Bulletin of the Seismological Society of America, Vol. 70, No. 5, pp. 1759-1770, October 1980

THE REPRODUCING EARTHQUAKES OF THE GALAPAGOS ISLANDS

BY KRIS KAUFMAN AND L. J. BURDICK

ABSTRACT

The largest swarm of earthquakes of the last few decades accompanied the collapse of the Fernandina caldera in the Galapagos Islands in June of 1968. Many of the events were relatively large. (The largest 21 had moments ranging from 6 × 10^{24} to 12 × 10^{24} dyne-cm.) They produced teleseismic WWSSN records that were spectacularly consistent from event to event. The entire wave trains of the signals were nearly identical on any given component at any given station. This indicates that the mode of strain release in the region was unusually stable and coherent.

The body waveforms of the events have been modeled with synthetic seismograms. The best fault plane solution was found to be: strike = 335°, dip = 47°, and rake = 247°. The depths of all the larger shocks were close to 14 km. Previous work had suggested that the seismic energy was radiated by the collapsing caldera block at a depth of about 1 km. The new results indicate that large scale extensional faulting at depth was an important part of the multifaceted event during which the caldera collapsed.

INTRODUCTION

In June of 1968, the caldera of the Fernandina volcano in the Galapagos Islands collapsed. The earthquake swarm associated with the event had two unusual characteristics. First, many of the events of the swarm were large enough to be well recorded teleseismically, and second, the records of all these earthquakes (more than 20) were nearly identical at any given station. The radiation field must have reproduced almost exactly from event to event because the waveforms can be correlated from the first body wave, through the surface waves right to the end of the coda. It has been established beyond doubt in recent years that the faulting process is often very unstable and influenced by many random factors. Fault planes have been known to bend within the course of a single event as in the San Fernando, California, earthquake (Langston, 1978). Sometimes the fault planes of aftershocks have been shown to be measurably different than their main shocks (McKenzie, 1972). Johnson and Hadley (1976) showed that the small events in the 1975 Brawley, California, swarm had strongly varying focal mechanisms. A failure process which behaved as stably as the Galapagos swarm certainly deserves note as a very unusual mode of strain release. Sykes (1970) pointed out in a more general study of swarms and seafloor spreading, that the 1968 Galapagos events offer a rare opportunity for study of focal mechanisms of oceanic swarm earthquakes.

Because the phenomenon of caldera collapse is in itself unusual, the Galapagos swarm has already been the object of extensive study. Simkin and Howard (1970) described the caldera collapse process, Filson *et al.* (1973) analyzed the seismicity and compiled a complete list, and Filson and Simkin (1975) applied a statistical model to the swarm sequence. Filson *et al.* (1973) also developed a model to relate the seismicity data directly to the dropping caldera block. They proposed that a roughly cylindrical block dropped in successive stages as magmatic support was removed from below. The model was used to explain the dilatational first motions at teleseismic distances and to relate the gravitational energy of the collapsing caldera to the seismic energy release. However, the model also calls for the release of most of the seismic energy from very shallow depths around 1 km. At that time, the control on the depth of the earthquakes was very poor. Modern methods of body waveform synthesis permit much more accurate depth determination, so this aspect of the Filson *et al.* (1973) model can be tested.

Summaries of body waveform analysis techniques can be found in Langston and Helmberger (1975) or Helmberger and Burdick (1979). A particularly relevant application of the methods was made by Langston and Butler (1976) to the Oroville, California, earthquake. This event had a focal mechanism very similar to the Galapagos events. Consequently, the waveforms from the two events share some important characteristics. Many of the results from the Oroville waveform modeling study can be carried over directly to the Galapagos swarm.

THE TELESEISMIC BODY WAVEFORMS

Figures 1 through 3 illustrate the stably reproducing character of the teleseismically recorded Galapagos signals. The complete body wave codas for three different events as recorded on the vertical component at station ATL are compared in the first figure. The major seismic phases like *P*, *PP*, vertical *S*, and the Rayleigh waves correlate closely. However, even the fine details of the coda between the major phases match. The major seismic phases represent a wide range of vertical takeoff angles from source to receiver. Some of the features of the coda most probably represent scattered phases from a range of takeoff azimuths. The fault mechanism could not have changed to any significant degree without the amplitudes of some of these arrivals changing. Likewise, the depth could not have changed without the relative timing of the depth phases changing.

