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Near-field seismic displacement and tilt associated with the explosive activity of Stromboli

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Abstract
Broadband seismic recordings in the near-field of Strombolian explosions, at 500 m distance, show pronounced effects of tilt. The tilt signal is predominant in the horizontal components beyond about 50 s period while it is negligible in the vertical component. The waveform of the tilt signal at the seismometer output is a double time integral of the waveform due to ground displacement. Since the waveform of the displacement is known from the vertical component, the waveform of the tilt signal in the horizontal seismogram can be reconstructed and both contributions can be separated from each other with a linear regression. We have analyzed data recorded in the summit region of Stromboli in 1995 and 1996. The regional tilt can be determined from the differential vertical displacement between instruments a few tens of meters apart. Local tilts determined with individual instruments scatter around the regional value, most probably due to local strain-tilt-coupling. Mogi's (1958) formulae for a pressure source in a homogeneous halfspace are used to interpret the results. The source displaces a volume of several tens of cubic meters of the surrounding rock before the explosive discharge; typical volumes were 25 m^3 in July 1995 and 60 m^3 in September 1996.

Key words *Stromboli – volcano seismology – seismic tilt – Mogi model – source mechanism*

1. Introduction

The persistent explosive activity of Stromboli produces seismic signals that have been observed and interpreted for more than a century; see Falsaperla and Schick (1993) for a summary. Conclusions on the source mechanism have, however, remained speculative due to the difficulty of separating the source signal from effects of wave propagation in the heterogeneous volcanic edifice, and because the observed signals are compatible with a variety of source models. Broadband seismometry has added a new dimension to such studies. At signal periods longer than a few seconds, the whole summit region of the volcano lies in the seismic near field, and the seismic displacements are directly proportional to the time-dependent volume displacement of the source, no matter what the elastic structure of the intervening medium may be. We refer here to the concept of a volume source (in contrast to a pressure source) that has proven useful in the theory of underwater explosions (Wielandt, 1975) and should be equally suitable to describe the excitation of seismic signals by volcanic processes. There is no physical difference between a pressure and a volume source but a mathematical one: the relationship between the source volume and the seismic displacement is more direct than between pressure and displacement, especially for explosive sources. The seismic data contain direct informa-

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tion on the displaced volume but no information at all on the size of the source or on the pressure.

It is, however, not a trivial task to record long-period seismic displacements on a volcano. Horizontal seismometers do not distinguish between true accelerations of the ground and apparent accelerations resulting from the combination of gravity and tilt. The tilt signal can dominate over the displacement signal at long periods within the passband of a broadband seismometer (fig. 1). The two contributions must be separated from each other before the displacement can be evaluated. The purpose of the present paper is to show how this can be done.

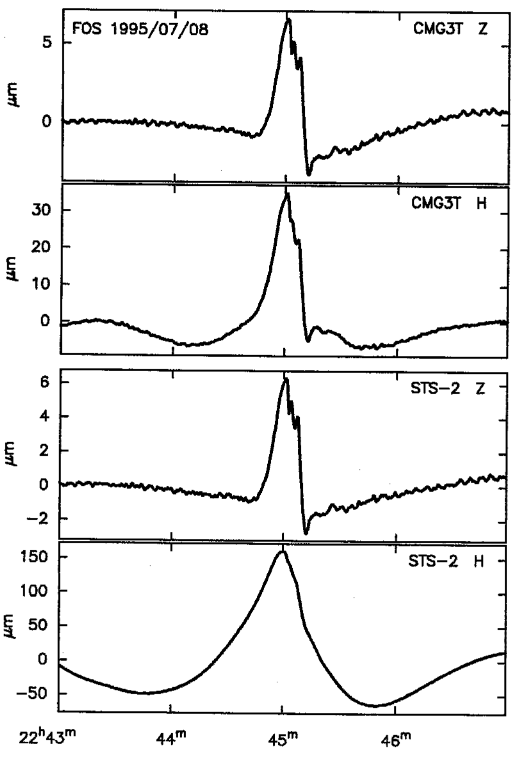

Fig. 1. Apparent ground displacement obtained from two seismometers, Guralp CMG-3T and Streckeisen STS-2, in a huddle test at station FOS in 1995. Z = vertical component. H = radial horizontal component. The vertical waveforms match between both instruments. Due to local tilt, the horizontal waveform from the CMG-3T differs slightly and the horizontal waveform from the STS-2 strongly from the vertical waveform. The signals are restituted for a phase-free seismometer response up to 180 s. See fig. 6 for a discussion of the restitution process.

