CHAPTER FIVE

K-ω MODELLING OF VLP SIGNALS AT STROMBOLI VOLCANO

5.1 Introduction

In this Chapter the modelling technique derived in Chapter 4 is applied to the VLP signals recorded at Stromboli. A vertical conduit is assumed, which lies directly beneath the vents. A conduit of up to 700 m in length is considered, since this was the depth of VLP phases found by *Luckett* [1997]. All other results indicate a somewhat shorter conduit [see Chapter 2].

5.2 Modelling parameters

The modelling parameters for Stromboli used in this chapter were discussed in Section 2.5. A summary is presented in table 5.1.

	Symbol	**Value**
Geometry		
conduit radius	r_c	1 m
conduit length	l	100-700 m
Fluid Properties		
viscosity	η	1000 Pa s (magma), 0 Pa s (gas)
density	ρ_f	2500 kg m^{-3} (magma)
P wave speed	α_f	500 m s^{-1} (magma)
S wave speed	β_f	290 m s^{-1} (magma)
Solid Properties		
P wave speed	α_s	1700 m s^{-1}
S wave speed	β_s	1000 m s^{-1}
density	ρ_s	2700 kg m^{-3}

Table 5.1: Parameters used for modelling of seismic signals recorded at Stromboli.

5.3 Amplitude modelling

5.3.1 Introduction

The aim of amplitude modelling is to produce synthetic data that match the size and polarity of VLP phases that were recorded at each station for eruptions in 1995. The assumptions for this to work are:

1. Site effects do not significantly affect the amplitudes of the signals observed at each station.

2. The free surface does not significantly affect the amplitudes of the signals observed at each station.

3. The conduit is vertical and directly below the vents.

Since the deepest source indicated by previous work was 700 m [*Luckett*, 1997], conduits of lengths 100-700 m are considered for the modelling performed in this chapter. The longest duration of VLP phases was about 20 s, so most of the examples will use assume that the source acts for 20 s, though this does not affect the results (only viscous forces and dynamic pressure depend on the rate of magma rise).

5.3.2 VLP signals at Stromboli

During 1992 and 1995, very-long period (VLP) signals were recorded at Stromboli whenever an eruption occured from vent 1 (the south-west vent) or vent 3 (the north-east vent). For the 1992 data, the characteristic waveform of a vent 1 eruption was a W-shaped signal. For vent 3 a V-shape or U-shape was characteristic. To observe these VLP signals it was necessary to reconstitute the raw signal down to at least 30 s [see Chapter 2 for more details].

5.3.3 Amplitude data to model

12 hours of data recorded on July 7th, 1995, were analysed. The six largest VLP signals corresponding to eruptions at vent 1 were measured in order to determine maximum radial and vertical displacements at each seismic station [Fig. 5.1 and Table 5.2].

		Time (s)					
Station	Channel	4000	4200	21700	22540	27210	38140
195	N	-20	-24	-27	-31	-21.5	-23
	E	20	24	30	31	23.5	20
	R	28	34	40	44	32	30
	Z	8	9	10	11	8	9.5
196	N	?	?	?	?	?	?
	E	18	19.5	27	26	23	21.5
	R	?	?	?	?	?	?
	Z	7.5	6.5	9	10	7	8
197	N	-20	-20.5	-35	-31	-26	-19
	E	-18	-27	-24	-26	-16.5	-18
	R	27	34	42	40	31	26
	Z	8.5	8	11	12	9	11
198	N	24	24.5	36	40	30.5	28.5
	E	-17	-29	-40	-41	-29	-27.5
	R	29	38	54	57	42	40
	Z	8	8	10	10.5	8	9

Table 5.2: Maximum changes in displacement (in micrometres) indicated by vent 1 VLP phases recorded during first 12 hours of 7th July 1995. Radial components are computed as the vector sum of the north and east channels. These measurements correspond to the inflation phase that precedes eruptions at vent 1.

The results from a fifth station (201) are ignored here because the site was very noisy. In addition, the north channel of station 196 recorded noisy data making amplitude measurements unreliable, so the radial component of displacement for station 196 could not be computed. No data from 1992 were available to make similar measurements, though data given in a table by *Luckett* [1997] do indicate that a radial displacement of 20 μm was typical for VLP signals at station 197. In the modelling that follows only the four good 1995 stations are considered. Station positions are given in Table 5.3 and shown in Fig 5.2.

