Intrusive Origin of the Matsushiro Earthquake Swarm

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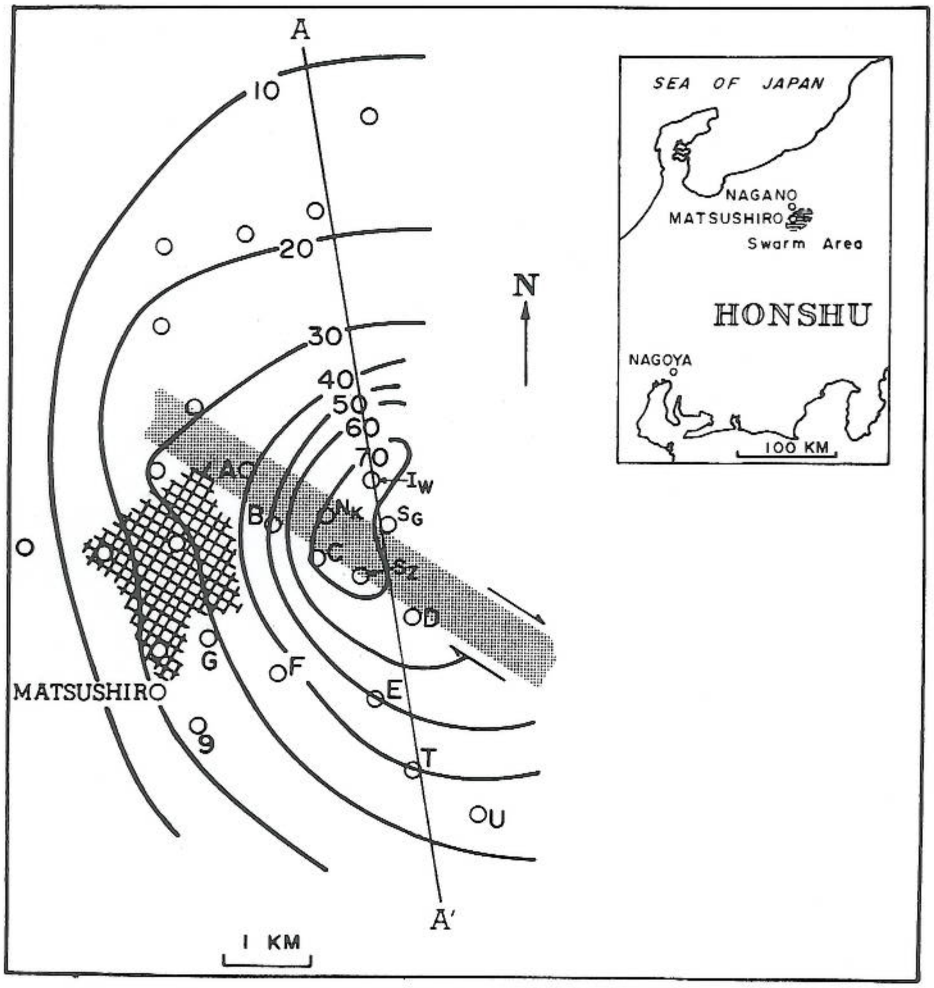

Figure 1. Local uplift in cm near Matsushiro during the period October 1965 to September 1966. Northwest-trending fault zone and sense of displacement marked by dotted pattern and arrows. Bench marks denoted by circles, identified alphanumerically. After Kisslinger (1975) and Tsubokawa and others (1967).

ABSTRACT

Vertical and horizontal displacements, seismicity, and local magnetic field variations observed during and after the Matsushiro earthquake swarm in central Honshu, Japan, appear to be consistent with inflation of a shallow magma reservoir within a crust containing pre-existing horizontal shear stresses. Theoretical analysis shows that increased magma pressure accompanying intrusion causes a domal uplift and also reduces the pressure in adjacent rocks. Reduced pressure implies lower frictional forces on fault planes and therefore accounts for the observed diffuse seismicity and left-lateral faulting. The coseismic increase of local magnetic field intensity is in accord with the piezomagnetic effect expected during growth of a magma inclusion; the subsequent slow decrease of the field in the five years following the swarm is explained by thermal demagnetization of host rocks. Concurrent gravity changes, although comparable to estimated errors, and spring-water outflow fluctuations are compatible with both the intrusion and dilatancy fluid-flow hypotheses.

