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Time Comparisons between Video and Seismic Signals from Explosions in the Lava Lake of Erebus Volcano, Antarctica

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Abstract

Sixty eruptions were recorded from a TV camera on the crater rim, and a 9 station seismic net and 2 infrasonic microphones on the mountain, to test a previous result that eruptions were being triggered by separate earthquakes of depth up to 4 km. The recording period was 16 December 1986 to 7 January 1987.

The seismic waveforms of similar large explosions were closely identical, and after stacking to improve the signal to noise ratio, plots of seismic arrival time versus distance from the eruption site showed that the seismic intercept time was 1.43 ± 0.06 s later than the TV explosion time, and the apparent velocity was 4060 ± 92 m/s. This velocity was much higher than that used for focal determinations (2.1 km/s), and it appears that the errors in reading emergent onsets, plus an erroneously low velocity, were responsible for the previously published pipe-like distribution of explosion earthquake hypocenters extending to 4 km depth. If so, the visible explosions were the source of the seismic waves.

Explosions were occurring from areas of 2 to 10 m across in the incandescent or convecting part of the lava lake, and were preceded by updoming for about 1 s. All eruptions ejecting bombs caused earthquakes, but ash eruptions from vents outside the lava lake were almost aseismic. Ejection velocities of bombs calculated from flight times ranged from 10 to 76 m/s. The fastest bombs followed an incandescent ash front expanding at up to 160 m/s. The highest velocity of bombs ejected without ash was 35 m/s.

All bombs thrown out of the crater were highly vesicular. Relevelling after explosions took 3-8 s the few times it was seen. More frequently, there was an upwelling at the site 8.8 ± 1.6 s later. This indicates a viscosity of ca. 10^4 Pas. High enough for the lava foam itself to explode.

1. Introduction

Erebus volcano of 3794 m elevation is situated at 77.5 deg. S, 167.1 deg. E on Ross Island (**Fig. 1**) near the western shore of the Ross Sea, Antarctica. It has a unique combination of a high latitude location within a tectonic plate, and an active lava lake of phonolitic composition. Though in an aseismic region[7], more than 100 volcanic earthquakes per day occur in the energy range 0.2-200,000 J (M-2 to 1). The largest accompany the 3.6 ± 2.7 strombolian eruptions per day observed in the summer seasons[3].

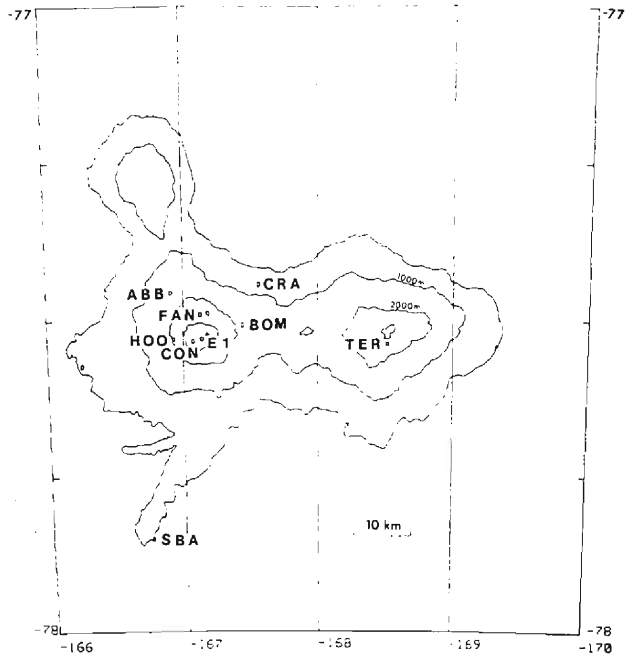

Fig. 1 Map of Ross Island, Antarctica, showing the seismic telemetry stations (small rectangles) and the Scott Base (SBA) recording station. ABB is Abbotts Peak, BOM is bomb site, CON is Truncated Cones, CRA is crash site, E1 is a primary trig station, FAN is Fang Ridge, HOO is Hoopers Shoulder, TER is Mount Terror. The crater of Erebus is marked by a star near E1. Graticule is degrees south and east.

During enhanced activity in 1984[4], eruptions peaked at 30 per day, with M up to 2.4, and infrasonic energy up to 10^9 J, and bombs averaging 2.4 m across were thrown up to 800 m above the lava lake (W. C. McIntosh, personal communication 1987).

From 1980 to 1986, the International Mount Erebus Seismic Study (IMESS) involving USARP, JARE, NZARP and VUWAE, was cooperating in running a telemetry network of geophones, infrasonic microphones, and a magnetic induction loop on the volcano. Although powered by solar cells and Gelcell batteries, data was collected 9-12 months of the year.