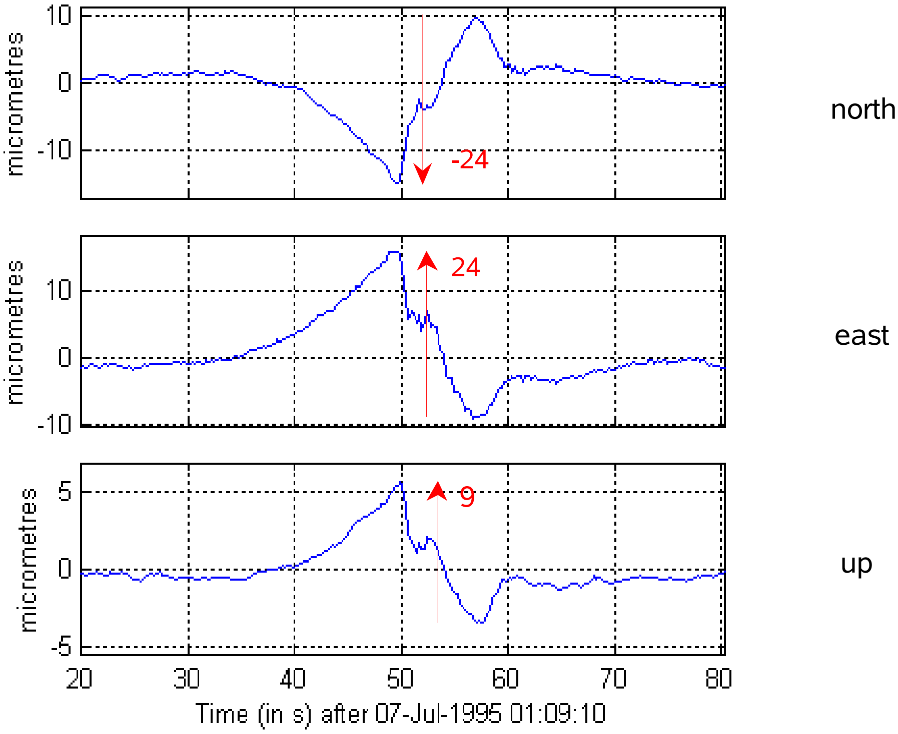

Figure 5.1: Three-component seismogram of VLP signals recorded at station 195 corresponding to an eruption at vent 1. Amplitudes tabulated in Table 5.2 are measured from minimum to maximum displacement. Station 195 is southeast of the vents, so in the top trace south is the direction of increasing displacement.

station	Radial distance from conduit (m)	Height above sea level (m)
196	210	830
197	397	864
195	563	741
198	703	733

Table 5.3: Position of 1995 seismic stations.

