Also, all secondary interactions between the inflation and the tides are ignored in using a constant scale factor.

The scale factor is a measure of the efficiency of the caldera to transmit external stress and it could obviously range from zero to unity: the former may correspond to an empty caldera, and the latter to the case where the caldera and magma chamber are filled with the host rock. It will be demonstrated *a posteriori* that a precise value of the scaling factor is not essential to the main conclusions drawn from this study.

We obtained an estimate of this scaling factor from the results of seismic studies at Pozzuoli. From an analysis of seismic traveltimes, Aster & Meyer (1988) found seismic shear wave velocities of 1.4–1.5 km s^{-1} at shallow depths of 1–3 km in the caldera. In comparison with the shear wave velocity in average crustal rock (3.5 km s^{-1}) and by assuming that rock density is about average in the caldera, this implies a shear rigidity of 1/6 normal in the caldera, or about 6 GPa. This rigidity is in close agreement with that of 4.8 GPa found in the uppermost 2 km above the magma chamber in the Bianchi *et al.* (1984) model. The reduction in shear rigidity of 1/6 is the scaling factor we have used. This scale factor is not unreasonable when compared to results from models with much simplified geometries and elastic properties. For example, Jaeger & Cook (1979, section 10.9) show that for a long cylindrical inclusion in an infinite homogeneous medium, the ratio of internal to external stress for the simple case of plane strain is given by $3k/(2k+1)$ where k is the ratio of internal to external rigidity. In this example, a rigidity ratio of 1/6 results in a scale factor of 3/8.

In using a constant scale factor, the stress response of the caldera is assumed to be independent of frequency in going from stress of seismic to tidal origin, and this point will be discussed further in our conclusions. We note that a simple scaling of the tidal stress would not be appropriate when tidal triggering of individual faults with specific orientations was being investigated because then the effects of crustal heterogeneities on the local stress field would require careful attention. This is not the case in the present study where changes in the rate of seismicity are being investigated, and our choice of tidal functions also allows for a wide variation in fault orientations (see section on Tidal Stress).

MODULATION OF THE SEISMICITY

Examples of tidal modulation are shown in Fig. 5 where the inflationary stress that was estimated previously at the different depths has been added to the solid-earth tidal stress (N–S normal stress) computed for Pozzuoli and scaled

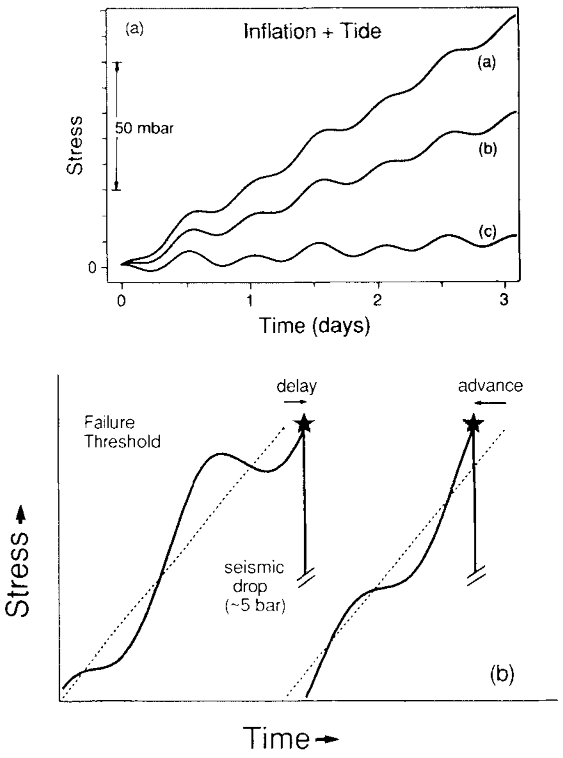

Figure 5. (a) Superposition of inflationary and solid-earth tidal stress (N–S normal stress) at Pozzuoli. Tidal stress is scaled by 1/6 and inflationary stress is drawn using rates inferred from model VI-b of Bianchi *et al.* (1984): (a) 11.3 bar yr^{-1} at a depth of 1.75 km, (b) 6.9 bar yr^{-1} near the surface, and (c) 1.3 bar yr^{-1} at a depth of 3.5 km. (b) Schematic of tidal triggering. The dashed lines are the effective stress from inflation and the solid curves are the inflation plus tide. Tidal stress can advance or delay earthquakes.

by 1/6. In drawing the figure, another condition for tidal triggering has been assumed, namely that the stress from inflation is smoothly varying. But the smoothness of the uplift in Fig. 1 supports the assumption that inflationary stress field also has a smooth temporal variation. We are aware of the possibility that other sources of stress, which do not contribute to the uplift, may be present; this means that our assumption of smoothness of stress based on smoothness of uplift may be erroneous. The important point, however, is that the huge increase in seismicity is directly related to the inflation and not to other sources of stress.