Figure 2 shows that the events reproduce at stations from a variety of azimuths. Two of the three events used in Figure 2 are different than those in Figure 1, and they are all separated in time by at least a day. Finally, Figure 3 compares 14 vertical *P* waves from what was perhaps the best station, ALQ. In the analysis to follow, we will use a data set consisting of events that had a long-period *P*-wave signal-to-noise ratio of at least 5:1 at several of the U.S. and Canadian long-period stations. These will include the 14 events of Figure 3 plus 7 others.

The worldwide net short-period records could potentially have been as important as the long period. However, the events of the swarm were strongly depleted in short-period energy, so very few good short-period records were available. The lack of high frequency signal in the Galapagos events can be illustrated by comparison with the very similar Oroville, California, earthquake. It has been shown to have a typical time function for its size and it fits into the usual $m_b - M_S$ pattern (Kanamori and Anderson, 1975; Helmberger and Johnson, 1977). Figure 4 compares the long- and short-period records from station BLA for Oroville and a Galapagos event. Conveniently, the station has nearly the same location on the focal sphere for both events. The correspondence between the long-period records is quite close. This is because the events had similar mechanisms, so the *P*, *pP*, and *sP* phases have similar amplitudes. The Galapagos record appears to be slightly longer period primarily because the depth is greater, so the relative times for the depth phases are greater. However, the Galapagos event also had a relatively low frequency time function. The swarm earthquake short-period record is obviously much lower amplitude and lower frequency than the Oroville record. It was found that on the average, the short-period-to-long period amplitude ratios were about 8 times smaller for the Galapagos events than for Oroville. At almost all stations, the short-period signal-to-noise ratio was too low to permit further analysis.

The Source Model

In the procedure used, synthetic seismograms are computed for a point double couple source buried in a plane layered crustal model. The problem is to find the double couple orientation, source depth, and time function which fit the observed