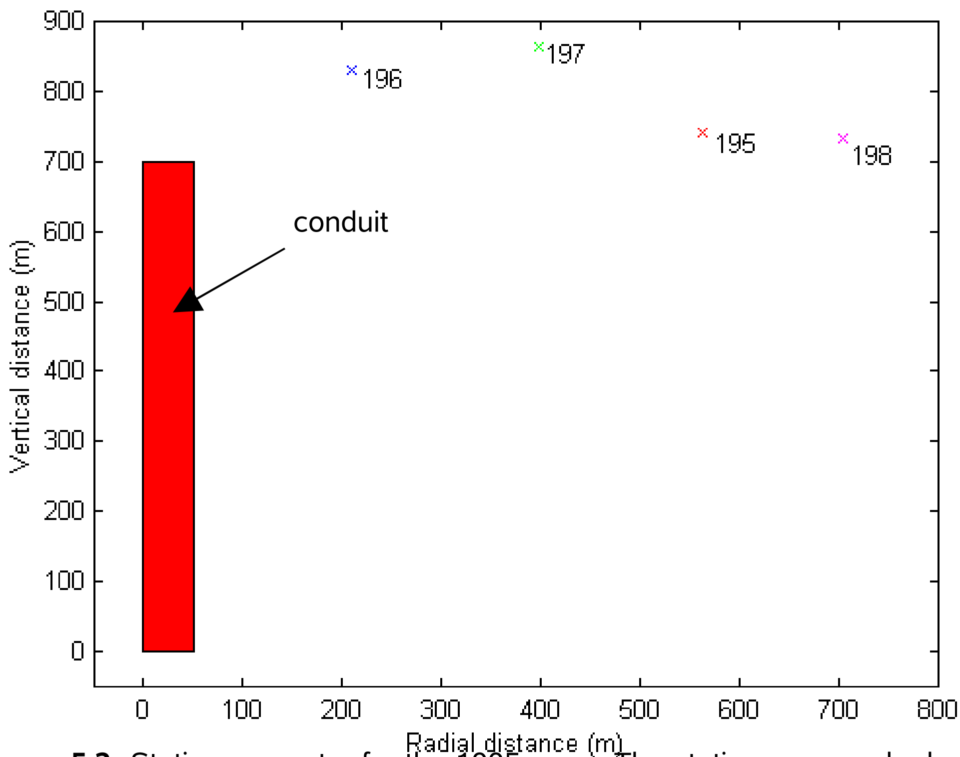

Figure 5.2: Station geometry for the 1995 array. The stations are marked with a cross which depicts the colour used on the synthetic seismograms that follow. For modelling, the upper end of the conduit is fixed at the vents (700 m above sea level) and the lower end of the conduit is varied, down to sea level.

Note that vertical displacements are almost the same at each station [Table 5.2]. Radial displacements increase gradually with station distance from the vents. The particle motion vectors at each station (for all events) indicate a contractive source with an epicenter near the vents.

Given the physical parameters presented in Table 5.1, the maximum radial displacements for the different source processes considered in Chapter 4 are computed. As will be seen, not all processes are capable of generating the displacements observed.

For most source types there is a family of models that will give the same result, as there is typically a trade off between pressure change and source radius [Section 4.5.2].

5.4 Results

5.4.1 Point source

Seismograms were computed corresponding to an implosive point source located at various source depths from 0-700 m below the vents. The source is activated after 10 s, and is a sustained source (step function) displacing a volume equivalent to that of a sphere of radius 5 m. The results for point sources at different depths were combined [Fig. 5.3].

Amplitude data shows that vertical displacements at each station should be about the same. This doesn't happen for a point source anywhere within 700 m below the vents, but the best match is obtained for a depth range of 300-350 m (height of 400-350 m above sea level). A depth of 350 m is the only depth for which radial displacements increase with distance from the vents indicating that the source is a point source 350 m directly beneath the vents [Fig. 5.4].

For a point source, seismic displacement is given by the proportionality:

$$u \propto \Delta V \qquad \textbf{(5-1)}$$

where ΔV is the volume displaced by the source (positive for explosion, negative for implosion). Using this equation, the results obtained for a source with an initial radius of 5-m can be scaled. This can be converted to pressure change, ΔP, by using 4-63:

$$\Delta P = \kappa_s \frac{\Delta V}{V_0} \qquad \textbf{(4-63)}$$

where V_0 is the initial volume of the source region and κ_s is the bulk modulus (incompressibility) of the solid and is given by:

$$\kappa_s = \rho_s \left(\alpha_s^2 - \frac{4}{3} \beta_s^2 \right) \qquad \textbf{(5-2)}$$

The parameters in Table 5.1 imply κ_s = 4.2 GPa. The source pressure computed is inversely proportional to the initial source volume. The product of pressure change and initial source volume is 2.2 x 10^{12} J. If the initial radius of the source is 5 m (a

Figure 5.3: Point source at different depths

Figure 5.4

conduit or bubble), 4-63 yields ΔP=4.2 GPa. If the initial radius of the source is 100 m (a magma chamber), 4-63 yields ΔP=0.5 MPa. A plot of initial source radius versus required pressure change is given in Figure 5.10.

These results agree with those found by the decay law modelling method in Chapter 3 for a point source at the same depth. This is encouraging, however, 1992 data were used in Chapter 3 whereas 1995 data were used in this chapter.