A consistant result of the focal determinations[14,10,17,8] has been a spread of 4 km in depth for earthquakes accompanied by eruptions, leading to the hypothesis that eruptions were triggered by separate earthquakes as deep as 4 km. Concern about uncertainty in the velocity structure, and consequent errors in the focal positions led to large test explosions being fired[12]. The revised velocity structure was 1.5 km/s at the surface, increasing linearly to 6.7 km/s at 9 km depth, and constant below that to the M-discontinuity. The distribution of foci in depth was hardly changed by the revised velocity structure.

Residual doubts led the senior author to propose TV monitoring the eruptions against accurate time, to see if they occurred later than the earthquakes, as required by the triggering hypothesis. This began on 16 December 1986, and with the IMESS data until 7 January 1987 when IMESS was dismantled, provide the data for this paper.

2. The equipment

A mixture of very special equipment to withstand the long cold winter night on the mountain, and VHS home-video equipment to reduce cost at Scott Base recording station, was employed. On the mountain, a Philips CCD video surveillance camera (Pal type-LDH 0600/00 with 16 mm auto-iris lens) was mounted in a rugged alloy box and tripod at the crater rim (**Photo 1**), and connected to a Broadcasting Corp. of N. Z. transmitter (BCTTX, 300 mW SSB, Ch 9) by 250 m of PE sheathed coaxial cable. Dual Yagi antennae were used with dipole covers. Power was from eight 40 AH 12 V gelcell batteries, and a 42 W Solarex panel, placed midway between the camera and transmitter, and connected by heavy TRS cable. The long distance between camera and transmitter was necessitated by the sight lines to the lava lake (**Photo 2**) and Scott

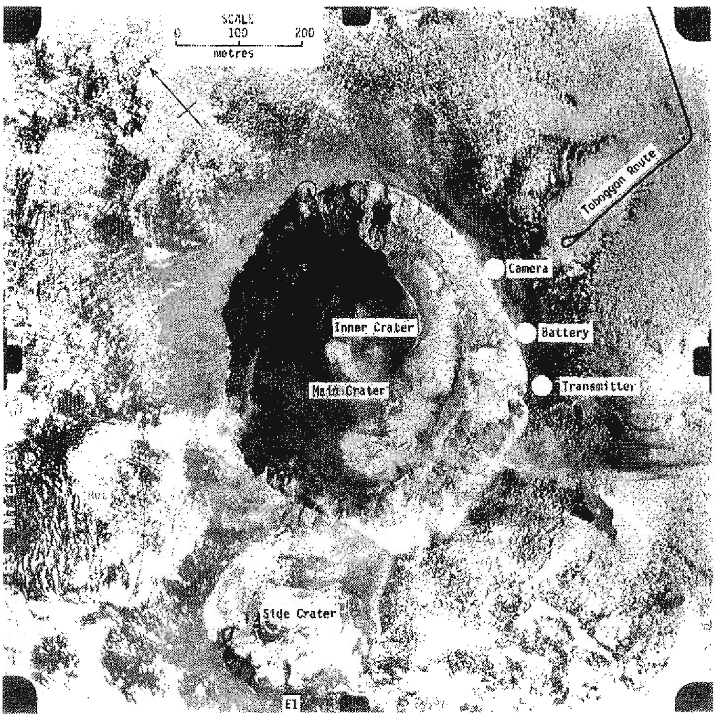

Photo 1 The TV camera mounted on the east rim of the main crater of Erebus volcano.

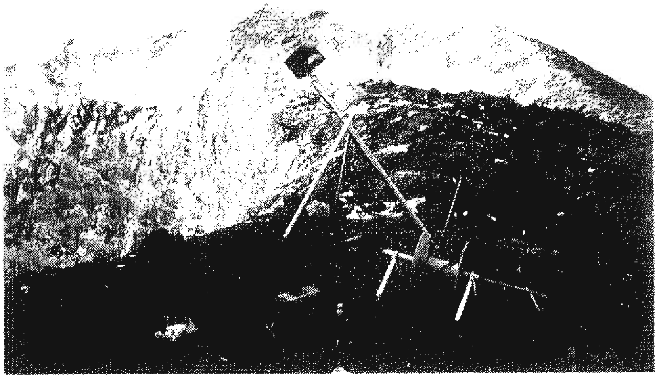

Photo 2 Vertical aerial photo of the main crater of Erebus volcano, showing the positions of the TV camera, power supply, and transmitter, in relation to the inner crater and lava lake. The main creater is 550 m across.

Base 37 km away. The cables were buried under old bombs to protect them fror fresh hot ones.

The total power requirement of only 3.5 W made continuous operation possibl over 9 months of the year, even with a low voltage off-switch to protect the batter from total discharge during the long winter night. All the components on the mountai were tested to −40°C, but the Achilles Heel proved to be the soda-glass window c the camera-box, which was corroded by the volcanic gas from the crater, and graduall became opaque.