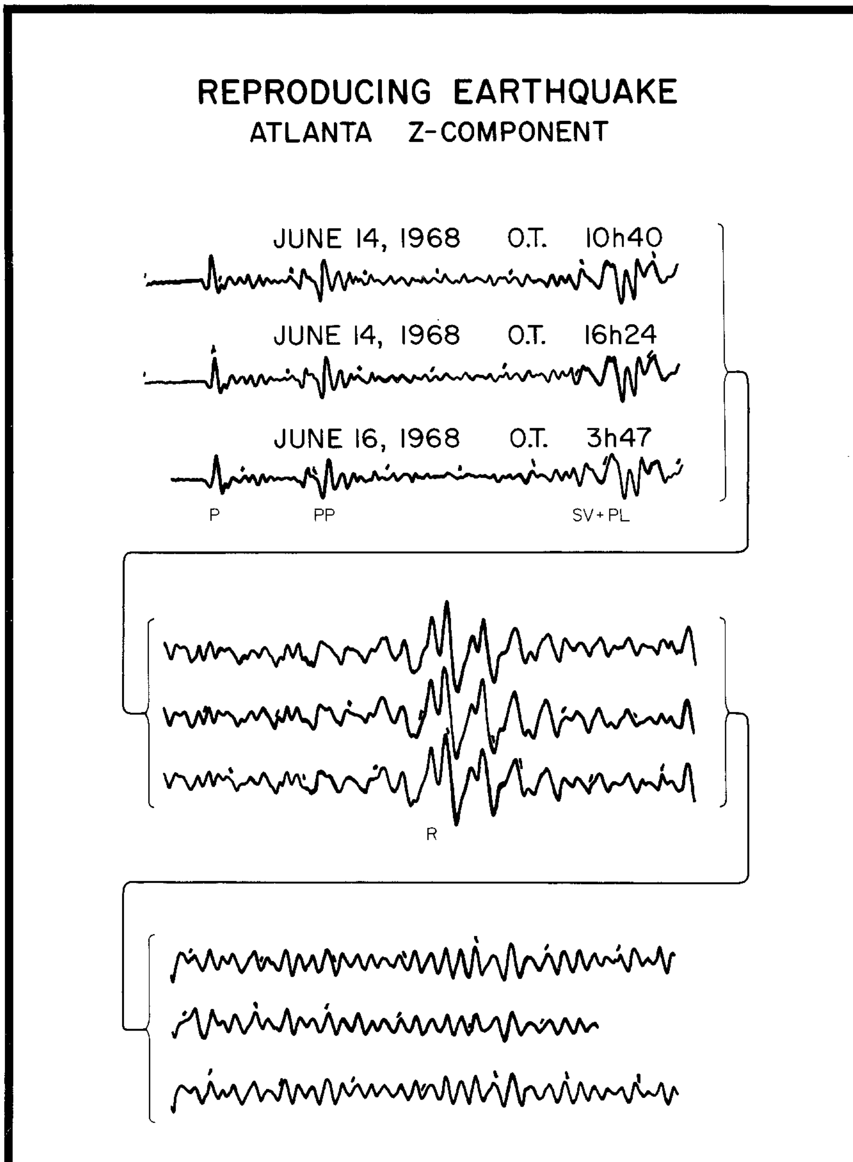

Fig. 1. Approximately 20 min of coda from three different Galapagos earthquakes recorded at Atlanta, Georgia, are compared. The correspondence of even the fine details of the records is most unusual.

seismograms. In some instances, linearized inverse techniques have been used in the parameter search (Burdick and Mellman, 1976), but in most cases, as in this one, the search is implemented by trial and error.

The best solution found was a dip-slip fault (strike = 335°, dip = 47°, rake = 247°) buried at 14-km depth in the crustal model given in Table 1. A triangular time pulse that was independent of azimuth and distance with a rise time of 2.5 sec and a falloff time of 3.5 sec was used to represent the source pulse. The crustal model was also determined by trial and error because no independent information about the seismic structure of the region was available. It is also unknown whether the events actually occurred under the islands or beneath the shallow ocean nearby. Several different models were tried and, as shown in Table 1, the best-fitting model did have a water layer. The resolution of the details of the crustal model is poor. Also, with the islands present in the region and with magma chambers very probably