5.4.2 Line source

The presence of an ash cloud associated with eruptions at vent 1 suggests that the conduit supplying vent 1 becomes blocked between eruptions (it is also possible that the ash is primary). It seems likely that once this blockage occurs, pressure in the conduit begins to rise again until the yield strength of this cap rock is exceeded, at which point the cap rock fails and another eruption is unleashed. The rising pressure in the conduit can be modelled as a line source, if the dominant period of the waves of interest does exceed the time required for a pressure wave to travel the length of the conduit. The pressure rise may be due to advective overpressure [Section 4.4.5].

Seismograms for line sources from 100-700 m long were computed [Fig. 5.5]. The conduit radius was assumed to be 10 m with a pressure change of 7.5 MPa acting throughout the conduit. It is interesting to note that at stations close to the conduit, conduit length has little effect, whereas for the furthest station, radial displacements change by a factor of 5.

Radial displacements alone suggest a conduit length of at least 300 m, since real data [Table 5.2] indicate that radial displacements increase with distance from the vent. Vertical displacements are not well matched for any conduit lengths but are best matched for a conduit length of 700 m. However, a conduit length of 300 m is a good match for radial displacements at all stations, and vertical displacements at the three furthest stations. However the vertical displacement at the nearest has the wrong sign.

Figure 5.5

Displacements versus line source lengths

It may be justifiable to ignore the vertical displacement at the nearest station. The modelling technique assumes that pressure forces only act horizontally. However, in reality it is likely that the conduit narrows in the final few tens of metres, in which case there would a vertical component to these pressure forces. Stations near to upper edge of the conduit would tend to be displaced vertically upwards. Station 196 is in such a position [Fig. 5.2]. The vertical displacements far from the vents are less susceptible to these ‘end corrections’.

So there are two possible line source models. Assuming a conduit length of 300 m, and a radius of 10 m, a pressure change of 7.5 MPa [Fig. 5.6] would best fit the largest VLP signals observed. For a conduit length of 700 m, a pressure change of 4 MPa is required. Displacement is proportional to conduit cross-sectional area, so the pressure change required varies inversely with conduit radius squared [Figs. 4.6 & 5.10].

Conduit lengths greater than 700 m were not tested, but should be since the 700-m-long model proved to be one of the best models. This shortcoming will be rectified in further work.

Figure 5.5 shows an example of Gibb’s phenomenon which occurs because the saw-tooth shaped source function is discontinuous. Attempting to model this impulse with a finite frequency range produces oscillations which increase in amplitude as the discontinuity is approached. These oscillations become smaller as a wider frequency band is used. Measurement is not impaired though, since the mean value is independent of the frequency range used. It is the mean value that is discussed in the results above.

5.4.3 Rising magma with pressure gradient only

This is the first of four sections discussing the seismic displacements resulting from fluid rising up the conduit. As a first step, the conduit is assumed to be 700 m long.

Fig. 5.7 shows the seismograms that result when overpressure, dynamic pressure and viscosity are ignored. As the magma rises from a depth of 700 m the pressure in the magmatic system is constantly changing and this has very different results depending on the station locations. However, the vertical displacements are never in phase. Since for the observed data, vertical displacements are in phase, the

Figure 5.6

Line source results for a 300-m-long conduit

Figure 5.7

Amplitude modelling results for a pressure gradient source conclusion is that if rising magma (or gas) is the source of the VLP phases, the pressure gradient does not contribute significantly to the seismic wavefield.

5.4.4 Rising fluid with viscous effects only

Viscous forces arise in the fluid because the centre of the flow rises more quickly than the fluid adjacent to the conduit wall. These shear forces produce SV waves at the conduit wall. Seismograms computed for a rising fluid with only viscous forces considered (no pressure forces) show very large vertical displacements and small radial displacements. This is expected because viscous forces are vertically directed, whereas pressure forces are directed horizontally.