The TV receiver and video-cassette recorder at Scott Base were standard hom appliances, modified slightly to connect in a FOR-A time code generator. The FOR- unit was modified so that it was reset every hour by the seismograph clock pulses.

Table 1 Locations of seismic telemetry stasions, and slant distances to the Erebus lava lake.

Station	Latitude deg. min.	Longitude deg. min.	Height m	Slant dist. m	Equipment
Lake	77S31.62	167E09.87	3580	0	Lava lake
E1	77S31.84	167E08.43	3713	723	SPZ LPH IFS
CON	77S32.05	167E04.44	3476	2332	SPZ IFS
FAN	77S29.53	167E07.54	2687	4099	SPZ
HOO	77S31.90	166E55.94	2121	5824	SPZ
BOM	77S30.54	167E26.41	2012	7136	SPZ
ABB	77S27.42	166E54.55	1789	10120	SPZ
CRA	77S26.67	167E33.55	830	13545	SPZ
TER	77S32.40	168E30.90	3158	32690	SPZ
SBA	77S51.02	166E45.37	6	37557	SPZ

The tapes were analysed on home video equipment, using frame by frame advance to obtain the TV eruption time, and fast search to locate eruptions and study lava dynamics. Time lapse video recorders could not give sufficient time resolution, and continous recording used too many tapes, so one tape per day was programmed to record in the early morning (14-18h UT) when eruptions are most frequent[3].

The seismic telemetry equipment of the International Mount Erebus Seismic Study (IMESS) has been described by Kienle et al.[10]. In 1986 it consisted of 9 short period vertical geophones (SPZ, To = 1 s) at stations listed in **Table 1**, and shown on **Fig. 1**, and **Photo 1**, and infrasonic microphones at stations E1 and CON. A long period horizontal (LPH, To = 4 s), oriented radially to the lava lake, was added at E1 in December 1986, to aid interpretation of the TV data.

3. Video observations

The eruptions recorded on video-tape are listed in **Table 2.** Apart from the slow convective motion of the lava lake, there were four types of eruptions, based on intensity and temperature:

1 Strong explosions of incandescent ash and bombs from the lava lake.
2 Medium explosions of incandescent bombs from the lava lake, but with no ash.
3 Weak explosions from the lava lake, in which an incandescent bubble domes up, ruptures, and folds back, with few of no detached bombs.
4 Nonexplosive eruptions of dark ash from vents beside the lava lake.

3.1. Incandescent ash explosions

Twelve of these were video-taped. Typically they occurred when the lake was not convecting. The glowing center of the lake began to bulge up and glow brighter 1 ± 1 s before the explosion. Outburst from an area of 4-10 m diameter was sudden and variable in direction, with the incandescent ash front expanding at up to 150 m/s (**Fig. 2**). Bombs followed immediately at initial velocities of 37-71 m/s, as determined from their flight times, assuming ballistic trajectories.

No obvious hole in the lake was visible when the ejecta had departed, but in two cases, inward motion of the lake towards the eruption site was visible for 3-7 s. In 6 others, a weak resurgence occurred in an area a few metre across 8.8 ± 1.6 s after the explosion.

Then the lake surface began to flow away from the camera (i.e. NW) into a grotto under the skin of the surrounding lake area for a few minutes, before reversing, and flowing strongly towards the camera at 20-30 metre/minute as an expanding lobe, for up to half an hour.

An exceptional event of incandescent ash type occurred at 08h50 m UT on 1 January 1987. Two bulges 15 m apart began to form on the lava lake, and over 25 s, grew to 9 m diameter. Three explosions suddenly occurred within one second, two from sources hidden behind the right hand bulge, and one from the right bulge itself. The left bulge then rapidly deflated without exploding. The event demonstrated that

Table 2 List of eruptions on video-tape, 1986/87.