If we assume that the sustained anomalous seismicity at Pozzuoli is produced by the inflation and that earthquakes are occurring because a critical level of stress has been reached, then a modulation of this stress should produce a corresponding modulation of the seismicity as shown in Fig. 5. Importantly, we have implicitly assumed that the failure threshold is independent of the frequency of the applied stress (i.e., the rate in this case), and that short-period diurnal and semidiurnal tidal stress are as effective as the slow inflation in producing earthquakes.

The amount by which the tides can modulate the inflation depends on both the rate of inflation and the scaling factor for the tidal stress (see the Appendix; also discussion by Souriau *et al.* 1982). Tidal influences on the seismicity would naturally tend to vanish if the inflationary rate is too large and/or the scale factor is too small. A tectonic build-up, however, appears indispensable since tidal forces alone are presumably too weak to generate earthquakes. At the average hypocentral depth of seismicity at Pozzuoli, tidal stress with 1/6 scaling would modulate the inflationary stress inferred from the Bianchi model by about 45 per cent (see the Appendix). Looking ahead, this represents a huge tidal influence on the catalogue since a modulation of almost a factor of 10 smaller could be detected.

Tidal stress

Tidal stress may trigger an earthquake in various ways: by increasing the shear stress (σ_S) across the fault until a critical level is exceeded, by decreasing the effective normal stress (σ_N) and hence the friction locking the fault such that the shear needed for failure is lowered, or by some combination of these stresses. When seismicity is governed by friction, the optimal combination of stress is given by Coulomb's failure criterion $\sigma_S + f\sigma_N$ (e.g., Souriau *et al.* 1982), where f is the coefficient of friction, averaging about 0.6 for dry crustal rocks in the laboratory. Conversely, a suitable application of tidal or other stress may suppress seismicity, for example, by increasing rather than decreasing the normal stress on a fault (Johnston 1987).

We use Schuster's method described in the Appendix to test for evidence of tidal triggering in the Pozzuoli catalogue. The choice of tidal function used in this method requires careful attention because certain components of the tidal stress tensor are inefficacious in triggering earthquakes: a catalogue may contain tidal triggering but it may elude detection if the wrong tidal function is used.

Guided by knowledge of the characteristics of the seismicity at Pozzuoli (Del Pezzo *et al.* 1987) and the above discussion on Coulomb failure, we chose the following as tidal functions; normal (σ_N), shear (σ_S), and optimum stress ($\sigma_S + f\sigma_N$) acting on a vertical plane. The normal of the plane was aligned along azimuths $\phi = 0°–180°$ in increments of 30° (measured clockwise from north), and stress was computed from tidal formulae adapted from Longman (1959) using a standard seismological earth model. This set of stresses provides a thorough sweep of possible triggers for all orientations of the strike of fractures and circumvents the problem of specific fault orientation mentioned earlier in the section on superposition of inflationary and tidal stress.

No attempt was made at using other combinations of σ_N and σ_S or other orientations of the plane. Also, no attempt was made to include stress from oceanic tidal effects; Chiaruttini (1976) has estimated that on the Italian Peninsula, the combined stress from the global oceans and the Mediterranean Sea is only 10–20 per cent (in amplitude) of the body tide, but this could be higher along the coast.

Clustering of events: earthquake swarms

The clustering of events (e.g., a mainshock–aftershock sequence) is usually the main reason why seismicity deviates from a random process (Kagan & Knopoff 1976). The Pozzuoli catalogue consists of a practically continuous background level of seismicity plus many bursts of events from earthquake swarms (Fig. 3). The swarms pose a problem in the Schuster test (see Appendix) because they produce highly non-random, and in worst cases almost linear, phasor walkouts; the most active swarm at Pozzuoli produced hundreds of events per hour for several hours. Although swarms are not uncommon in volcanic regions, they usually represent a small percentage of the total catalogue and are readily identified and eliminated (e.g., Rydelek *et al.* 1988). At Pozzuoli, however, the swarms form a large percentage of the total event count and are blended into the background seismicity.

De Natale & Zollo (1986) found the Pozzuoli catalogue to be highly non-Poissonian because of large numbers of events occurring within relatively small time intervals, i.e., swarms. They noticed that the positioning of the individual events within the swarms, namely that the largest event occurs almost at the centre of the swarm sequence, follows a characteristic pattern that has been widely observed in other seismically active volcanic regions. To obtain temporally independent data, De Natale & Zollo (1986) modelled the Pozzuoli catalogue as a generalized Poisson process (Vere-Jones 1970). They demonstrated that by defining a 'cluster length' and then putting all events—both swarms and background—that occur within this time interval into a cluster, the resulting set of time intervals between clusters was Poissonianly distributed. Their procedure resembles in part a moving window average of the catalogue and differs from normal declustering of a catalogue where clusters are identified with an algorithm and then omitted from subsequent analysis (e.g., Reasenberg 1985). By a trial-and-error approach, De Natale & Zollo (1986) found that a cluster length of 1 hr, which is also used in this study, gave the best fit to a Poissonian distribution. They also found that a plot of the frequency of the clusters $f(N)$ versus the number of events N within a cluster displayed a power-law dependence of the form $f(N) = N^{-E}$, where $E = 2.2$ is more or less consistent with values of 2.4–3.7 reported by Shlien & Toksöz (1970) for various regions throughout the world.