INTRODUCTION

Although a variety of geophysical phenomena accompanied the Matsushiro earthquake swarm, no compelling synthesis appeared until Nur (1974) asserted that, collectively, the phenomena confirmed the dilatancy fluid-diffusion model (Nur, 1972). According to Nur (1974), the dilatancy fluid-diffusion hypothesis accurately predicts the observations during the swarm of symmetric upheaval and subsidence, the symmetric horizontal deformation related to left-lateral faulting, the increased spring-water outflow, and the temporary decrease of local gravity. This hypothesis, however, loses some validity because the spring outflow and gravity data are ambiguous and easily explained by other means. Moreover, the observed slow variations of the local magnetic field are not easily reconciled with the dilatancy model.

Furthermore, it should be noted that the dilatancy fluid-flow idea was originally conceived to explain temporary decreases in the ratio of shear to compressional wave travel times prior to solitary or a few dominant earthquakes. Later, dilatancy was extended to account for additional precursory phenomena, including elevation changes and dissolved radon content in ground water (Scholz and others, 1973). Therefore, it is not clear how the study of a dispersed swarm, but not the individual earthquakes and their associated forerunners, can test a hypothesis formulated for discrete earthquakes when the detailed mechanics of neither are well understood.

The obvious alternative explanation for the Matsushiro swarm is a shallow magma intrusion, an otherwise reasonable possibility in a region of Quaternary volcanism and numerous hot springs. A magmatic origin probably has been rejected because of an apparent incompatibility between observed left-lateral fault motions during the swarm and radially symmetric motions expected for an intrusion. Fortunately, the incompatibility is illusory, and the case for a fundamentally intrusive origin of the Matsushiro swarm in light of observed horizontal and vertical displacements, seismicity, local magnetic field, and gravity will be considered. In the proposed model, crustal deformations are assumed to result from two superposed stress states: (1) a pre-existing horizontal shear stress of unknown origin that tends to produce left-lateral faulting and earthquake focal mechanisms, and (2) a perturbation due to intrusion of magma into the prestressed crust.

MAGMA INTRUSION

Other than seismicity, the most prominent phenomena concurrent with the Matsushiro swarm were rapid uplift and left-lateral faulting, both centrally located within the elliptical area of seismicity. The uplift varied in both space and time, but it appears to have commenced by early 1966 and increased to a maximum of about 70 cm in September or October 1966 (Fig. 1). During the three years following the swarm, the surface subsided approximately exponentially to about 40 cm maximum uplift (Tsubokawa and others, 1967; data revised and amended by Kisslinger, 1975). At least half of the uplift values shown in Figure 1 are probably underestimates because bench marks A through G were installed in April 1966, T and U in August 1966, and I_W, N_K, S_G, and S_Z in September 1966. Several areas as far as 12 km from Matsushiro seem to have experienced more than 5 cm uplift.

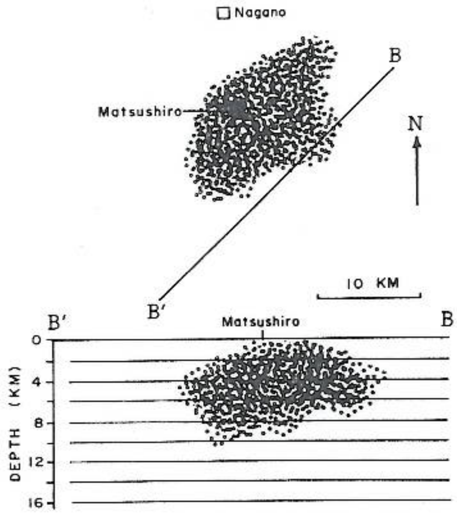

Figure 2. Map and cross-section area of earthquake hypocenters near Matsushiro from October 1965 to October 1967. From Hagiwara and Iwata (1968).

The majority of earthquake hypocenters were diffusely distributed over an area roughly 15 km wide throughout depths ranging from 1 to 12 km (Fig. 2).