Date	Time UT	Type	T/C /Dur	Rebnd time	Vent diam	B'ble diam	Bomb vol	Bomb time	Vel m/s	Bulge time	Rem
			s	s	m	m	m^3	s		s	
16/12	0820	4	28								makes wind
〃	1008	3	—	5							cloudy
〃	1207	3	—	5	4	10					
〃	1955	1	3-4	—	8	20		11.6	57	2	a/flow
17/12	0421	2	4ca		5	13		6.2	31	4	a/flow
〃	1420	2	4	—	8	20		6.1	30	1/4	a/flow
〃	1500	3			5	10		2.8	14		
〃	2034	1	—	10	4			9.0	44	1	a/flow
〃	2329	1	8	—	4			10.0	49	1	a/flow
18/12	0804	2	2?	—	10	20		8.1	40	1/2	a/flow
19/12	1417	2	—	—	4	6		1.8	9		
〃	1432	3			2	3					back wall
21/12	0646	4						9.0	44	1/2?	black
〃	1139	3			2	6					polyp
〃	1415	3			4	8					
〃	1417	3			6	9					
〃	2320	1	—	8				14.5	71		cloud
22/12	1042	3	4ca	—	7	15		4.2	20	1/4?	a/flow
〃	2345	3			5	10		2.8	14		
23/12	1621	2									obscured
26/12	0230	3									cloudy
27/12	1543	3				10					cloud
〃	1908	3				8					double
28/12	0142	2	—		4	12		7.5	37		ash
〃	0222	3			3	7					cloudy
〃	0449	3			3?	10		3.4	17		
〃	0601	4	18								LHV
〃	0630	3			3	8		1.8	9		flow
〃	0643	1	—	10	6	10+		11.3	55		a/flow
〃	0717	3				6		2.2	11		flow
〃	0738	3						1.8	9		cloudy
〃	0942	1	—	9	8	10+		13.0	64		raft
〃	1005	4	24								bombs. LHV
29/12	0827	3	—	5	4	7		1.2	6		
〃	0905	1	—	10	5	20		10.5	51	1/2	a/flow
〃	1159	?									obscured
31/12	2315	4									MV
1/1	0239	4									L & MV
〃	0710	1/2			3	6					double
〃	0850	1/2	—	—	3	9		14-15	75?	25	quad
〃	1107	3									
〃	1712	3			4	13				1	
〃	2233	1	—	—	4	12		9.8	48	1/4	

2/1	0243	1			4	10		7.5	37	misty
3/1	0000	3								cloudy
〃	0129	3			3	7				
〃	0137	3								cloudy
〃	0221	3				9				cloudy
〃	0407	2						13.2	65	obscure
〃	1538	2	3	9	4	12		9.3	46	subsides
〃	1643	3				12		2.4	12	misty
〃	1934	2	—	10				9.3	45	misty
4/1	0043	3				10		2.4	12	
〃	0056	3				4	8			
〃	1250	3	—		12	15				bright
〃	1317	2						6.1	30	cloud
〃	1403	3			5	10		2.2	11	bright
5/1	0101	3			4	10		3.2	16	
〃	0348	1	—	6	4	13		11.7	57	misty
〃	0709	3	long		5	8		1.9	9	flow
〃	0723	3			3	8		1.6	8	drains
〃	1717	2								fume
〃	2330	3	1		4	5		1.3	6	polyp
6/1	0131	3				7				
〃	0229	3				7				
7/1	0056	2	—	—	6	15		7.6	37	hole

Legend: T/C /Dur=Time constant or duration. Rebnd=Rebound. B'ble=Bubble. Vel=Velocity of ejection. Rem=Remarks. a/flow=afterflow. LHV=Left hand vent. quad=4 simultaneous events.

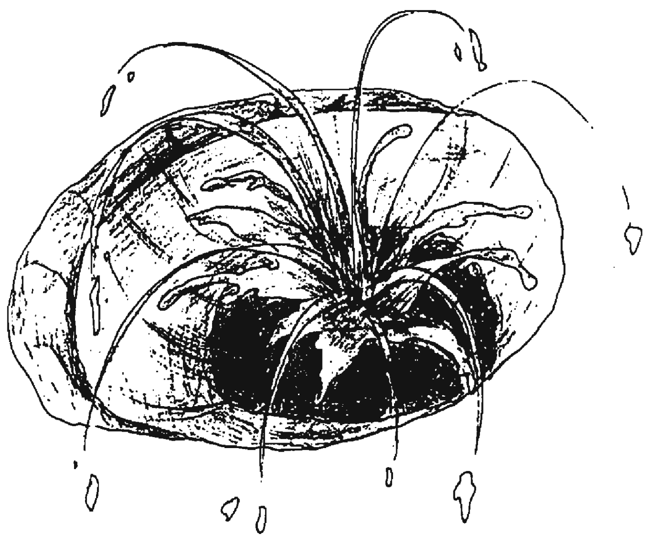

Fig. 2 An illustration from the TV recording of a strong explosion of incandescent ash and bombs from the lava lake.

the entire area of the lava lake could be pressurised simultaneously as though by a rising bubble of diameter equal to that of the lava lake.

3.2. Strong explosions without ash

Twelve of these were video-taped, but four were more or less obscured by cloud. Clean bombs were ejected at 9 to 65 m/s, with a mean of 37.0 ± 13.6 m/s. Three events were followed by lava flows, one (at 15h38m UT on 3 January 1987) by a small subsidence or drain back within the lake, and one (at 00h56m UT on 7 January) caused a hole in the lake 6 m across, into which a slab of dark skin toppled about 30 s after the explosion. Two were followed by resurgences 9–10 s later.

3.3. Weak bubble bursts

These were of two varieties : Bubbles which burst open, and were laid out away from the site (23 events) ; and bubbles which punctured and collapsed on top of the site (11 events).