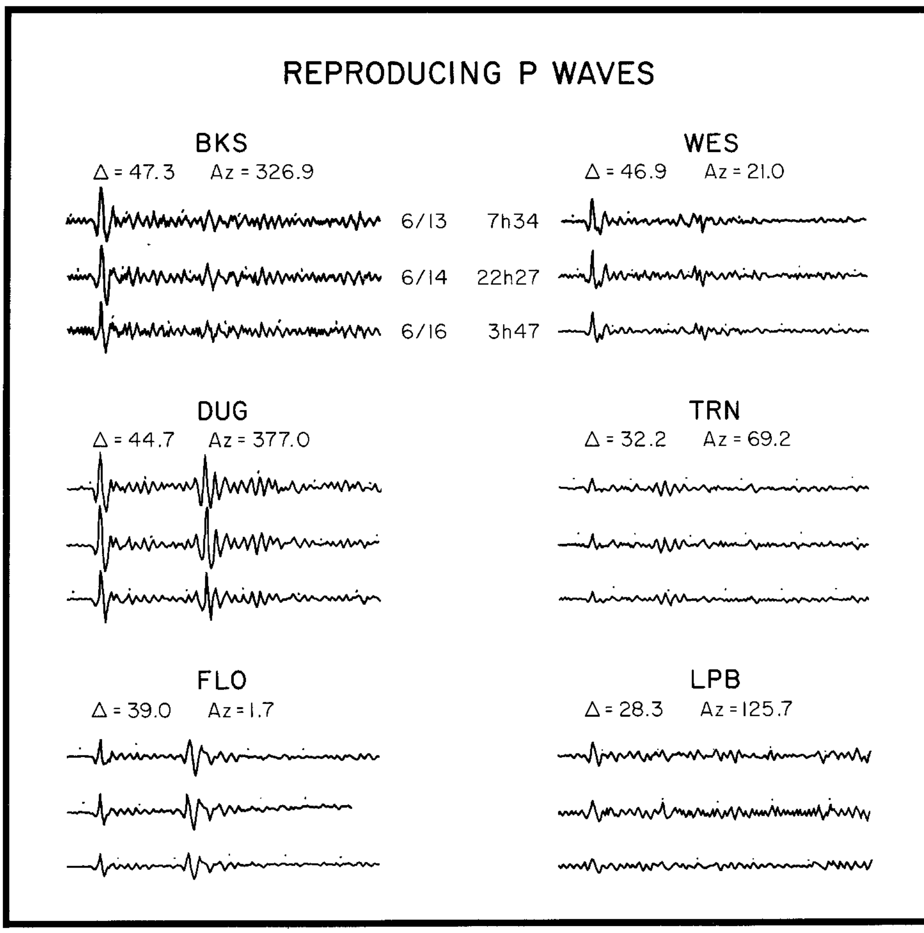

FIG. 2. These are P-wave long-period records from a range of azimuths for three Galapagos events. The records could not have been so consistent at so many stations if the fault plane or the source depth were changing.

present, the model should be considered as nothing more than a plane layered approximation to a crust which has substantial lateral variation. A Futterman Q operator has been used with $t_\alpha^* = 1.0$ and $t_\beta^* = 4.0$. The model for the time function depends on this choice, but the derived source depth and fault plane solution do not.

The projection of the final fault plane solution on a standard lower hemisphere plot is shown in Figure 5. All first motions were dilatational which generally constrains the mechanism to be a dipping normal event. There is little or no control on the strike. A similar situation occurs with the P waveform data. Figure 6 compares synthetic P waveforms with observed for one of the events in the Galapagos swarm (6/14/68, 22h, 27m). The correlation between data and synthetics is reasonably good, although there are differences. These are most probably due to the details of the velocity structure at both the source and receiver. The depth of the event is fixed by the time difference between P and pP. However, neither the observed nor the predicted waveforms vary strongly with azimuth. The theoretical fault plane solution can be rotated substantially without changing the predicted waveforms. This means that the fault is again constrained to be a dipping normal event, but the strike is weakly constrained. It can only be determined through the use of the S-wave data.