A short historical note will be permitted at this point. The first mechanical seismographs around 1880 were designed as displacement sensors, supposedly measuring the ground motion against the resting seismic mass. The sensitivity of long-period horizontal seismographs to local tilt was of course soon noticed and when Ernst von Rebeur-Paschwitz unexpectedly recorded a Japanese earthquake with tiltmeters at Potsdam and Wilhelmshaven in 1889, most seismologists became convinced that the signal to which horizontal seismographs responded was tilt. August Schmidt, a high-school teacher and seismologist at Stuttgart, had to remind his colleagues in 1897 that horizontal acceleration and tilt are equivalent for a seismograph. In 1899 W. Schlüter, a Ph.D. student of Emil Wiechert's, built what he called a klinograph, a balanced pendulum that would respond to rotational but not to linear acceleration. The klinograph did not respond to earthquakes although it should have done so if tilt was the predominant signal. This swung the opinion back in favour of linear motion as the essential signal, at least in Wiechert's school; but it took another decade for other prominent seismologists including Galitzin to accept the result.

The effect of tilt is generally small but not negligible in earthquake seismology. The relative contribution of tilt is proportional to period^2/distance in the near-field and to period/phase-velocity in the far-field. It causes an amplitude error of about 5% when a Rayleigh wave with a period of 100 s is recorded on a horizontal seismograph. A thorough discussion of the response of horizontal seismometers to tilt is given by Rodgers (1968).

2. How a seismometer responds to displacement and tilt

No matter what its frequency-dependent response may be, an inertial seismometer basically detects changes in acceleration along its sensitive axis. Such changes may either result from a translatory motion or from a re-orientation of the sensitive axis against the vector of gravity, *i.e.* from tilt. (Most seismometers are also sensitive to rotational acceleration but this is not noticeable in normal seismic recording). While in a precisely vertical sensor the effect of tilt is of second order and thus in most cases negligible, for a horizontal sensor tilt causes a first-order change in acceleration. When the sensor has a response flat to ground velocity, its output signal represents both the time derivative of the ground displacement and the time integral of the tilt angle. In the near-field of a seismic volume source, the waveforms of displacement and tilt are identical. A horizontal seismometer will then respond to the tilt with an output waveform that is a twice-integrated version of its response to the displacement. At the same time, unless the tilt is large, a vertical sensor will show the pure waveform of the displacement. The two waveforms that make up the horizontal record are therefore known and their amplitudes can be recovered by a linear regression.

Mathematically, we can express these relationships as follows. In the near-field of a volume source, all ground motions are proportional to a source function $f(t)$ that describes the time history of the volume displacement. We normalize it to a maximum value of 1 so that the source volume $V(t) = V_0 f(t)$. For brevity we present here only formulae for a cylindrically symmetric displacement field although this is not an essential assumption, and we have evaluated our data in three dimensions. The subscript r denotes the radial direction in space (the origin being in the source) and the subscript x the radial direction in a horizontal plane. We write

$$u_x(\vec{r},t) = X(\vec{r})\, f(t)$$
for the horizontal displacement,

$$u_z(\vec{r},t) = Z(\vec{r})\, f(t)$$
for the vertical displacement (2.1)

$$u_r(\vec{r},t) = R(\vec{r})\, f(t)$$
for the radial displacement,

$$\tau(\vec{r},t) = T(\vec{r})\, f(t)$$
for the angle of horizontal tilt.