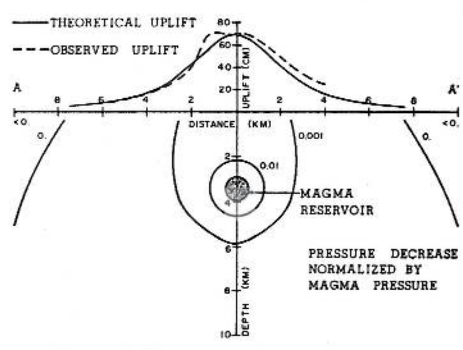

Figure 3. Theoretical solution for free surface uplift and pressure drop near a spherical pressure source in an elastic half-space. Contours are multiples of source pressure; depth = 3.5 km, diameter = 1 km. Observed uplift profile along section A-A′ from Figure 1.

Earthquakes occurred frequently during the early stages of the swarm at about 4 km under the region of greatest uplift. Later, the zone of greatest earthquake density extended slowly outward and deeper. Peak seismicity and rate-of-uplift periods were November 1965, April 1966 (the dominant peak), and late August through early September 1966. Focal plane solutions were consistent with the observed left-lateral displacement of the northwest-trending fault trace (Ichikawa, 1967).

The uplift and seismicity data, plus magnetic field changes, are the principal bases for postulating an intrusive origin of the Matsushiro swarm, although thermal and other mechanical consequences of intrusion can explain the remaining geophysical observations. Magma reservoirs in general must be irregular and have time-dependent geometries, but for analysis, it is assumed that the uplift shown in Figure 1 is due to emplacement or enlargement of a spheroidal reservoir. The word "reservoir" implies only that the state of stress within is on the average hydrostatic, not necessarily that the reservoir is occupied exclusively by magma.

As seen in Figure 3, the observed uplift along a northwest-southeast profile (A–A′, Fig. 1) is in good agreement with the theoretical uplift produced by a 1-km-diameter pressure source 3.5 km deep in an elastic half-space. The theoretical solution was approximated with the finite element numerical method by assuming equality of Lame's elastic constants. For lack of independent evidence, the diameter of 1 km was rather arbitrarily chosen, and a smaller but higher pressure reservoir would produce a similar uplift. A nonspherical reservoir is a more realistic model in view of the imperfect symmetry of uplift.

In addition to causing a domal uplift, a spheroidal intrusion lowers the pressure (that is, the mean normal compressive stress decreases) in rocks surrounding the intrusion. Generalized contours of theoretical pressure drop in Figure 3 demonstrate that pressure decreases well beyond the chamber and changes slowly with distance, except near the chamber wall. At Matsushiro, where the crust is prone to left-lateral faulting, the diminished pressure should promote seismic slip because of lowered frictional forces on potential fault planes. This interpretation is reinforced by the observed diffuse distribution of seismicity throughout the uplifted area and by the coincidence of major faulting and greatest seismicity with maximum uplift.

Inversion of geodetic measurements to more accurately determine reservoir depth and shape is difficult. Normally, horizontal displacement data further constrain reservoir depth and shape (Dieterich and Decker, 1975), but few are available at Matsushiro. The fault slippage also contributes to the horizontal displacement field. A finite element solution for a long, 1-km-diameter cylindrical reservoir extending downward from 2 km yields an uplift profile similar to that of the sphere, as well as a comparable region of pressure drop. Thus it may be safe to assume that, qualitatively, the uplift and region of pressure drop are not heavily dependent on details of reservoir geometry.

The best analog of Matsushiro may be Kilauea Volcano, Hawaii, where recent studies show uplift and seismicity patterns similar to Matsushiro. Summit and rift eruptions are preceded by periods of domal uplift of 2 to 22 months. Uplift maxima are 70 cm or less and the horizontal extent of uplift can be modeled by reservoirs from 0.7 to 3 km deep (Fiske and Kinoshita, 1969; Dieterich and Decker, 1975). During more recent inflations, earthquake swarm activity was greatest over the inferred chamber but extended over vertical and horizontal distances for approximately 10 km (Koyanagi and others, 1975). Unlike Matsushiro, where the post-swarm subsidence is considered to be due primarily to magma contraction during solidification, the more rapid subsidence at Kilauea is coupled with magma flowing from the reservoir to nearby rift extrusions.