The set of clusters formed as outlined above is shown in Fig. 3(b). All clusters containing relatively large numbers of events that violated the above power law have been omitted. The total number of clusters is 3049, of which only 57 are omitted. This set of clusters, rather than the individual events within clusters, is tested for tidal triggering, although in the majority of cases a cluster comprises a single event. Note that even when the clusters are uncorrelated and the time intervals between clusters appear to be random, the absolute times of the clusters could still be highly non-random. This will be clearly demonstrated in the next section where a pronounced daily periodicity is shown in the catalogue.

Schuster test results

The results of the Schuster test on the Pozzuoli catalogue are given in Table 1 for the above set of tidal stresses. The entries in the 'potential' column give the probability (in per cent) of rejecting the null hypothesis that the seismicity is unaffected by tidal stress. The phasor walkout corresponding to the entry with the lowest probability (2.6 per cent; optimal stress when $\phi = 120°$) is plotted in Fig. 6(a). The circles in the figure, which represent 95 and 99 per cent confidence levels of rejecting the null hypothesis, are determined from the Schuster test (see the Appendix). Thus, based solely on the length of the walkout in Fig. 6(a), one could reject the null hypothesis of random events at the 95 per cent confidence level and conclude that a statistically significant correlation between seismicity and tidal stress is present in this catalogue. We will show below, however, that this conclusion is not acceptable when other aspects of the data are considered and evaluated.

Table 1. Schuster test probabilities.

Stress Component	Azimuth (ϕ, degrees)	Probability (%) (Potential)	Probability (%) ($M_2 + O_1$)
normal	0	16.9	23.8
"	30	7.5	20.2
"	60	8.4	19.3
"	90	3.8	20.2
"	120	19.2	22.7
"	150	15.2	25.5
shear	0	48.8	48.7
"	30	67.8	59.0
"	60	53.1	48.1
optimal	0	35.1	93.6
"	30	5.7	10.0
"	60	4.7	46.3
"	90	37.5	31.5
"	120	2.6	14.0
"	150	12.1	25.8
24-hour clock		0.12	

Contamination of the catalogue

It is traditional to test for tidal correlations as above by using the full tidal function. Certain tidal periodicities are prone to contamination from strong diurnal signals, however. We have already shown that the Pozzuoli

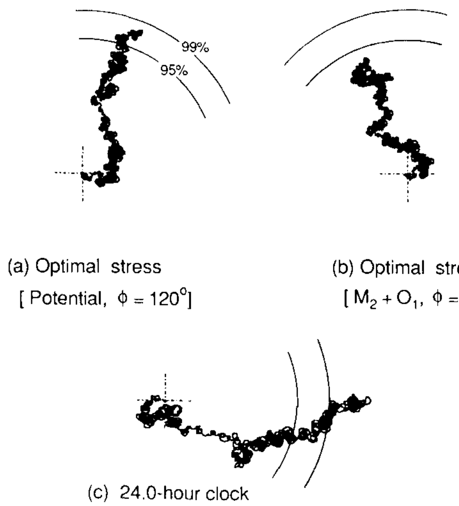

Figure 6. Phasor walkouts from the Schuster test (see Table 1) using (a) optimal stress from the complete tidal potential, (b) optimal stress from only $M_2 + O_1$ tidal components, and (c) a 24 hr clock. Each walkout consists of 2992 unit phasors. The circular arcs correspond to 95 and 99 per cent confidence levels of rejecting the null hypothesis of random walkout.

catalogue contains a day-to-night variation in seismicity as a result of higher noise levels during the day, reducing the number of small events detected (Rydelek & Sacks 1989). This is evident from the phasor walkout in Fig. 6(c) where the catalogue is tested against a local 24 hr clock; the walkout has a low probability of 0.12 per cent (≈99.9 per cent confidence) of random behaviour.

While the S_1 term (24 hr) in the tidal function is too small to have a significant effect, we have found, from separate investigations of other catalogues, that an S_1 term in the recorded seismicity can affect the Schuster test to the extent of producing a false positive result. The explanation is that the S_1 term in the seismicity interferes indirectly with the tidal function used in the Schuster test, especially since Pozzuoli is near the northern latitude where the diurnal tides attain their maximum amplitudes (at ±45°).