The waveforms of the signals from the 1995 experiment have been studied by Kirchdörfer (1996, 1999). He finds that for a given event, the waveforms of the vertical displacement at frequencies below 1 Hz are practically identical at all summit stations. Since tilt is the horizontal derivative of the vertical displacement, it must also have the same waveform. In the present paper we are essentially interested in the amplitude ratios between different components of displacement and tilt at a given station. As positive signals we define motions in outward and upward direction, and outward dip. Thus, displacements and tilt are positive when $V(t)$ is positive. Observed tilts are in the order of 10^{-7}; we will therefore not distinguish between the tilt angle and its sine or tangent.

While the vertical acceleration is simply $a_z(t) = \ddot{u}_z(t)$ the horizontal acceleration $a_x(t)$ seen by the seismometer is

$$a_x(t) = \ddot{u}_x(t) - g\,\tau(t) \qquad (2.2)$$

where g is the gravitational acceleration. Expressing everything by the vertical ground displacement, $u_z(t)$, and omitting the argument t, we have

$$a_x = \frac{X}{Z}\ddot{u}_z - \frac{gT}{Z}u_z = \frac{X}{Z}\ddot{u}_z - \frac{gT}{Z}\iint \ddot{u}_z \qquad (2.3)$$

where $\int u$ is short for $\int_0^t u(t')\,dt'$. The seismometer convolves all acceleration-type signals with the same transient response (at least it is supposed to do so) and hence the relationship between the horizontal and vertical output signals is

$$s_x = \frac{X}{Z}s_z - \frac{gT}{Z}\iint s_z \qquad (2.4)$$

Here the symbol s may represent the electric output signal or an apparent ground motion calculated from that signal in a certain bandwidth. Figure 4 demonstrates that the observed horizontal signal does in fact contain the two contributions predicted by the last equation. The records are from a Guralp CMG-3T broadband seismometer located at 500 m from the craters of Stromboli; details are given later.

3. Theoretical source models

Before we present our experimental results, let us consider two simple source models. Their basic assumption is that the seismic signal is generated by the expansion of a spherical cavity in a homogeneous elastic medium, and that a quasi-static solution of the boundary value problem is sufficient, *i.e.* we are in the near-field of the source.

For a spherical cavity in a homogeneous full space with shear modulus μ, the radial displacement is found as

$$u_r = \frac{P}{4\mu}\frac{\rho^3}{r^2} = \frac{V}{4\pi r^2} \qquad (3.1)$$

where P is the excess pressure in the source, ρ its equilibrium radius, and V the displaced volume. The medium does not experience any bulk compression; it responds to a volume source like an incompressible fluid and hence the source volume may directly be determined from the radial displacement at any distance. The quantities ρ, μ and P cannot be inferred separately from seismic observations; one would have to know two of them in order to determine the third, which is unrealistic.

Our second model is known as the Mogi model (Yamakawa, 1955; Mogi 1958) and describes the displacements in a halfspace with $\lambda = \mu$ originating from an embedded small spherical pressure source. At the free surface, the model predicts a purely radial displacement (radial in space)

$$u_r = \frac{3P}{4\mu}\frac{\rho^3}{r^2} = \frac{3V}{4\pi r^2}. \qquad (3.2)$$

Remarkably, this differs from the full-space solution only by a constant numerical factor of 3. In the interior of the halfspace, Yamakawa's solution is of course different and more complicated. Ishihara (1990) has used the Mogi model to estimate depth and volume of an eruptive source (Sakurajima volcano) from tiltmeter and strainmeter records.

The Mogi model permits, at least theoretically, an estimation of the source location from a single three-component broadband seismogram. The source-receiver direction is given by the spatial direction of the ground displacement and the distance follows from the ratio of displacement and tilt. The horizontal distance x_s and the depth z_s of the source are obtained as

$$x_s = \frac{3Z}{T}\left(\frac{X}{R}\right)^2, \quad z_s = \frac{3X}{T}\left(\frac{Z}{R}\right)^2. \qquad (3.3)$$

Due to the occurrence of local strain-tilt-coupling in a heterogeneous medium, local tilt may deviate considerably from the value predicted by the Mogi model. However, we can determine the regional tilt over any desired baseline from the differential vertical displacement between two well-calibrated seismographs. This makes it practical to determine the source depth from eqs. (3.3). We will come back to this point when we discuss our results.