3.4. Dark ash eruptions

Five were video-taped, coming from 2 of 3 vents in the inner crater floor on the SE side of the lava lake. In 3 cases a strong jet was erupted, and in the event at 10h05m UT on 28 December, some incandescent bombs were also ejected. They bounced as if they were solid, unlike the bombs from the lava lake, which neither bounced nor splattered.

4. Seismic and infrasonic data for incandescent ash explosions

The seismograms of 5 of the explosions were closely identical at a given station (FAN in **Fig. 3,** and ABB in **Fig. 4**), and excepting that at 08h50m on 1 January 1987, when 3 explosions occurred in one second from different places in the lava lake, the others were nearly the same. The differences were most apparent (**Fig. 5**) on the long period horizontal seismograph at the closest station E1, and related to small low frequency motions preceding the large high frequency motion by about 1 s. The infrasonic signals recorded on the microphone at CON (**Fig. 6**), which is at an effective ray path distance of 2.6 km, were also identical. The waveforms have been time shifted so they match down the page. The TV explosion instants are accurately marked on each record, and their misalignments are within the error of determination (0.04 s).

Earthquake seismologists are aware that identical seismograms for different events recorded at the same seismograph are rare, inspite of the common response of the seismograph and surrounding earth structure[16]. Prospecting seismologists are aware that exactly repeated shots produce identical waveforms at the same geophone site, and systematically varying waveforms along a spread of geophones. The later also occurs if a spread of shots are recorded at the same site. Marine reflection seismologists are aware that changing only the source function can cause considerable changes in the

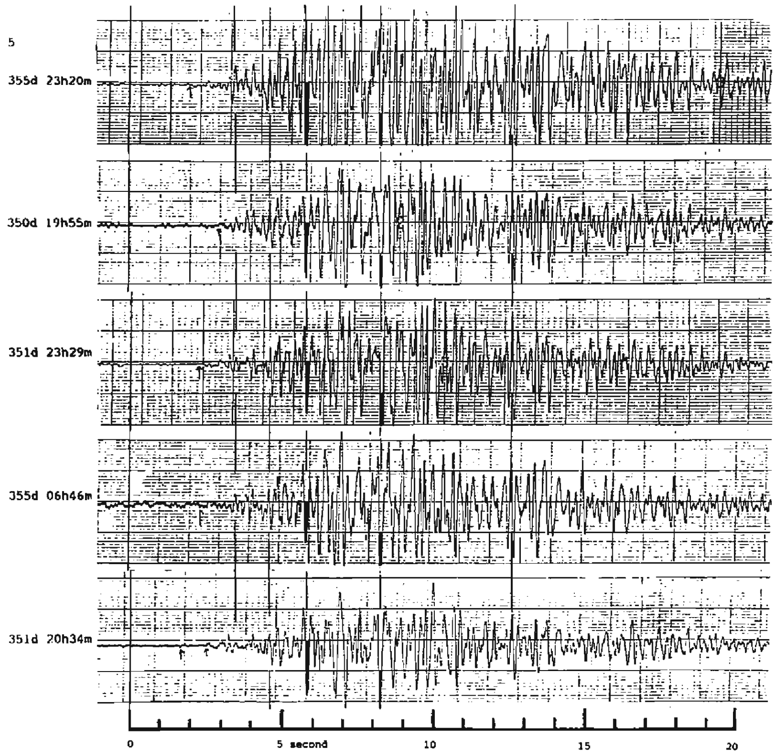

Fig. 3 Identical seismograms of explosions of incandescent ash and bombs from the Erebus lava lake, recorded at Fang Ridge (FAN) 4099 m distance. Prominent excursions have been inked in to aid aligning the seismograms. The TV eruption instant has been marked on each, and defines the zero of the time scale. Event times from the top are: 1986, 355d 23h20m, 350d 19h55m, 351d 23h29m, 355d 06h46m, 351d 20h34m.

waveform.

Thus, identical waveforms imply that source function, transmission channel, and recording characteristic remain closely the same. Identical seismograms for different events have been reported for both tectonic[16),6)] and volcanic earthquakes[4),11)], and exactly repeated sources are a likely phenomenon in long lived 2-phase fluid systems such as lava lakes.

In the present investigation, identical waveforms are regarded as evidence that the sources have the same location and mechanism, and that stacking the waveforms will enable more accurate arrival times, and hence locations of the repeated sources to be obtained. Second order differences between the waveforms are regarded as evidence of small differences in location and mechanism, especially in regard to the initiation of the event.