For display purposes, a clear example of this interference from another study is shown in Fig. 7, which is a spectrum of the number of shocks per hour recorded at Mt Merapi, central Java (Fadeli *et al.* 1991). The spectrum, as well as a visual inspection of the catalogue, shows that the Merapi data contain a pronounced daily variation in seismicity, the source of which is still under investigation. The S_1 term in this (and any) catalogue is distorted and noisy; thus, higher harmonic terms (S_2, S_3, etc.) are present. In addition, any long-term modulation of the S_1 term, such as a slow temporal change or a summer–winter effect, will cause leakage of spectral energy from the S_1 peak into frequencies of adjacent tides P_1 and K_1 (Fig. 7). These are major tidal components related to the sidereal rotation of the Earth and they differ in frequency from the solar tidal component S_1 by only ±1 per year. Because of harmonics and spectral leakage of S_1, the catalogue therefore contains non-tidal signals at tidal frequencies S_2, P_1, and K_1 (Fig. 7). At normal latitudes, the tidal potential has strong signals at S_2, P_1, and K_1 (diurnal tides theoretically vanish on the equator) and thus the catalogue correlates with the tidal function used in the Schuster test and gives a false positive result, even though a 24 hr S_1 term is, for all practical purposes, absent in tidal theory. Unfortunately, we cannot issue a general quantitative summary about the effects of S_1 contamination in the Schuster test because geographic location, seismicity rate, duration of the catalogue, and strength of the S_1 term all need to be considered.

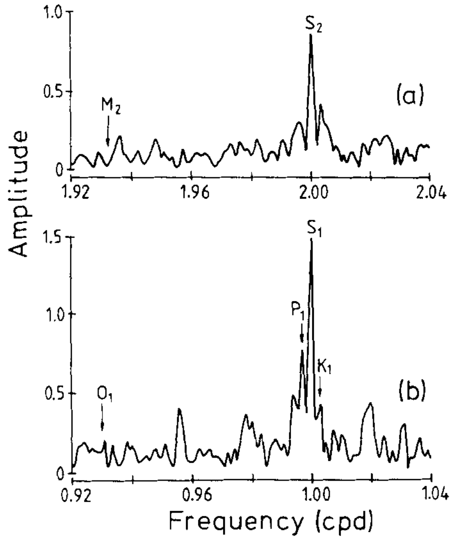

Figure 7. An illustrative example showing the spectrum of the catalogue from Mt Merapi in the (a) semidiurnal and (b) diurnal frequency bands (from Fadeli *et al.* 1991). The Merapi catalogue contains a strong S_1 (or 24 hr) modulation of seismicity. Harmonics and spectral leakage of the S_1 peak result in non-tidal signals at tidal periods S_2, P_1 and K_1 that will correlate with the tidal function used in the Schuster test and produce a false positive result.

In the presence of S_1 contamination, the most reliable approach is obviously to exclude those periodicities (S_2, P_1, K_1) from the tidal function used in the Schuster test. We have approximated this by using only the two largest terms, O_1 and M_2, which account for about 56 per cent of the total tidal power at Pozzuoli. ($P_1 + K_1$ contribute another 42 per cent of the power, but the relatively short length of the Pozzuoli catalogue prohibits removing the effects of S_1 contamination from these components, as discussed above.) The amplitudes and phases of O_1 and M_2 were determined with the aid of the HYCON program for tidal analysis (Schüller 1977). As done previously in the section on tidal stress, normal, shear, and optimal stress were used and varied along azimuths $\phi = 0°–180°$ in 30° increments. The results of the Schuster test indicate no significant tidal triggering (Table 1), and the probability for the longest phasor walkout (optimum stress at $\phi = 30°$) shown in Fig. 6(b) was only 10 per cent.

These results may be compared with the probability of 0.12 per cent for the 24 hr term which could be accounted for by only about 5 per cent missing events during the day. It is not likely that the inclusion of more terms into the tidal function, which would account for more tidal energy, would significantly change our conclusions below. Even when the complete tidal function is used, the best triggering possibilities are 3.8 per cent for the normal stress and 2.8 per cent for optimal stress (see Table 1), but these are undoubtedly biased low because of S_1 contamination.

We may compare the above results with those expected from the inflationary model. Assuming that the scaling factor of 1/6 used in superimposing the tidal stress with the inflation is more or less correct, then Fig. 5 indicates that the amount of tidal modulation would be about 45 per cent, a value that could be detected certainly with the Schuster test (see the Appendix). We anticipated that the tides would affect the seismicity more than a diurnal variation in noise level that is only a 5 per cent effect.