Fig. 2. The deployment at the huddle test station FOS in 1995. While the Guralp CMG3T (bottom) was buried directly the Streckeisen STS-2 (top) was placed on an aluminum plate.

4. The field experiment

We have analyzed broadband seismic data collected in July 1995 and September-October 1996 in the summit region of Stromboli. The experiments were commonly conducted by field parties from the Department of Earth Sciences, University of Leeds, and from the Geophysical Institute, University of Stuttgart. Two types of seismometers were used: Guralp CMG-3T with a response flat to velocity up to 120 s by the Leeds group, and Streckeisen STS-2 with the same nominal response by the Stuttgart group. The seismometers were buried in soft ground (ashes) at a bottom depth of about 80 cm (fig. 2). The installation procedure was slightly different for the two types of instruments. Guralp seismometers can be buried directly while the Streckeisen instruments require some sort of container. In 1995, where only one STS-2 was used, it was put on an aluminum plate and covered with a plastic bucket. Since this arrangement did apparently not provide firm coupling to the ground, we prepared stainless-steel containers – actually large cooking pots – for the 1996 experiment. They made the setting of the STS-2 seismometers similar to that of the CMG-3T and in fact removed the conspicuous difference that had previously been observed between the two instruments. Data were recorded with MARS88 and PDAS100 digital recorders.

The present paper is mainly based on data from the station FOS, located near the saddle between the Fossetta and the Rina Grande, about 500 m SSE of the craters (fig. 3). One Guralp and one Streckeisen instrument were installed there in 1995, two Streckeisens and one Guralp in 1996. The mutual distance of the sensors was about 1 m. One of the Streckeisens was moved by 66 m towards the craters to station SLO at the end of the 1996 experiment, in order to measure the regional tilt over a longer baseline.

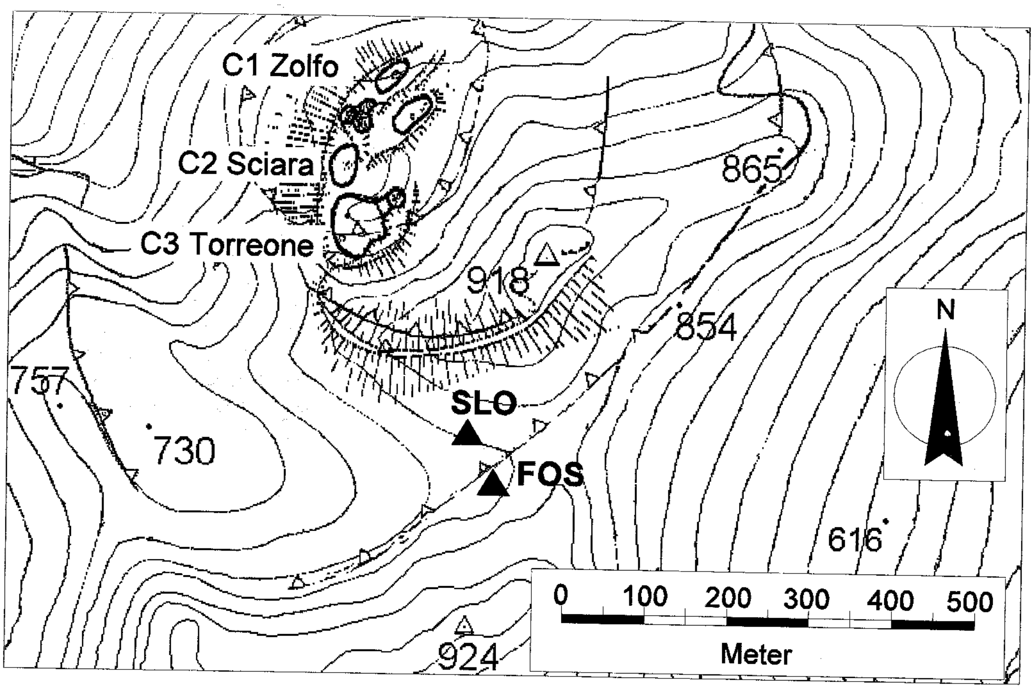

Fig. 3. Map of the Stromboli summit region (courtesy of M. Kirchdörfer, based on maps by Keller and Harris). Data from stations FOS and SLO are analyzed in this paper.