The vertical displacements are very similar at all stations during the entire time that magma rises from a depth of 700 m to the surface [Fig. 5.8]. Therefore they do not constrain the conduit length at all. Because the radial displacements are very small, pressure forces must also be considered. Vertical displacements for the VLP phases were approximately -10μm at all stations, which indicates magma descent. To produce this for magma falling from the surface to a depth of 700 m at a speed of 35 m/s, a viscosity of ~80 Pa s is required. Realistically, its unlikely that magma could drop at more than, say, 5 m/s. If it did this for 20 s (approximately the duration of the longest VLP phases) it would fall 100 m. In this case a viscosity of more like 4000 Pa s would be required. It is more likely that the magma moves even more slowly, and over less of a vertical range, so 4000 Pa s is a minimum value. This is already higher than values generally assumed for Strombolian magmas [Section 5.2]. The conclusion is that viscous forces do not contribute significantly to the VLP phases observed at Stromboli.

5.4.5 Overpressure

Results [Fig. 5.9] were calculated for a rising fluid which has only an overpressure component (this is reasonable if the overpressure is very large, and if density and viscosity are low). The conduit radius is 5 m, the fluid rises from a depth of 700 m, and the overpressure is 4 MPa.

The vertical displacements are only in phase for the upper 40 m of the conduit, but they do not have similar amplitudes, as required by the observed data. However, if

Figure 5.8

Viscous effects.

Figure 5.9

the vertical displacement at the nearest station is ignored, the radial and vertical displacements are quite well matched for a source between 525 m and 600 m above sea level. However, the radial & vertical displacements are all positive, so the sharp contractive motions of the VLP signals indicate fluid *descent*.

So consider a conduit with a radius of 10 m, and an overpressure of 4 MPa. For magma descending from a height of 600 m above sea level to 525 m seismograms were computed. These match the amplitudes of VLP phases quite well [Table 5.2]. Interestingly it has been reported that the magma level at the NE vent (vent 3) drops immediately prior to eruptions [*Neuberg*, pers. comm.]. For larger initial conduit radii the equivalent overpressure, ΔP, can be computed from:

$$u \propto \Delta P V_0 \qquad \textbf{(5-3)}$$

where u is seismic displacement and V_0 is the initial source volume. This is graphed for conduit radii of 1-100 m in Fig. 5.10. Conduit radiii less than ~ 15 m are ruled out for this source process since the overpressure required is too large.

5.4.6 Dynamic pressure for a rising fluid

If only the dynamic pressure of a rising fluid is considered, the resulting seismograms are identical in shape to those for an overpressure source [Fig. 5.9] but opposite in sign, and proportional to $0.5\rho v^2$ rather than the overpressure. The conclusions are therefore quite similar: only for the upper 40 m are the seismograms in phase. The sign difference means that a rising rather than falling fluid is indicated.

However, the dynamic pressure term is very small, because the mass flux, Q, at Stromboli does not exceed 1000 kg/s during normal activity [Chapter 3]. When this constraint is considered, dynamic pressure is maximised by minimising density. The dynamic pressure for a rising magma is given by Bernoulli's equation:

$$\Delta P = -\frac{1}{2}\rho v^2 \qquad \textbf{(5-4)}$$

For a rising magma pressure source, seismic displacement is given by the proportionality:

$$u \propto \Delta P V_0 \qquad \textbf{(5-5)}$$

Which gives:

$$u \propto \rho v^2 r^2 \qquad \textbf{(5-6)}$$

since the conduit is assumed to be cylindrical. Mass flux, *Q*, is the product of conduit cross-sectional area (πr^2), density, and velocity of the flow, *v*. Eliminating *v* gives:

$$u \propto \rho\left(\frac{Q^2}{\rho^2 r^4}\right)r^2 \propto Q^2 / \rho r^2 \qquad \textbf{(5-7)}$$

Therefore seismic displacement increases as density and conduit radius decrease. It is therefore strongest for gas issuing from a narrow vent. For a conduit with radius of 1 m, which matches that observed at the surface, a mass flux of 1000 kg/s and a density of 3 kg/m^3 (consistent with maximum ejection speeds of gas speed at Stromboli, of ~100 m/s [e.g. *Chouet*, 1974]), the dynamic pressure is only 15 kPa even for this 'maximised' case and the displacements predicted are several orders of magnitude too small. But a dynamic pressure of 4 GPa is required [Fig. 5.9], which is about 250,000 times larger than the maximum possible dynamic pressure at Stromboli. The Bernoulli effect can be ruled out at Stromboli.