DILATANCY

Dilatancy, originally defined by Reynolds (1885) as a change of volume caused by a change of shape, has been considered in a more general treatment by Stuart and Dieterich (1974) to be a nonlinear and elastic volumetric strain in brittle media that depends, in the first approximation, on the square of the pressure (first-stress invariant) and on the distortion (second-stress deviation invariant). In contrast, classic dilatation, also a volumetric strain, is proportional to pressure in an isotropic medium. Physically, dilatancy is the volumetric strain due to cracks opening or closing. Thus dilatant expansion of the crust can originate either by distortion or by decreasing the confining pressure. It is the thesis of Nur (1974) and Kisslinger (1975) that the uplift at Matsushiro is due solely to increasing horizontal shear stresses, which initiate crack opening leading to vertical swelling. In comparison, the intrusion model asserts that the vertical uplift is mainly due to a magma chamber of slightly higher-than-ambient pressure. Because the rock pressure decreases near the reservoir, a portion of the total volumetric strain is due to dilatancy; but judging from laboratory results, the ratio of dilatancy to dilatation is likely to be less than one. It should be noted that, in general, dilatant strains in the crust cannot be reliably estimated because of poorly known constitutive laws and boundary conditions.

It is tempting to relate the generally negative correlation of spring-water outflow and seismicity to magma-pressure fluctuations or, as in the case of Nur (1974), to the dilatancy fluid-diffusion hypothesis. In the first case, the reasoning is that spring flow should decrease during magma reservoir inflation because the crust is expanding and cracks are opening and, conversely, reservoir pressure is dropping slightly. Spring-water yield appears, however, to be well correlated with precipitation measured at Nagano, a town located 10 km north of Matsushiro (Figs. 2 and 4). This observation, in addition to the common disruption of spring- and ground-water flow regimes by crustal movements related to earthquakes, suggests that tectonic significance should not be attached directly to water outflow history.

GRAVITY CHANGES AND UPLIFT

Without more spatial and temporal coverage of gravity data, discrimination between the fluid-flow and the intrusion hypotheses on the basis of gravity changes does not seem possible because magma mass and distribution, rock porosity, and degree of saturation are weakly constrained. Unfortunately, the error bars on the gravity-uplift data from the most frequently occupied base station (Fig. 5; Harada, 1968; Kasahara, 1970; Kisslinger, 1975) do not sufficiently restrict slopes of straight lines through sets of points for an unambiguous interpretation. For example, during the swarm period October 1965 to September 1966, lines with slopes that exceed the range from free air to Bouguer gradients lie

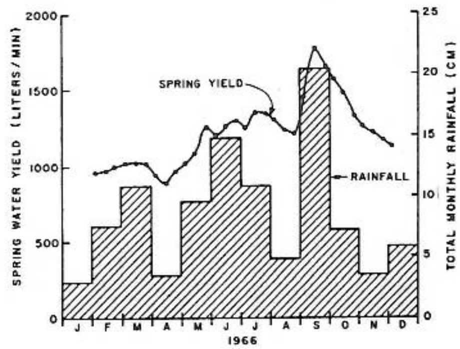

Figure 4. Comparison of water outflow from a representative spring near Matsushiro (Tsuneishi and Nakamura, 1970) with monthly rainfall at Nagano, 10 km north (Japan Statistical Yearbook, 1967).

within the error bars of ±0.02 mgal given by Kasahara (1970; Kasahara's statement that "Observational error is supposed as 0.02 mgal or less . . ." is assumed to mean one standard deviation equals 0.02 mgal). The precise meaning of the estimated gravity error is not known, however, nor are the relevelling errors; a standard deviation of 1 to 2 cm is typical for comparable surveys. In view of the large estimated errors, the scatter of data, and the uncertainties of gravity and relevelling survey procedures, the data do not seem to warrant identification of a specific mechanical model.