5. Data processing

The effects discussed in this paper are most easily observed at periods between 20 and 200 s. At longer periods the signal is disturbed by the general long-period seismic noise (most probably of atmospheric origin), at shorter periods we enter the domains of marine microseisms and continuous volcanic tremors. In all of our data, displacement is the predominant signal at the short-period end of this band and tilt at the long-period end.

For our analysis we have band-pass filtered the broadband velocity data from 20 to 100 s. Events were automatically detected and appropriate time windows taken from the vertical, twice-integrated vertical, and horizontal traces. The coefficients $X/Z = C$ and $gT/Z = D$ in eq. (2.4) were then determined so as to minimize the residual

$$n = s_x - C\, s_z + D \iint s_z \qquad (5.1)$$

in a least-squares sense (fig. 4). Only events where the residual had less than 5% of the energy of s_x entered into the averages listed in table I. In the final analysis, the procedure as described here was performed for the EW and NS seismic traces separately, and the three-dimensional direction of motion or tilt determined from the resulting directional coefficients.

While the geometric meaning of $C = X/Z$ is obvious (its arctangent is the inclination ϑ_d of the particle motion against the horizontal), we found it useful to associate also $D = gT/Z$ with a geometric quantity. When the seismometer is vertically displaced by u_z and at the same time tilted by τ, this can be represented as a rotation around a horizontal axis at a horizontal distance $L = Z/T = g/D$ from the sensor (fig. 5). We call this distance the baseline length and list it in our table of results (table I). In the Mogi model, L approaches one-third of the source-receiver distance when the latter is large against the source depth.

The regional tilt was determined from the difference between the vertical displacements at the stations SLO and FOS. The amplitudes at SLO were 1.40 times larger than at FOS (fig. 6) and the inferred tilt at the FOS station is equiv-

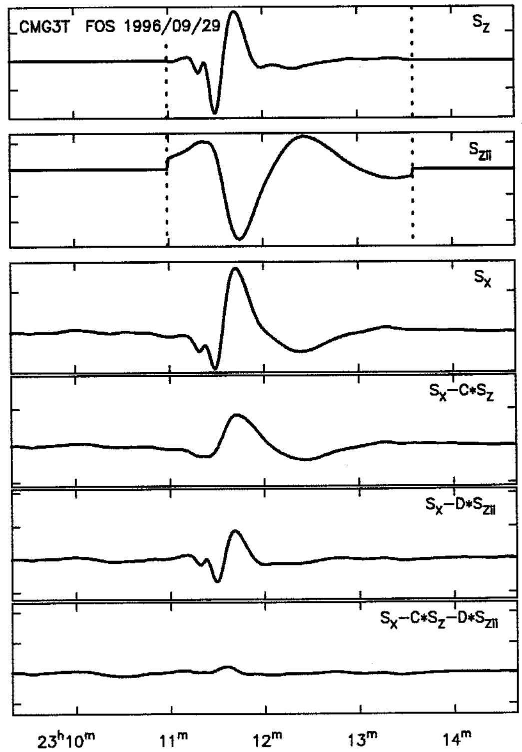

Fig. 4. Decomposition of a horizontal signal into displacement and tilt components in a passband from 20 s to 100 s. S_z = vertical signal; S_{Zii} = twice-integrated vertical signal; S_z and S_{Zii} are shown only in the time window for which the coefficients C and D were determined; S_X = radial horizontal signal; $S_x - C\, S_z$ = horizontal signal after removing the displacement component; $S_X - D\, S_{Zii}$ = horizontal signal after removing the tilt component; $S_X - C\, S_z - D\, S_{Zii}$ = residual signal after removing both components. The lowermost four traces have the same scale.