Another point is that other independent analysis revealed no evidence of tidal triggering. If seismicity was influenced by the earth tides, then a Fourier analysis of the times of the events in a catalogue should, in principle, show peaks with lunar and solar periodicities. The tidal potential, however, has a rich spectrum with numerous spectral lines in both the diurnal and semidiurnal tidal bands, with amplitudes that are mainly latitude dependent. Thus, if tidal triggering was weak, then doling out the small effect over many bandwidths and in the presence of noise, may prevent a positive determination of whether a correlation is present or not. This is the main reason why the Schuster test that uses the full tidal potential is favoured in many studies of tidal triggering. Nevertheless, the Pozzuoli catalogue was Fourier analysed after first filling the gaps between clusters with zeros and then applying a Hanning window. No significant spectral peak at M_2 was found, even though this is the dominate term in the tidal potential at Pozzuoli. The S_1 term mentioned previously was clearly visible in the spectrum.

We conclude that tidal triggering is not detected in the clusters of the Pozzuoli catalogue.

DISCUSSION AND CONCLUSIONS

Since tidal triggering is not observed at Pozzuoli, the problem now becomes that of determining what, if anything, is wrong with either the inflationary model we have used or our assumptions.

Assuming that all the conditions for tidal triggering are met, we turn the problem around in the Appendix and show that triggering would most likely not be observed (99 per cent confidence level) if the tidal stress was scaled down by an additional factor of 1/5 (total of 1/30) prior to superposition with the inflationary stress. Generally speaking, this would seem to imply that major features and/or parameter values in the Bianchi *et al.* (1984) model would have to be in error by about this same factor. We believe such an error is highly unlikely considering the fact that this model provides an excellent fit to the deformation data and it is consistent with another independent estimate of the stress rate from the chronology of the seismicity. Therefore, we do not suspect that the model is a major source of error but instead tend to suspect that one or more of our assumptions may be wrong.

The assumptions made in this study are simply stated: (a) the inflationary stress is smoothly varying, both spatially and temporally; (b) tidal stress and inflationary stress can be superimposed; and (c) earthquakes occur when some critical stress is reached. The tidal modulation shown in Fig. 5 suggests a tidal influence on the seismicity if these assumptions are correct.

Assumption (a) is based on the smoothness of the uplift seen in Fig. 1. We can provide no other direct evidence to support this assumption other than the finding by De Natale & Zollo (1986) that the seismicity, which is controlled by the inflation, is stationary and can be modelled as a generalized Poisson process once the swarms have been taken into account with a cluster model. Recall that the clusters, not their individual events, are tested for tidal triggering. If the seismogenic stress is noisy, characterized by large sporadic jumps in stress compared with smooth tidal stress fluctuations, then the coherent phase angle of a tidal trigger would be hidden because of what is essentially a poor signal-to-noise ratio. Such a noisy inflationary stress, however, may seem to produce seismicity that is non-stationary, which is not the case.

Another important point is that the stress function used in the Schuster test was chosen in view of the characteristics of the seismicity at Pozzuoli, namely fault plane solutions (or fault orientations) that were estimated from local seismograms (Del Pezzo *et al.* 1987). Thus, we have implicitly assumed that these fault orientations are representative of the entire process of fault rupture, from the initial fracture of a small fault, to subsequent growth of this nucleation crack which spreads out and forms the final displacement on the macroscopic fault plane. Since the rupture plane is assumed to be fixed during the earthquake process, the tidal stress component that is reckoned optimal for tidal triggering from the fault plane solution would therefore also be optimal to trigger the nucleation fault. Tidal triggering may not be detectable in the unlikely event that the nucleation cracks are randomly orientated, unlike the aligned pattern formed by the fault plane solutions (Gaudiosi & Iannaccone 1985), because the optimal stress would then vary from earthquake to earthquake in an unknown random manner. Since most earthquakes occur on pre-existing faults, however, we feel that it is highly unlikely that the initial slip would be substantially different.

There is no *a priori* physical reason to suspect that inflationary and tidal stresses cannot be superimposed and that assumption (b) is wrong. The problem, however, is how the two should be combined in the presence of small-scale heterogeneity. The solution would be straightforward, albeit numerically complicated, if the inflationary model of Bianchi *et al.* (1984) were available to us. Since this is not the case, and for reasons of simplicity, we have instead resorted to a scaling procedure. Inflationary and tidal stresses were superimposed after a scaling factor of 1/6 was applied to the latter. This factor is taken from the reduction in the bulk shear rigidity of the caldera, inferred from the velocities of seismic shear waves. We show in the Appendix that since tidal triggering is not detected in the Pozzuoli catalogue, this scaling factor is probably at least another factor of 5 smaller, assuming that the inflationary model and the other assumptions are valid (see above). Thus, the null results for tidal triggering at Pozzuoli are inconsistent with the scaling factor estimated from short-period seismic data. In summary, the slow inflation produces seismicity, but the tides do not modulate this seismicity when they are taken on an equal footing, elastically speaking, with seismic waves.