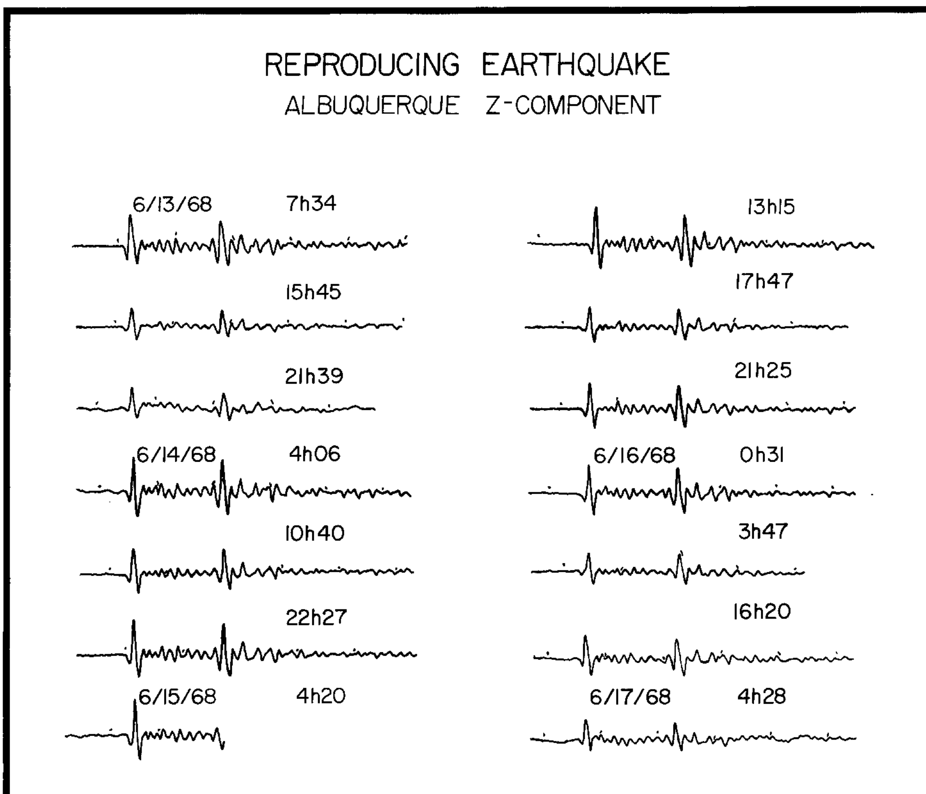

FIG. 3. These are 14 of the events from the Galapagos swarm for which seismic moments were calculated. The events were selected on the basis of their signal-to-noise ratio.

The SH data from the Galapagos swarm were particularly useful because they contained clear evidence of an SH node. This information served to limit the possible value for fault strike to a relatively small range. Figure 7 summarizes the evidence for the node. Rotated S-wave components for the key stations are shown there. The stations at ALE and DAL were almost exactly aligned so that the N-S component was SV and the E-W component SH. The effect of the rotation procedure was minimal. In both cases, the SH arrival appeared distinctly later than the SV arrival. The SV was a clear down break as it should be for a dipping normal event. (Sp phases from the moho would break upward.) Furthermore, at nearby stations like BLC in the figure, a small direct S arrival did appear at the same time as SV. At other stations at much different azimuths such as LPB, a strong SH arrival is coincident with *SV*. This is a case where direct *S* is nodal at ALE and DAL and the first *SH* arrival there is actually *sS*.

Figure 8 shows that the model fits the observations at the *SH* node and at other azimuths as well. The records are displayed around a lower hemisphere plot of the *SH* nodal pattern. [The formulation for the nodal pattern can be found in Burdick (1977).] The *SH* fits are not generally as good as the *P* waveform fits. The data seems to have a ringing character later in the signal that is not predicted by the model. Since magma can strongly affect shear wave propagation, it is perhaps not too surprising that the *SH* data should be more difficult to model using only a plane

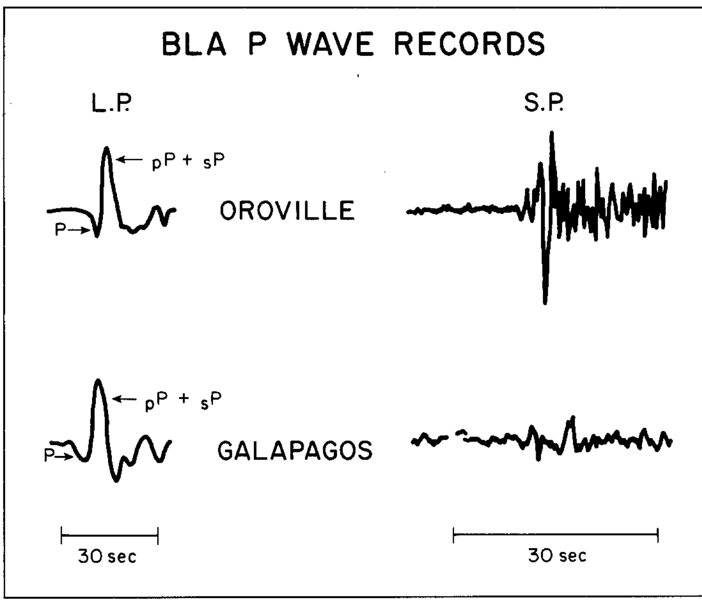

FIG. 4. The long-period to short-period amplitude ratio at station BLA was much different for the Galapagos swarm and Oroville events. The long-period records for the two events appear very similar because the station locations on the focal sphere were similar. However, the Galapagos short-period record is relatively depleted in energy which is a manifestation of a low stress drop. The short-period records are shown at 100 times the gain of the long period.

TABLE 1

THE CRUSTAL MODEL

α (km/sec)	β (km/sec)	ρ (gm/cm^3)	Thickness (km)
1.5	0.0	1.0	1.8
5.9	3.4	2.7	14.0
7.5	4.2	3.2	∞

layered crust structure. The *SH* node observation and the *P* data constrain the Galapagos source mechanism to have been a N-S striking, dip-slip event with east-west extension and a small component of strike slip.