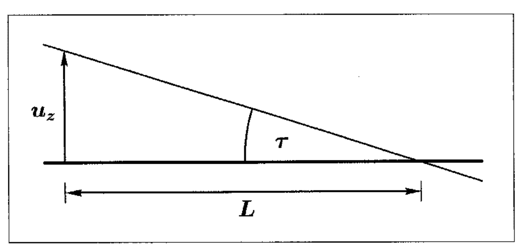

Fig. 5. Definition of the geometrical baseline L representing the ratio of displacement u_z and tilt τ.

Table I. Decomposition of the horizontal traces into displacement and tilt. The data sets assembled in subtables cover essentially the same time interval. N = total number of events in the data set. $N_{25\%}$ = number of events for which the relative energy of the residual is less than 25%. $N_{5\%}$ = number of events with a residual of less than 5%. The results are mean values and r.m.s. deviations for those events. L = baseline length in direction of steepest descent, φ_t, to the center of rotation. T_c = crossover period at which displacement- and tilt-generated signals are of the same amplitude. φ_d = horizontal direction of the displacement vector. ϑ_d = inclination of the displacement vector against the horizontal plane. Azimuth is measured from north to east.

Data set	N	$N_{25\%}$	$N_{5\%}$	L[m]	T_c[s]	φ_t[°]	φ_d[°]	ϑ_d[°]
FOS 1995 STS-2	50	41	24	49 ± 5	32 ± 3	151 ± 5	151 ± 4	13.1 ± 1.4
FOS 1995 CMG-3T	28	26	21	600 ± 200	92 ± 16	91 ± 8	140 ± 2	15.6 ± 0.6
FOS 1996 STS-2a	118	115	77	120 ± 12	49 ± 4	138 ± 4	145 ± 3	11.5 ± 0.9
FOS 1996 STS-2b	118	108	65	200 ± 22	60 ± 5	140 ± 5	148 ± 3	12.6 ± 0.7
FOS 1996 CMG-3T	107	100	62	135 ± 16	49 ± 4	158 ± 6	143 ± 3	12.8 ± 0.8
FOS 1996 STS-2a	137	132	89	110 ± 10	47 ± 4	134 ± 3	144 ± 3	11.5 ± 0.9
SLO 1996 STS-2b	165	148	108	274 ± 25	68 ± 4	152 ± 8	144 ± 3	13.5 ± 0.4
FOS 1996 CMG-3T	141	139	108	117 ± 12	46 ± 4	159 ± 3	143 ± 2	12.8 ± 0.8