According to assumption (c), earthquakes occur when a critical level of stress has been reached. A failure threshold that is time dependent, however, could explain the lack of tidal triggering at Pozzuoli. We envision a failure threshold that is normal for slow stress variations (such as the inflation), with earthquakes occurring when the gradual build-up of stress exceeds this threshold. But suppose that the failure threshold is increased for more rapid stress changes. Thus, a certain level of stress, which was found to produce failure when the stress changed slowly, would now be ineffective if the stress changed rapidly and did not persist for a long time because the fault appears 'stronger'; alternatively, the high-frequency seismogenic stress appears to be attenuated.

If this frequency dependence is modelled as a single-pole low-pass filter, and taking the inflation as the DC limit, then it can be shown that a relative attenuation factor of 1/5 (see above) at the period of the dominant tide M_2 of 12.42 hr implies a filter time constant of 20 hr. Since tidal triggering is not observed, this time constant is a lower limit because the attenuation could be greater than 1/5, suggesting a stronger fault (or weaker stress) and hence a longer time constant.

In conclusion, even though some assumptions had to be made, the attenuation of any tidal triggering effect has to be so large that a failure threshold that is time dependent seems inescapable.

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APPENDIX

Schuster test

The Pozzuoli catalogue is tested for tidal triggering following the method of Schuster (1897) which is described in detail by Heaton (1975) and only a brief description is given here.

The first step in Schuster's method is to determine the tidal phase angle for each event in the catalogue. For a given tidal function (or clock), this phase angle depends on the position of the event with respect to the times of adjacent tidal maxima that are defined to be 360° apart. For example, an earthquake occurring at a time that is exactly centred between the times of adjacent tidal peaks would be assigned a tidal phase angle of 180°. Each event in the catalogue can thus be represented by a phasor of unit length with the tidal phase angle as determined above. (In the case of Pozzuoli, the clusters of events are used.) In the next step, the phasors obtained from the N events in the catalogue are summed vectorally, which produces a phasor sum, or walkout, of length R. This length can then be checked for non-randomness using equation (3) below. If the events in the catalogue follow a Poisson distribution, then the phase angles will be uniformly randomly distributed and the path of the walkout resembles Brownian motion, with an expected length of $\sqrt{N}$. When the walkout, however, exceeds some certain length [e.g., 95 or 99 per cent confidence level in equation (3)], then the null hypothesis of random event phases can be rejected and there is a significant correlation in the catalogue between the occurrence of seismicity and the tidal function used in determining the phase angles. Selecting the proper tidal function is, of course, crucial to the success of this method of analysis. This method is not strictly limited to tidal phenomena; Rydelek & Sacks (1989) used a similar method in developing a completeness test for earthquake catalogues based on a daily 24 hr clock.

The amplitude R and phase ψ of the vector sum of N unit phasors with tidal phase angles ϕ_i are

$$R = \sqrt{A^2 + B^2}, \qquad \psi = \tan^{-1}(B/A), \tag{1}$$

where

$$A = \sum_{i=1}^{N} \cos(\phi_i), \qquad B = \sum_{i=1}^{N} \sin(\phi_i). \tag{2}$$

The Schuster test gives the probability of exceeding the length R from a sum of N unit phasors with phase angles from a random uniform distribution, i.e., from a Poissonian catalogue,

$$\text{probability} = \exp(-R^2/N). \tag{3}$$

Thus, the smaller the probability, the higher the confidence in rejecting the null hypothesis of random data. A probability of 0.05 (95 per cent confidence level) corresponds to a phasor length $1.73\sqrt{N}$; 0.01 probability (99 per cent confidence level) is $2.15\sqrt{N}$.

Perfect triggering

The sensitivity of the Schuster test in the case of perfectly triggered earthquakes is investigated by considering a catalogue of N total events, in which N_1 events occur at random and N_2 events are triggered with $\phi_i = \text{constant}$; these produce phasor sums of length R_1 and R_2, respectively. Adding (or subtracting) these two lengths produces the longest (or shortest) possible walkout,

$$R = R_1 \pm R_2, \tag{4}$$

which corresponds to the best (or worst) case of detecting the triggered events among the events that occur at random. The walkout of the random events resembles Brownian motion and will have a length that scales as $\sqrt{N_1}$, while the triggered walk is linear, scaling as N_2, thus,

$$R^2 = N_1 + N_2^2 \pm 2\sqrt{N_1}N_2. \tag{5}$$

The number of triggered events N_2 is assumed to be some percentage α of the total number of events, $N_2 = \alpha N$. Using R from (5) together with the constraint that $N = N_1 + N_2$ in the probability (3), we obtain

$$\text{probability} = \exp\{-[(1-\alpha) + \alpha^2 N \pm 2\alpha\sqrt{(1-\alpha)N}]\}. \tag{6}$$

A plot of this probability versus α is shown in Fig. A1(a) for several values of N relevant to seismic catalogues. The plot indicates that the worst-case sensitivity of the Schuster test for the Pozzuoli catalogue (2992 clusters) is 5.6 per cent at a probability of 0.01. This means that if only 5.6 per cent of the clusters in the catalogue were triggered, albeit perfectly, the length of the walkout would be sufficient to reject the null hypothesis (99 per cent confidence) of random tidal phases, or equivalently, of Poissonianly distributed clusters in the catalogue. Best-case triggering of 2.2 per cent could be detected at a probability of 0.01.