Gravity and elevation changes associated with magma intrusion should have gradients between free air and Bouguer, depending on the assumptions, as should changes accompanying subsidence due to magma freezing after the swarm. If new pore space were created during the swarm and were subsequently filled with water after the swarm, the gravity would be perhaps a few hundredths mgal greater than the gravity for the same swarm-period uplift. Permanent emplacement of magma also implies that both gravity and elevation will not necessarily return to their pre–October 1965 values.

MAGNETIC FIELD CHANGES

The observations of five-day means (7,200 values per mean) of the local magnetic field differences between Matsushiro and the Kanozan observatory for the five-year period from November 1965 to February 1970 reported by Yamazaki and Rikitake (1970) are shown in Figure 6. These data were taken with absolute proton magnetometers, which are drift-free and insensitive to temperature. Because the permanent

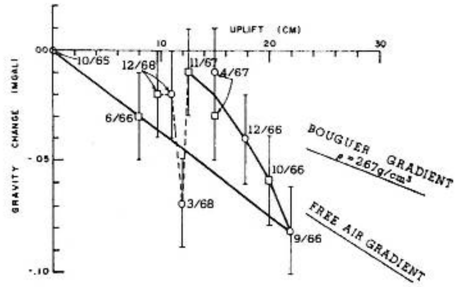

Figure 5. Observed gravity change and uplift at Matsushiro bench mark 9 (Fig. 1) as a function of time. Squares denote observations by Geographical Survey Institute, circles by Earthquake Research Institute. 10/65 = October 1965, and so forth. Error bars indicate ±0.02 mgal observational error. After Harada (1968), Kasahara (1970), and Kisslinger (1975).

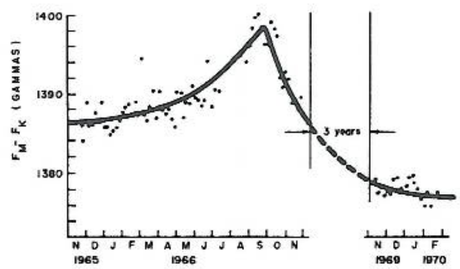

Figure 6. Five-day means of local magnetic field differences between stations at Matsushiro (F_M) and Kanozan (F_K) for the years 1965 to 1970. From Yamazaki and Rikitake (1970).

sensor holders remained in position during the three-year recording gap between November 1966 and November 1969, the latter data can be referenced to the 1965 to 1966 data, as indicated by the dashed line. Although the orientation of the pair of stations used is ideal for detecting changes in the gradient of the nondipole field as it drifts westward, the amplitude of the changes, the coincidence of the peak anomaly with cessation of earthquake activity, and the trend reversal make this explanation of the data unlikely. Taking data from Vestine and others (1947) on the rate of secular variation change for Japan and allowing for a westward migration of about 0.2° of longitude per year gives an apparent positive secular variation change between Matsushiro and Kanozan of not more than a few gammas during the five-year period, in agreement with more recent data by the Geomagnetic Research Group on Earthquake Prediction (1973).

Significant long-term local magnetic field changes associated with magma intrusion could derive from the two more important processes, piezomagnetism and thermal demagnetization. Piezomagnetism is the stress modification of the magnetic properties of rocks (Stacey and Johnston, 1972) and can reflect both the long-term and short-term stress changes in crustal rocks with substantial content of magnetic minerals, such as are found near Matsushiro. Thermal demagnetization is caused by migration of the Curie point isotherm through a sufficient volume of rock and is a slow process due to the low thermal diffusivity of crustal rocks.

Surface magnetic field anomalies can be produced both by a strong perturbation of the stress field near the intrusion, because the magma inclusion has vanishing rigidity, and by magma pressure fluctuations. In the latter case, the surface field changes are small because the radially symmetric stress field set up by magma pressure allows elemental contributions to the piezomagnetic field to effectively cancel one another.

The piezomagnetically induced change in magnetization for shear-stress relaxation resulting from a magma inclusion has been calculated by Stacey and others (1965). They use a chamber 5 km in diameter centered 10 km deep in a region where the maximum principal stress is horizontal and assume the least principal stress to be vertical and half the magnitude of the maximum horizontal compressive stress. This case is sufficiently similar to the proposed model of a chamber 1-km diameter at 3.5-km depth that the results can be scaled directly. The greatest uncertainty with the calculation is the assumption of simple geometry, but as they point out, these calculations are relatively insensitive to geometric details.