5.4.7 Summary of amplitude modelling results

The four models most consistent with the amplitude data are:

1. A point source 350 m above sea level which displaces a volume of ~ 500 m^3.
2. A 300-m-long line source with its base at 400 m above sea level.
3. A 700-m-long line source with its base at sea level.
4. An overpressured magma that descends from 600 m above sea level to 525 m above sea level.

For each source type there is a trade off between initial source radius and the pressure change required to explain the VLP amplitude data [Table 5.2]. These trade-offs are plotted in Fig. 5.10. If 20 MPa is considered as an upper bound on pressure in the magmatic system [*Tait et al.*, 1989] then the minimum source radii for each source type can be estimated. For a point source this turns out to be 30 m, for a line source of length 300 m, 4 m, for a line source of length 700 m, 4 m and for an overpressure source, 13 m. It is unlikely that the conduit radius could exceed 10 m within the upper 200 m since thermodynamic arguments [Section 2.4] suggest a narrow conduit (~1 m). Therefore the overpressure source can be immediately ruled out. It is conceivable that there may be a small magma chamber at a depth of 350 m, since a shallow chamber has been indicated by numerous other studies [Section 2.4]. A conduit length of 700 m is marginally more likely than a conduit length of 300 m since (a) it requires a slightly narrower conduit to produce the same displacement and (b) the conduit radius is likely to increase with depth. So the source is either a point source, representing a shallow magma chamber, or a line source, representing a narrow conduit.

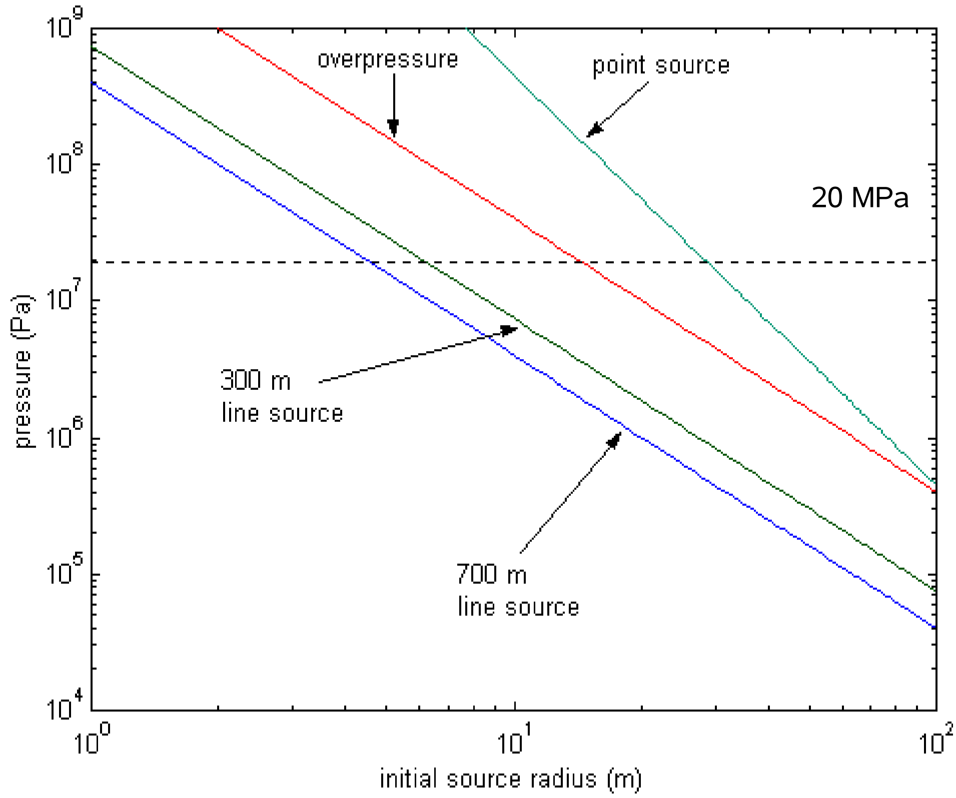

Figure 5.10: Plots of pressure required (in Pa) to match the maximum change of displacement observed for vent 1 VLP signals. Four families of source models are shown: a line source extending from 0-700 m below the vents, a line source extending from 0-300 m below the vents, overpressured magma moving from 100-175 m below the vents and a point source at a depth of 350 m. Pressures above 20 MPa are believed to be an upper limit in volcanic systems. This constraint implies a 700 m line source must have an initial source radius of at least 5 m. A point source must have an initial source radius of 30 m.