Tidal influences: imperfect triggering

Perfectly triggered events ($\phi_i = \text{constant}$) are, of course, never realized in real earthquake catalogues because earthquakes influenced by tidal stress will most likely be scattered (but not completely randomly) within a tidal cycle. To investigate the sensitivity of the Schuster test on catalogues that may be partially influenced by tidal modulations, such as suggested in Fig. 5, pseudo-random synthetic catalogues were constructed and analysed as follows.

Two auxiliary earthquake catalogues with Poissonian rates $\lambda(1+\beta)$ and $\lambda(1-\beta)$ were generated, where λ represents the mean Poissonian rate of seismicity and β is the amount of tidal modulation (see next section). At Pozzuoli, we assume that λ represents the seismicity from the steady rate of inflation of the caldera, while β comes from tidal stress that causes positive and negative fluctuations about this rate (see Fig. 5). Therefore, a synthetic catalogue was constructed by drawing events from the first auxiliary catalogue (with increased Poissonian rate) during the time intervals when the theoretical tidal stress was locally increasing and then by drawing events from the second auxiliary catalogue when the tidal stress was locally decreasing. We used the mean Poissonian rate $\lambda = 0.447$ events per hour calculated from 2992 clusters of events in 6694 hr at Pozzuoli and then varied both the total number of events in the final synthetic catalogue and the modulation parameter β.

The synthetic catalogues were then tested with Schuster's method against the same tidal function used in forming the auxiliary catalogues (N–S normal stress at Pozzuoli) and the results are given in Fig. A1(b). (These results have been smoothed by averaging over 500 random trials in each case.) Fig. A1 indicates that a 7 per cent tidal modulation of the seismicity in the Pozzuoli catalogue could be detected, on average, with a probability of 0.01, which is surprisingly only slightly in excess of that for worst-case perfect triggering of 5.6 per cent found above. Evidence of tidal triggering would tend to disappear (probability > 0.05) if the modulation drops below 5 per cent. We point out that the curves shown in Fig. A1(b) depend only on the number of events in the catalogue and not on the average Poissonian rate; thus, these results could be extended to other studies of tidal triggering using tidal stress at latitudes similar to Pozzuoli (40.8°).

Notice that in catalogues with relatively small numbers of events (of order hundreds), a large change in the Poissonian rate is required (~20 per cent) before tidal triggering becomes statistically significant. This severely limits the chances of detecting weak tidal triggering in catalogues with small numbers of events, at least with the Schuster method of testing catalogues. Also, the results in Fig. A1(a) are