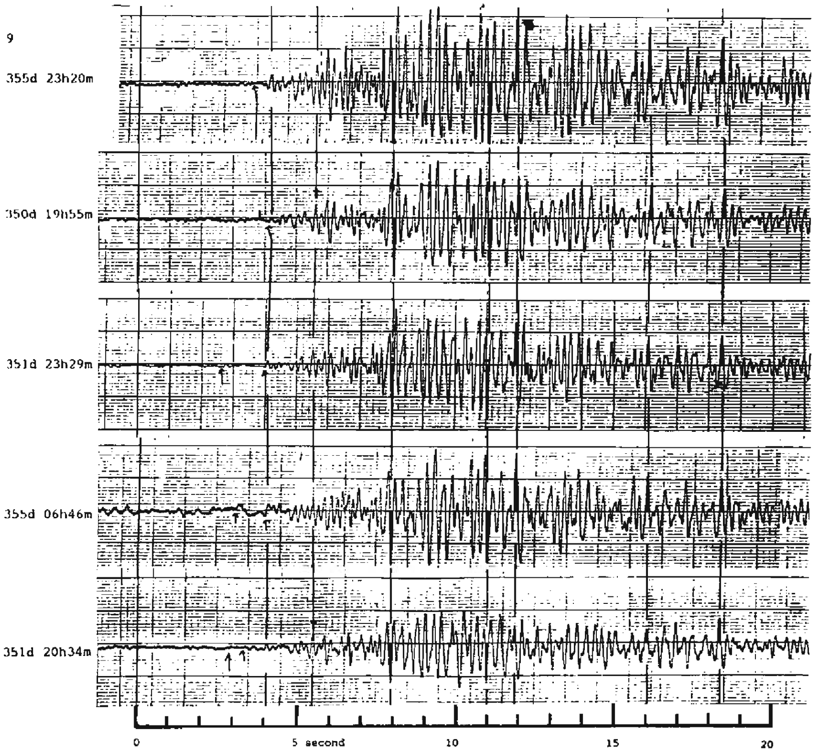

Fig. 4 Identical seismograms of explosions are in Fig. 5, but recorded at Abbotts peak (ABB) 10120 m distant.

The earliest points on the records at which similarity was evident were marked, and the times read for event 355d 23h20m, which gave the clearest records. A plot of arrival times versus slant distance from the lava lake (**Fig. 7**) shows a single line with intercept time 1.43 ± 0.06 s later than the TV time, and velocity 4060 ± 92 m/s. The velocity of the surface layer defined by the TV and E1 time is 460 m/s.

The stacked velocity was higher than that from the initial arrival time readings of any of the individual events. By plotting amplitude against apparent velocity for each event, it was shown that the apparent velocity increased with amplitude up to a maximum near 4 km/s, and then decreased again for larger amplitudes. The decrease at small amplitudes is normal for emergent onsets due to late readings at distant geophones. The decrease for large amplitude is explained by the small forerunners showing up at only the closest stations, and giving early arrivals there.

To check the TV explosion time, the travel time of the infrasonic wave to E1, calculated from the theoretical velocity and the expected (but unknown) ray path via a reflection from the back wall of the crater, was subtracted from the infrasonic arrival time. The result was 0.3 s later the than TV time, but confirms that the eruption did not

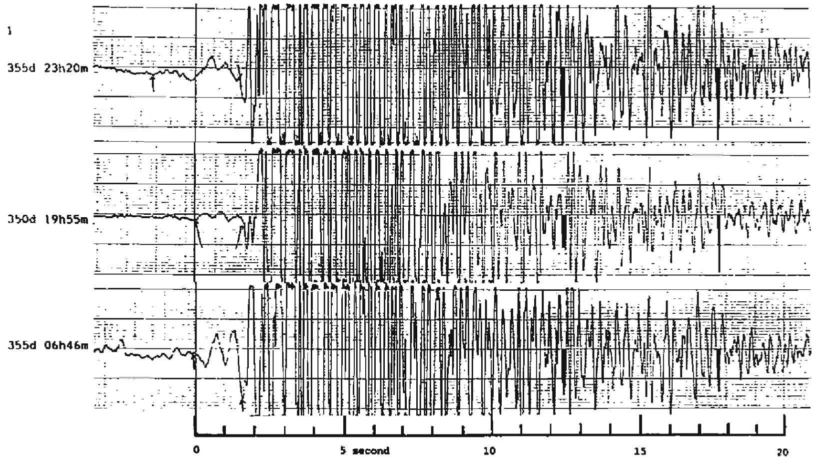

Fig. 5 Seismograms of explosions as in Fig. 5, but recorded at the nearest station E1, 723 m from the lava lake, by a long period horizontal (radial) seismometer. A low frequency forerunner of small amplitude is visible which is not identical for all events. It accompanys the upbulging of the lava lake proir to explosion. Event times from the top are: 355d 23h20m, 350d 19h55m, 355d 06h46m. The seismometer was tilted off scale during the other two identical explosions.