An interesting aside is that the product of pressure change and initial source volume for each source type is a constant, and can be interpreted as some measure of the energy of the source [Fig 5.10]. For a point source at a depth of 350 m the product of initial source volume and pressure is 2.2 x 10^{12} J. For a line source of length 300 m this product is 6 x 10^{11} J. For a line source of length 700 m this product is 3.8 x 10^{11} J. It is encouraging that these products are within a factor of 10.

5.5 Discussion

5.5.1 The notch phase problem

According to *Luckett* [1997] the W-shaped signal can be broken down into a underlying wavelet, with a period of 16 s, and a notch phase, with a period of 2 to 4 s. This underlying wavelet resembles the V- or U-shaped signal characteristic of vent 3 eruptions (which has a period of ~ 13 s) indicating they may have the same source.

Luckett [1997] found that the eruptions from vent 1 occured at the same time or shortly after the notch phase. His results suggest that a large pressure change occurs at a depth of 600 m below the vents < 2 s before material is ejected from the vent. Magma or gas cannot move from 600 m depth to the surface in such a short period of time, so there are three possibilities:

1. Some process occurs at a depth of 600 m, causes a large pressure change which generates the notch phase. A pressure wave from this disturbance travels through the magma column with a speed of at least 300 m/s, and causes the eruption.
2. The actual source of the notch phase is much shallower, perhaps as shallow as 135 m as indicated by the results of *Forbriger and Wielandt* [1997].
3. The notch phase and eruption are not related, though they may both be caused by some other process, occuring elsewhere, or at some earlier time.

Modelling, however, indicates an alternative solution that may account for the observations of *Luckett* [1997]. There is substantial evidence for a shallow magma chamber [Section 2.3], so the effects of this should be included in the line source model. Therefore, consider a conduit with a length of 600 m, radius 1 m, but at the base of this there is a spherical magma chamber whose radius is 100 m. Throughout this magmatic system, suppose there is a constant pressure change ΔP.

Results show that the contribution from the line source is very small, so in effect the conduit cannot be detected. So even though the pressure change occurs in the chamber *and in the conduit*, the hypocentre appears to be within the magma chamber. Results were computed for initial chamber radii of 1-100 m [Fig. 5.11] to see at what chamber radius the point source and line source would be of equal importance. This happens at an initial chamber radius of ~ 6 m.

The implication is that although the notch phase appears to have a location 600 m below the vent region, it does not necessarily indicate that the pressure change is concentrated at that depth. Instead it may indicate a constant pressure change throughout the magmatic system (which leads to failure of a cap rock) but that *the source appears to be much deeper because there is a magma chamber at 600 m depth*. This model could explain why the notch phase is observed almost simultaneously with eruptions at vent 1: the notch phase itself originates when the pressure drop caused by failure of the cap rock has been communicated to the magma chamber, which might take as much as a few seconds, depending on the amount of bubbles in the conduit. The eruption would be observed a short time after the cap rock failed, depending on how deep the cap rock was.

However, a magma chamber at a depth of 600 m is not consistent with amplitude modelling results [Section 5.4.7]. So if this combination of a line source and point source is applicable then either the point source is at a depth of 350 m, implying that the source location results of *Luckett* [1997] are wrong, or the point source is at a depth of 600 m, implying the amplitude modelling results are unreliable. In either case, it is possible to generate a strong seismic phase at approximately the same time as the eruption is observed. This seismic phase corresponds to the decompression wave reaching the magma chamber, which acts as a strong seismic source because of its large radius relative to the conduit.

Figure 5.11: Point-line results.