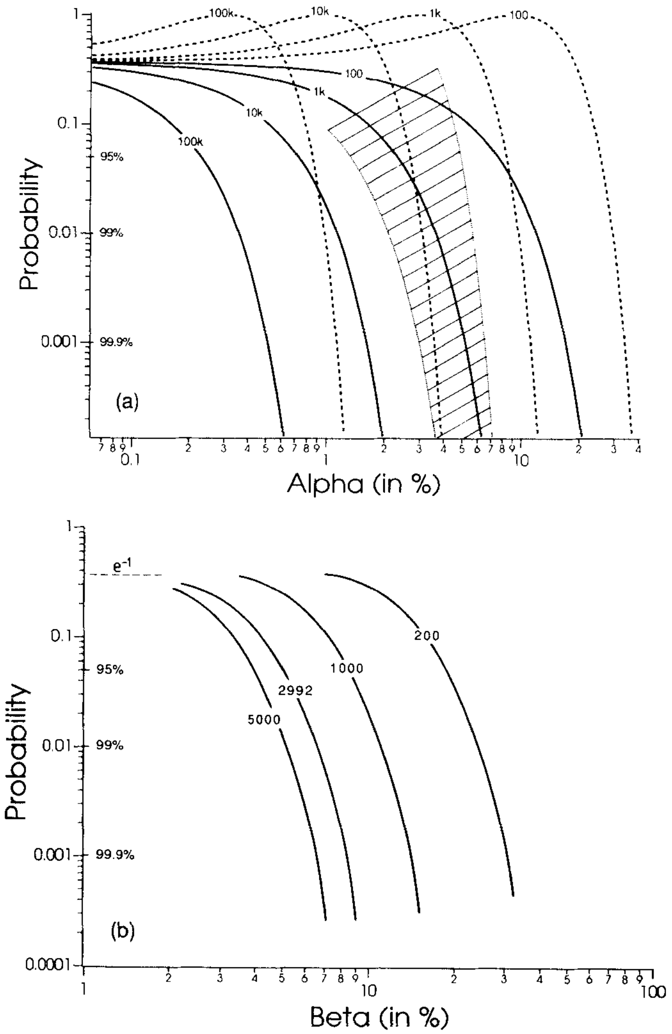

Figure A1. (a) Plot of the probability from the Schuster test versus α, the percentage of perfectly triggered events, for different values of N. The solid and dashed lines correspond to the best- and worst-case phasor alignments, respectively, of the triggered events with the walkout of the random background. The hatched area corresponds to the number of clusters (2992) in the Pozzuoli catalogue. (b) Results of the Schuster test on synthetic catalogues. β is the modulation of the Poissonian rate by a tidal influence (see the Appendix).

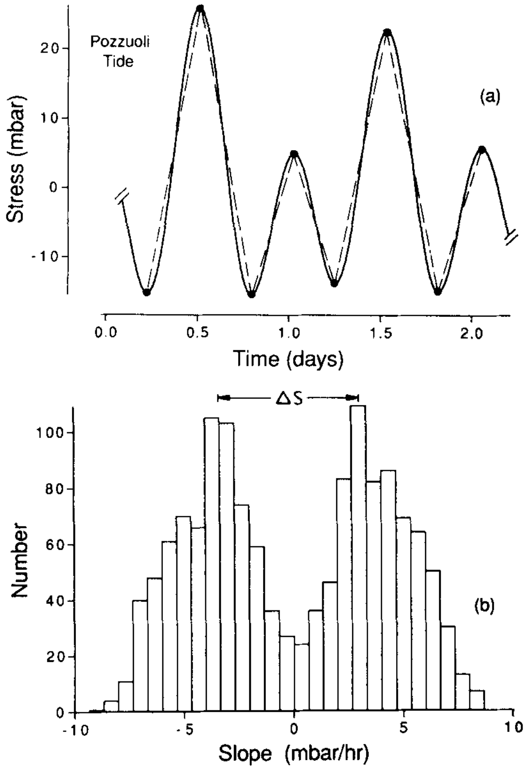

Figure A2. (a) Plot of the theoretical tidal stress at Pozzuoli (unscaled, N–S normal stress). The dashed lines connect the extremum points and the slopes of these lines from a 1 yr tidal record are plotted as a histogram in (b).

independent of the type of clock used in the Schuster test, since perfect triggering was assumed.

Tidal modulation

The modulation parameter β used above, depends on both the rate of inflation and the factor used in scaling the tidal stress (see main text). At one extreme, consider the case where tidal stress is small compared to the build-up of tectonic stress (e.g., inflation); the latter may be very rapid or may occur in jumps that are large and sporadic. In this case, tidal stress may not have a significant influence on the tectonic stress and earthquakes may not be triggered (see Souriau *et al.* 1982). At the other extreme, a very slow build-up of tectonic stress might result in diffuse seismicity with events occurring infrequently, if at all, and tidal triggering may be difficult to detect because of limited sample size, regardless of the possibility of strong tidal effects.

A 2 day section from a 1 year record of tidal stress (unscaled, N–S normal stress) at Pozzuoli is shown in Fig. A2(a). The dashed lines that connect the extremum points in the figure provide a simple approximation of the average tidal stress rates between these points (for a pure sinusoid, this approximation is exact). The slopes of these lines from the full 1 year record are plotted as a histogram in Fig. A2(b). It is easily shown that tidal stress would modulate the inflation by an average amount

$$\beta = \frac{\Delta s F}{2s} \tag{7}$$

where Δs is the distance between peaks in the histogram, s is the rate of the inflationary stress, F is the scaling factor for the tidal stress, and the factor of 2 comes from considering $\pm$ changes in the Poissonian rate. At the depth of 1.75 km at Pozzuoli, which is close to the average hypocentral depth of 1.23 km (Pujol & Aster 1990), a stress rate of 1.3 mbar hr^{-1} is inferred from the inflationary model of Bianchi *et al.* (1984). This rate, combined with the value $\Delta s = 7$ mbar hr^{-1} from the histogram, and by using our preliminary estimate of $F = 1/6$ from seismic considerations, results in a tidal modulation of about 45 per cent (Fig. 5, curve a), an amount that would definitely be detectable in the 2992 clusters of the Pozzuoli catalogue with the Schuster method (see Fig. A1b). In fact, 45 per cent modulation would produce time intervals where the inflationary stress is reversed by the tide.

The fact that no significant tidal triggering is found in Table 1 (99 per cent confidence or greater) allows us to determine an upper bound on the scaling factor, provided that the inflationary model is more or less valid and that superposition holds. A prudent value of 8–10 per cent for the modulation parameter (>99 per cent confidence in Fig. A1b) implies a scale factor of about 1/30 that is five times smaller than our preliminary estimate of 1/6.