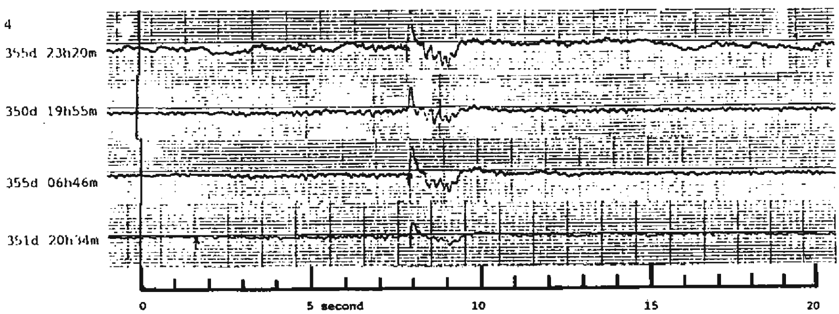

Fig. 6 Identical infrasonograms of the explosions in Fig. 5, but recorded on a microphone at Truncated Cones (CON) 2.6 km distant along the airwave path. Event times from the top are: 355d 23h20m, 350d 19h55m, 355d 06h46m, 351d 20h34m. The microphone was inoperative at 351d 23h29m.

follow the earthquake as required by the triggering hypothesis. The early low frequency onsets at E1 and CON do precede the TV explosion, but their absence on more distant recordings implies that they do not have a deep origin. They correlate with the slow upbulging of the lake surface before the explosion, and are interpreted as the motion of an expanding gas bubble.

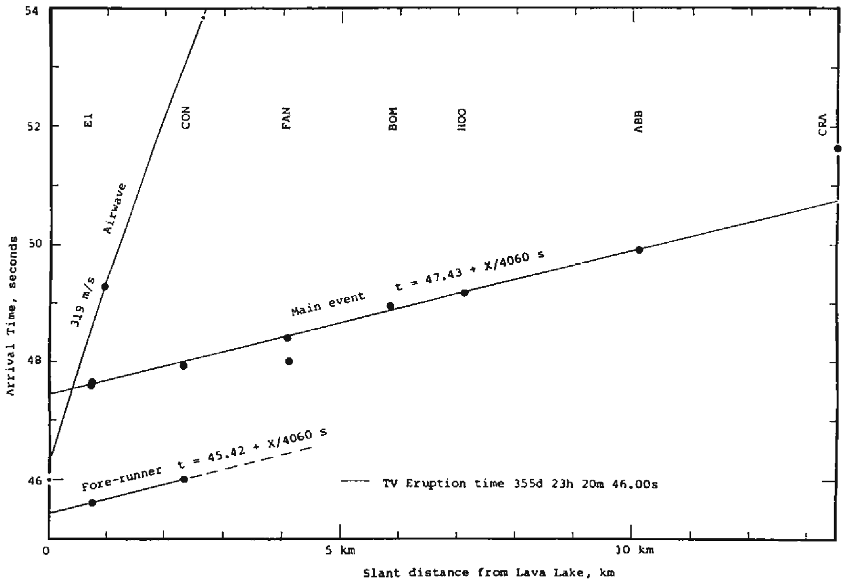

Fig. 7 Composite travel time graph for 5 identical explosions in the lava lake, stacked with the best recorded one at 355d 23h20m46s. The other event times are: 350d 19h55m, 351d 23h29m, 355d 06h46m, 351d 20h34m. The airwave arrival times are plotted at distances along paths reflected from the back crater wall.

5. Interpretation

The simplest interpretation of the data is that the explosion earthquakes occur at shallow depth in the lava lake, and that the apparent vertical distribution previously reported was caused by a combination of late readings of emergent phases at more distant stations, and a model velocity which was less than the true velocity. The new 4 km/s velocity is supported by the value of 4.5 km/s found between sea level and the summit by Dibble et al.[3] from the times of P-waves from large very distant earthquakes.

However, the possibility that eruptions are triggered by deeper earthquakes, as reported at Sakurajima by Ishihara[5], and that the trigger signal travels up the conduit at sufficient velocity to give an anomalously early explosion time needs to be considered. In this case the model velocity of 2.1 km/s used by Shibuya et al.[14] can be adopted, and the depth of the triggering earthquake adjusted to give the 4 km/s apparent velocity. Of course the travel time graph is a hyperbola, so the velocity will only be correct for a particular pair of stations.