5.5.2 Waveform modelling

Waveform modelling, in which the aim is to match the waveform recorded at all stations, was not attempted at the outset because it is a much more complicated problem, and would require too much time. However, amplitude modelling has eliminated various sources, so that now pressure gradient, viscosity and dynamic pressure can all be ignored.

VLP signals show the same waveforms at each station, and modelling has shown this can only be produced by point sources and line sources, therefore the more exotic sources involving descending magma can be discarded. For point sources and line sources, the seismograms have waveforms which are identical to the source function. This means that the source function must have the same shape as the VLP signals. (Many would be quick to make this assumption anyway, although the modelling in this thesis has shown this is not generally true). Therefore waveform modelling has nothing further to teach us about VLP signals; instead we need to model more complex fluid processes which will lead us to an understanding of the source function itself.

It may seem that the work on rising magma has little application then, because it always leads to signals at each station that are somewhat different in waveform, indeed sometimes completely out of phase, and vastly different in amplitude, and such signals are rarely seen. However, one application may be to even longer period (100-1000 s) signals observed at Stromboli. Though these ‘signals’ are probably just noise, it is possible that they may be due to magma migrating throughout the feeding system. As modelling has shown, such signals would appear to be incoherent – that is they would resemble noise. The difficulty is that this is a continuous signal, and therefore it is difficult to choose of segment of this signal for modelling, and also that the feeding system is very poorly known. Perhaps in the future, ultra-long-period phases will be identifiable with magma moving through different parts of the feeding system.

5.6 Conclusions

The modelling techniques employed in this chapter were used to estimate pressure changes associated with volcano-seismic signals. Both near and far field terms were considered. Modelling has been applied to the VLP phases observed in broadband seismic data from Stromboli, acquired in 1995. The models most consistent with observations are:

1. A shallow magma chamber, approximately 350 m beneath the vent region.

2. A cylindrical conduit extending from a vent to a depth of 300 m below the vents.

3. A cylindrical conduit extending from a vent to a depth of 700 m below the vents.

For each of these models it was found that the pressure change and initial source volume are inversely proportional. Unfortunately there are no independent measurements of conduit or chamber radius so it is impossible to estimate the pressure change. Pressure changes of more than a few MPa seem unlikely though, which suggests the conduit must have a radius of at least 10 m. The point source model requires the largest pressure change, but the existence of a shallow magma chamber has been suggested by many studies [Section 2.4].

It is reasonable to assume that eruptions from the south-west vent (vent 1 which leads to W-shaped VLP phases) are due to failure of a cap rock. Also the continuous activity at Stromboli suggests that the magmatic system extends to a depth of at least several kilometres (there needs to be a big enough volume of magma to have fed the activity for the past 5000 years). Bearing these points in mind, and the results of amplitude modelling, what are the possible geometries for the magmatic system?

One possible geometry for eruptions from the south-west vent is a spherical magma chamber centred on a depth of 350 m, connected to the vent by a cylindrical conduit. Another conduit or system of conduits connects this chamber to some deeper source, but this plays no part in the generation of VLP signals, except for the possibility that injection of new magma to the shallow chamber may cause eruptions. When the cap rock (or skin) fails, a decompression wave travels from the vents and is reflected either at some constriction in the conduit, or at the base of the magma chamber. The wave is reflected again when it reaches the vents. With each passage of the wave, the pressure in the region between these two reflecting boundaries decreases.

A constriction in the conduit acts as a strong reflection boundary because the impedance increases. In this case, the pressure drops only in that section of conduit between the vents and the constriction. This corresponds to a line source model.

If there is no constriction in the conduit, the decompression wave travels into the magma chamber, which acts as a strong seismic source because of its larger radius, and the wave is reflected at the base of the chamber, where again there is a large impedance increase. If the chamber radius is more than ~6 times the radius of the conduit, the point source (chamber) dominates over the line source (conduit) to such an extent, that it appears as if there is only a point source.

Since amplitude modelling results are not consistent with a point source at a depth of 700 m, we assume that a line source of 700 m corresponds to a conduit with a constriction at a depth of 700 m. Below this constriction there may be a magma chamber, or perhaps the conduit gradually widens with depth – VLP phases tell us nothing about this region.