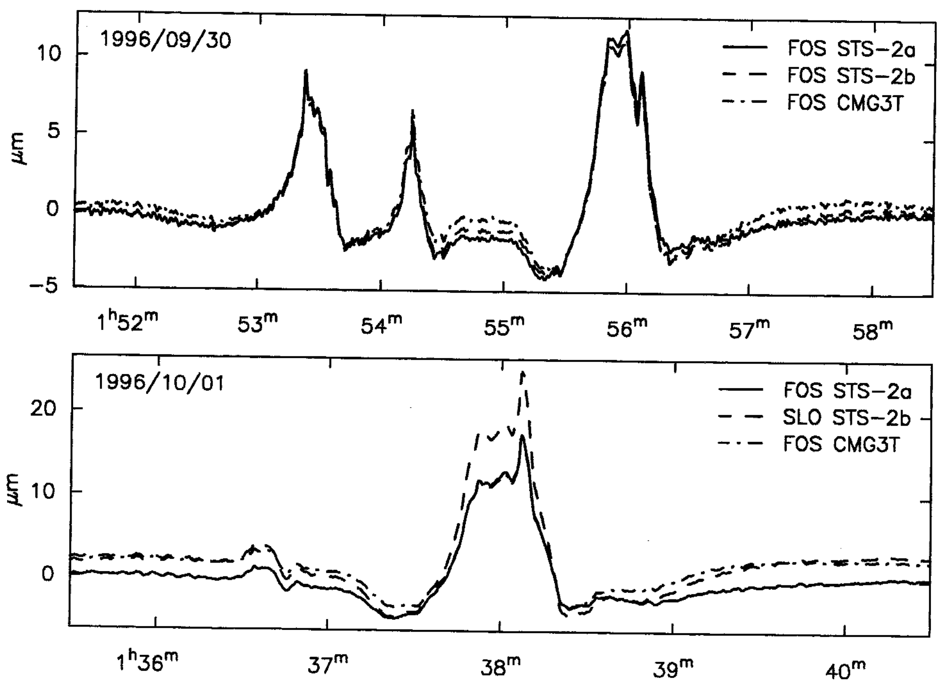

Fig. 6. Ground displacement obtained from three seismometers at FOS and SLO in 1996. The waveforms from the instruments in the huddle test are identical apart from very long period noise. The waveform at station SLO matches the one at FOS but is 40% larger in amplitude. This is a phase-free restitution to 180 s. The true waveform is best reproduced by a phase-free restitution. However this leads to acausal artefacts like the minima before each impulse. Restitution to longer eigenperiods reduces acausal effects but increases long period noise amplitudes.

alent to a baseline length of 210 m. Our results for the local tilt in table I should be compared to this value. At periods up to 5 min or so, the regional tilt is most conveniently measured as a differential vertical displacement between suitably spaced seismometers.

Finally, we note that the ratio D/C is the square of the angular frequency at which the horizontal accelerations (and hence output signals) produced by tilt and displacement are equal. The corresponding crossover period, $T_c = 2\pi\sqrt{C/D}$, is also listed in table I.

6. Results

Table I gives a summary of our results. The data sets are characterized by the station code (FOS or SLO), year, and instrument. FOS is the «huddle test» station at the upper end of the Fossetta and SLO is displaced 66 m towards the craters (N30°W) from FOS. Data are essentially synchronous within each section of the table, except for short time intervals where individual instruments were disturbed. The numerical entries are explained in the caption.

As a general result, our T_c values show that the contribution of tilt to the horizontal seismic signal is significant. A separation of displacement and tilt is mandatory even if one is not interested in the tilt as such but in the magnitude and waveform of the seismic displacement. In our data the tilt signal typically predominates at periods longer than 50 s. (For other situations, the crossover period can be predicted from the Mogi model). For most events the energy of the residual in eq. (5.1) is less than 5% of the energy in the band-pass filtered version of s_x. In the average over all events within the 5% limit, the residual is about 2%; if we set the limit at 25% residual energy, thus using the vast majority of all recorded events (table I), the average residual is still only 5%. An inspection of the events with large residuals shows that these overlap with other events or have an insufficient signal-to-noise ratio, but do not violate the assumptions on which eq. (2.4) is based. The quality of the fit does not depend on the amount of tilt in each data set, indicating that we have correctly modelled the waveform of the tilt signal.

While the displacements seen by different instruments at the same site agree closely (fig. 6), the observed tilt scatters considerably around the regional value. This is not an instrumental problem but caused by local heterogeneity and imperfect ground coupling. We will discuss this in the next section. Despite the scatter in the magnitude of the tilt, its direction is generally close to that of the seismic displacement and to the radial direction from the craters (N150°E).

Apart from the locally disturbed tilt, all observations can be explained with Mogi's source model. The best overall agreement is found for an assumed source depth of 135 m relative to the station and a horizontal distance of 600 m. However, what this means in the real topography is not clear. The source appears to be near or slightly beyond the most distant crater (Zolfo) in direction to the Sciara, and close to the local surface. This agrees quite well with other results (Neuberg and Luckett, 1996; Kirchdörfer 1996, 1999; Wassermann, 1997), all of which are however subject to systematic errors because of heterogeneity and topography. We should therefore not give too much weight to this coincidence and conclude only that the source of the tilt must be near the craters and shallow, and cannot be distinguished from the source of other seismic signals.