Choosing CON and BOM as the pair, the triggering earthquake would have occurred 4.6 km below the lava lake at time 355d 23h20m 45.4 s. The triggering signal would need to travel 4.6 km in 0.58 s -a velocity of 7.9 km/s -which is most improbable. Selecting CON and ABB as the pair, the triggering earthquake would have occurred 7.0 km below the lava lake at time 355d 23h20 m 44.5s. The triggering signal would

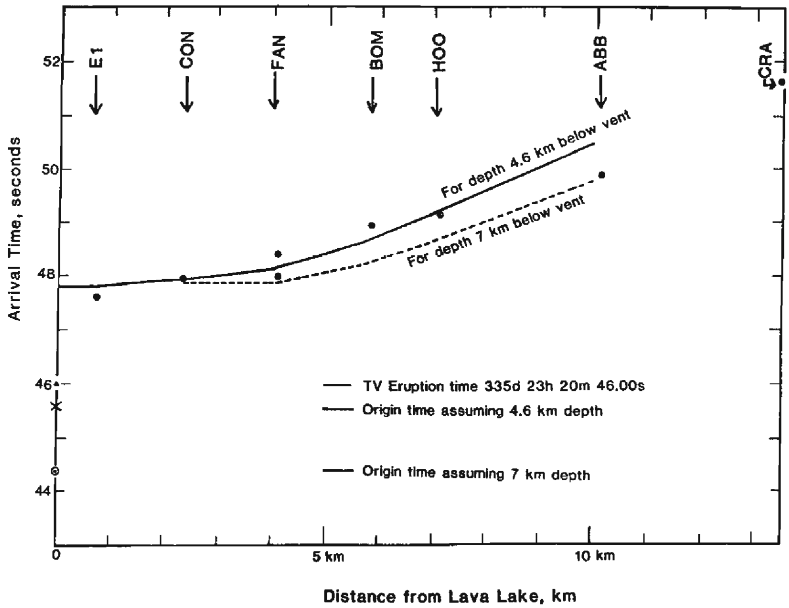

Fig. 8 Theoretical travel time graphs for hypothetical triggering earthquakes below the lava lake. Curve (a) is for 4.6 km depth, which would give apparent velocity 4.0 km/s between CON and BOM. A trigger signal velocity of 7.9 km/s would be required. Curve (b) is for depth 7.0 km, which would give 4.0 km/s between CON and ABB. A trigger signal velocity of 4.6 km/s would be required. Neither curve is a good fit to the data.

need a velocity of 4.6 km/s. This is possible in cold massive lava, but not in liquid magma, and the depth is improbably great. The theoretical time distance curves are not a good fit to the data (**Fig. 8**), and the simple interpretation seems much to be preferred.

6. Viscosity of the lava lake

The viscosities of planets and moons have been estimated from the decay time of craters due to viscous gravitational flow[13),15)] (Steve Blake, personal communication 1986). Basically, the depth of a shallow depression of radius Ro decays to 37% (1/e) in a time:

$$t = 20u/g\rho Ro \qquad (1)$$

where u is kinematic viscosity, g is gravity, and ρ is density. If the depression is hemispherical, and decays in diameter as well as depth, the 37% time will be:

$$t = ku(1/R - 1/Ro)/g\rho \qquad (2)$$

where k is a coefficient, and R is the new radius when the depth is 37% of initial depth.

The two expressions give essentially the same result. No expression has been located for deep narrow pits, such as may be responsible for the 8 s resurgence time after the explosions in the lava lake.

Substituting instead for the 10 m diameter depressions which were recorded on video-tape as filling laterally in $t=4$ s, and using $g=10$ N/kg, and $\rho=600$ kg/cubic m from bomb samples, we get:

$$u=1.2\times 10^4 \text{ Pas} \tag{3}$$

This is based on only 2 data, and is possibly in error by up to an order of magnitude, but it is 10 times greater than Dibble et al.[3] calculated at 1200°C by the Bottinga and Weill[1] method.

7. Conclusion

TV surveillance has shown that shallow explosions from the Erebus lava lake were the source of the biggest earthquakes at Ross Island during December 1986 to January 1987, rather than that quakes a few kilometre deep triggered the eruptions as previously concluded.

The sharp cannon-like eruptions of incandescent bombs and ash were preceded by upbulging of the incandescent exploding area beginning 0.2 to 15s earlier. The sharp seismic onsets of the explosions at the nearest seismic stations in the telemetry net were preceded by a small low frequency emergent vibration beginning about 1s earlier. These seismic forerunners were different for different events, but the main events often had very similar waveforms at any one seismograph.

Stacking the waveforms enabled more reliable P-times to be determined. This showed that the seismic velocity in the upper part of the volcano was 4 km/s, rather than the 2.1 km/s which had previously appeared to be supported by the data. Consequently, the published focal depths determined independently by each of the international group of seismologists cooperating on Erebus (IMESS) was overestimated. That the error was caused by weak forerunners recorded only at the nearest stations, and emergent onsets sometimes read late at far stations is confirmed by a correlation between apparent velocity and seismic amplitudes.

We conclude that the normal P-time method of locating low frequency volcanic earthquakes, which have emergent P-waves, and almost no S-waves, is unreliable unless additional steps such as TV surveillance of eruptions, stacking of similar waveforms, or analysis of apparent velocity (or depth) and seismic amplitude is performed.

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