The relative arrival times of the *S* and *sS* phases in Figure 8, and the *P* and *pP* in Figure 6 show that the earthquake swarm was relatively deep. Although it would have been very interesting if all of the seismic energy in the swarm was coming directly from the caldera block, the apparent depth of the swarm indicates this was not the case. The strong correlation between the Oroville and Galapagos event body wave records in Figure 4 and the success of modeling the swarm with a point double couple show that the seismic energy was most probably radiated by ordinary shear failure. The exact relationship between the caldera collapse and the swarm is difficult to ascertain, but it is not unreasonable to suggest that the extensional faulting at depth permitted the magma to drain which allowed the caldera to collapse.

The tectonic setting of the Galapagos Islands is very complex (Hey *et al.*, 1977; van Andel *et al.*, 1977; Almendinger and Riis, 1979). Even if the location of the swarm events were accurately known, it would be difficult to relate the mechanism to the overall plate stresses because the Galapagos Islands must perturb the field to some extent. Extensional faulting, however, is consistent with the withdrawal of magma and the collapse of the caldera block.

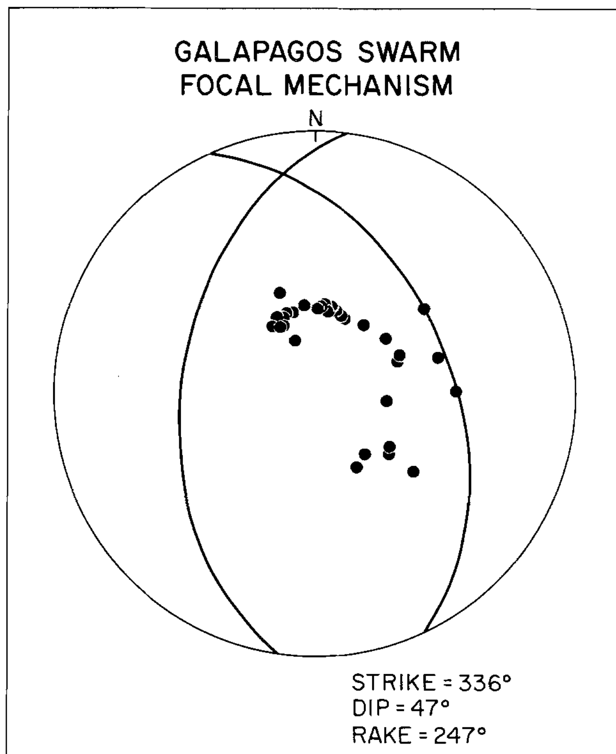

FIG. 5. This is a standard lower hemisphere equal-area projection of the teleseismic *P*-wave first motion data. All of the stations had dilatational first motions. The solution is constrained to be a dipping normal event, but the strike of the planes is almost completely unresolved.

The seismic moments of the 21 largest events were computed from the body wave amplitudes observed at five WWSSN stations. The amplitude data are presented in Table 2. It is interesting to note that although the moment determinations from the various stations scatter by a factor of about 2, the relative amplitudes between the stations are consistent. For instance, station FLO always records a much smaller amplitude than any other. The cumulative moment for the 21 events selected for good signal-to-noise ratio was 1.5×10^{26} dyne-cm. There were many other events that were not quite large enough but which definitely had the same waveshape as those included in the study. The cumulative moment is thus a lower bound on the amount of deep extensional faulting. If these 21 shocks had occurred in a single event at a stress drop typical of continental earthquakes, they would have probably had an M_S between 6.5 and 7.0 (Kanamori and Anderson, 1975).