The peak amplitude of the radial displacement was typically about 25 μm in 1995, 60 μm in 1996, and another two or three times larger for the largest events in each series. By coincidence, one micrometer of radial displacement at a distance of 500 m corresponds to a volume displacement of nearly one cubic meter, according to eq. (3.2). The typical volume displacement was thus about 25 and 60 m^3, respectively. Within the framework of the Mogi model, this volume quantifies the expansion and subsequent contraction of the source cavity. This must be distinguished from the volume of material released from the cavity during the explosive process. One might conceive a purely hydraulic model where the cavity is filled with an incompressible fluid; then the contraction of the cavity must be associated with the release of an equal volume of fluid. It is however likely that the remaining source cavity is partially emptied by the explosion, so the amount of material released must be substantially larger, even when normalized to peak pressure.

On the other hand, there is no simple relationship between the seismically determined volume displacement and the amount of material thrown up at the surface. During the 1996 experiment, the surface activity was unusually low, and only a few weak explosions per day could be visually observed. Nevertheless the long-period seismic events were as frequent as ever (about 250 per day) and substantially stronger than in 1995. It appears thus that in 1996, most of the material driving the seismic source did not reach the surface, or escaped inconspicuously as gas. At other times, it has been possible to correlate nearly all seismic events with visible explosions (Schick and Mueller 1988).

7. Tilt-strain-coupling

In the 1995 experiment, the tilt of the CMG-3T at FOS was three times smaller than predicted by the Mogi model while the tilt of the STS-2 at the same site was four times larger. This made the horizontal records look totally different at long periods (fig. 1). In the 1996 experiment the STS-2 seismometers were installed in stainless-steel containers; the agreement between the instruments was then much better and no systematic difference between the Guralp and Streckeisen sensors remained. The scatter in the tilt measurements must be due to local, small-scale tilt produced by the seismic strain in the heterogeneous ground. Strain-tilt-coupling is well known from the study of tidal tilts (Harrison, 1976) but not normally seen at seismic frequencies because the effect of tilt is generally small there, except near the source. The intensity of strain-tilt-coupling is usually expressed as a numerical coupling factor relating the magnitude of the tilt to that of the causing strain (both quantities being dimensionless small numbers). As estimates for the «regional», *i.e.* uncontaminated strain and tilt we take the differential displacements between stations FOS and SLO, divided by the distance between the instruments. We then need coupling factors up to 0.3 to explain the observed local tilts, except the large tilt of FOS 95 STS-2 that is apparently due to an improper installation. Harrison (1976) finds coupling factors of this magnitude by finite-element calculations for realistic situations. From the fact that the local tilts are incompatible between the 1995 and 1996 experiments at the same site we conclude that most of the local tilt is controlled by the installation procedure; the enhanced tilt in four out of five FOS 1996 data sets may indicate an additional site effect.

8. Conclusions

We have shown that broadband horizontal seismic records of Stromboli's typical explosions are strongly influenced by signal-generated tilt, and we have developed a procedure by which the displacement and tilt components in the seismogram can be separated. The method is based on the assumption that all components of displacement have the same waveform, as expressed by eqs. (2.1).

Different instruments buried at the same site record the same displacement but different tilt. Even in our better data sets, the tilt amplitudes scatter by a factor of two between instruments and the tilt directions scatter by 25 degrees. We explain this by the occurence of local tilt that is generated by strain-tilt-coupling at the interfaces between the walls of the vault, its filling, and the seismometer itself. Coupling factors up to 0.3 were observed even in those cases where we consider the installation procedure as correct. This problem is certainly not limited to seismometers or to seismic frequencies; it must also affect borehole-type tiltmeters in a volcanic environment.

In a period range up to 5 min or so, regional tilt and strain are best determined from the differential vertical and horizontal displacements between broadband seismometers installed a short distance apart. The individual measurements are precise enough to observe differential displacements over baselines whose length is a few percent of the epicentral distance.

Despite the complications introduced by heterogeneity and topography, the Mogi model provides a useful framework for an interpretation of long-period seismic displacement and tilt observations. Location, depth, and volume displacement of the source can theoretically be determined with a single three-component seismometer by comparing the magnitudes of displacement and tilt. In practice at least two seismometers are required in order to measure the regional tilt with sufficient accuracy. We cannot check the accuracy of our source location but the agreement with previous results suggests that the systematic errors in our method are comparable to those in the classical seismic network methods.

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