Using the average magnetization of surface rocks of 3.9×10^{-3} emu measured by Rikitake and others (1966), which is assumed to be representative of the region, the calculated piezomagnetically induced field change exceeds $8\,\gamma$ if the maximum horizontal compressive stress is 945 bars. This process is proposed to explain the $12\,\gamma$ field increase during the year prior to the last peak in seismic activity at Matsushiro.

The volume of intruded magma that accounts for the vertical uplift ($\sim 3 \times 10^7\ m^3$) can be used to estimate the magnitude of the magnetic field decrease due to thermal demagnetization of host rocks. Assuming a magma temperature of 1300°C, a host-rock temperature of 200°C, a Curie point of 600°C, and heat of crystallization equal to 80 cal/g, the heat from freezing and cooling of magma could cause about a $14\,\gamma$ intensity decrease at the surface. This value is only two-thirds the observed $20\,\gamma$ decrease, but contributions from magma intrusion at greater depths and sub-Curie point thermal demagnetization could easily account for the difference. The observed rate of decrease with time is difficult to model precisely, but it appears to be consistent with estimates of several meters per year for the migration rate of the Curie point isotherm into host rocks.

Although the dilatancy fluid-flow model conceivably could account for the magnetic field increase during the swarm if local shear stresses were sufficiently relieved by faulting, the postseismic field decrease is incompatible because shear stresses would have to increase again. Increasing shear stress would result in additional uplift, instead of the observed subsidence. Therefore, the reversal of magnetic field trend at the end of swarm activity and the similarity of subsidence and magnetic field decay rates support the intrusion model and apparently rule out a dilatancy fluid-flow model.

CONCLUSIONS

Inflation of a shallow magma reservoir in a crust subject to pre-existing regional shear stresses appears to explain satisfactorily the Matsushiro earthquake swarm, as well as the observed concomitant uplift, left-lateral faulting, local magnetic field anomaly, and gravity fluctuations. Seismicity and faulting, although having attracted greatest attention, are of secondary importance tectonically and are only one mechanical consequence of reservoir inflation, the other being a domal uplift. Gravity and uplift changes, despite large uncertainties, are at least consistent with permanent emplacement and solidification of magma. Spring-water outflow shows a negative correlation with seismic activity but a positive correlation with rainfall and, thus, is of questionable utility, as is the gravity-uplift data. Local magnetic field changes, however, favor the intrusion hypothesis because of both the large changes and the reversal of trend at the conclusion of swarm activity. Additional evidence for magma intrusion might result from analysis of temporal changes of shear wave attenuation during and after the swarm. Identification of distinctive long-period earthquakes, such as observed at Kilauea and thought to be related to magma flow through feeder conduits (Koyanagi and others, 1975), could also indicate magma intrusion at Matsushiro.

The fundamental issue at Matsushiro is not whether the crust at Matsushiro became dilatant, for most brittle crustal rocks probably do near failure. Rather, the issue is the origin and history of the stress state causing the uplift, a part of which may be related to dilatant strain. In the dilatancy fluid-diffusion model, horizontal shear stresses are postulated to increase rapidly during the period of seismicity. These enhanced stresses are then assumed to distort the crust locally to induce seismicity and also simultaneous swelling and vertical uplift. With the intrusion model, horizontal shear stresses are assumed to have increased slowly over a large region prior to the swarm but then to have diminished locally during the swarm by fault slippage, which became possible by upward migration of magma. The other mechanical consequence of the magma was the localized uplift.

Even though the conventional dilatancy fluid-diffusion hypothesis may not be applicable to the Matsushiro swarm, dilatancy should not be abandoned as a viable mechanism for some of the phenomena observed prior to a number of earthquakes in other parts of the world. Decisive testing of the dilatancy fluid-diffusion hypothesis, as well as the possibility proposed by Stuart (1974) that fluid diffusion is in general unnecessary, will probably come from extensive and careful measurements of tilt, gravity, and elevation changes related to single earthquakes.

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