Discussion

The consistency of the waveforms of the Galapagos events can most easily be explained if all of the events occurred on a nearly identical fault plane. Their depth must also have been fairly constant and, to a lesser extent, their time functions must have been similar. Even though the earthquakes occurred in a swarm-type sequence,

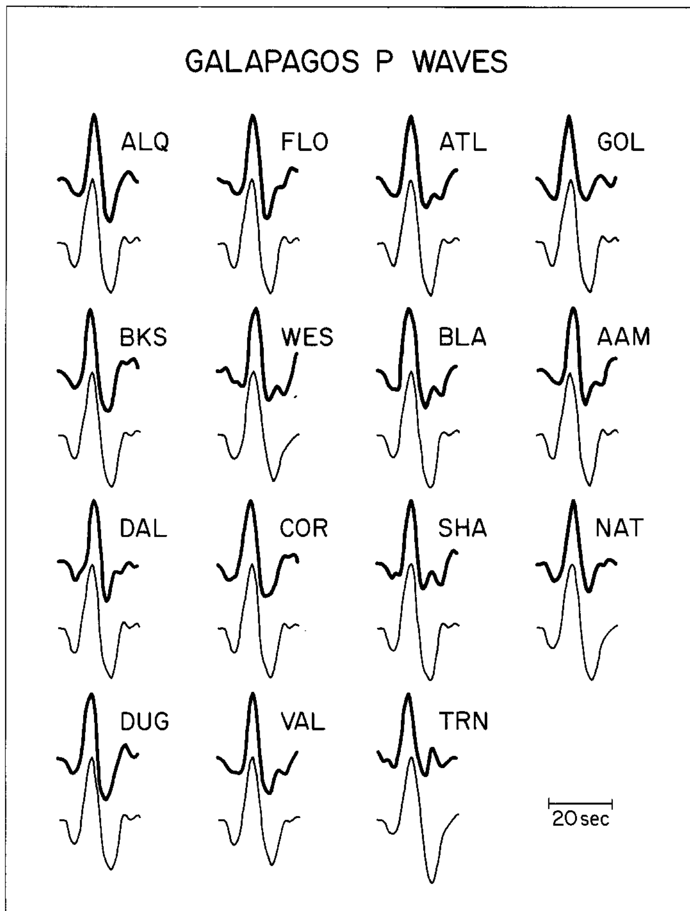

FIG. 6. Long-period P-wave records are compared to the synthetic seismograms predicted by the final model. The observed records are shown in dark line and the synthetics in light line.

there were definitely elements of the failure process that were very stable and reproducible. Kanamori and Stewart (1976) found that the oceanic crust in the Gibbs fracture zone generally fails in a very coherent fashion, on a constant fault plane at a low stress drop. By contrast, they found that the 1976 Guatamala earthquake in a continental regime contained many high stress drop component events (Kanamori and Stewart, 1978). They were presumably caused by high strength asperities in the continental crust. Several lines of evidence suggest that the Galapagos swarm events were in the low stress drop category. First, the WWSSN short-period band was depleted in energy. Second, the time-function duration was

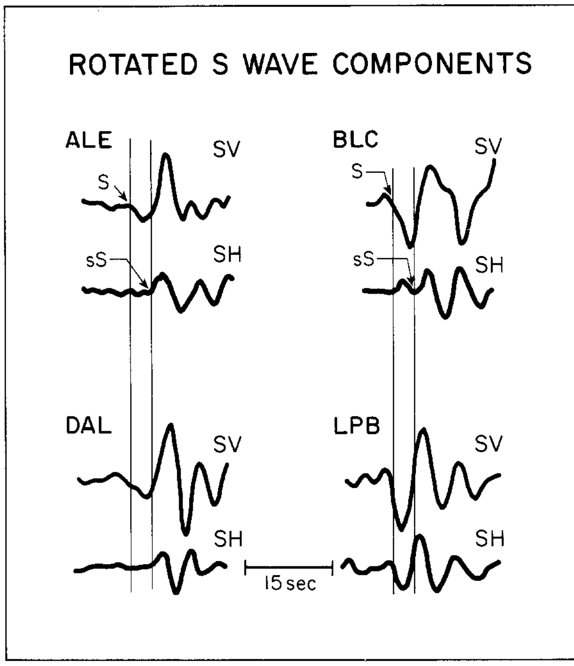

FIG. 7. These S-wave records show evidence for a direct SH node at ALE and DAL. The down-breaking SV pulse arrives distinctly earlier than the first SH arrival at these stations. At the nearby station BLC, there is a small but distinct direct SH arrival and at LPB there is a strong arrival. The first SH energy which does arrive at DAL and ALE is sS.

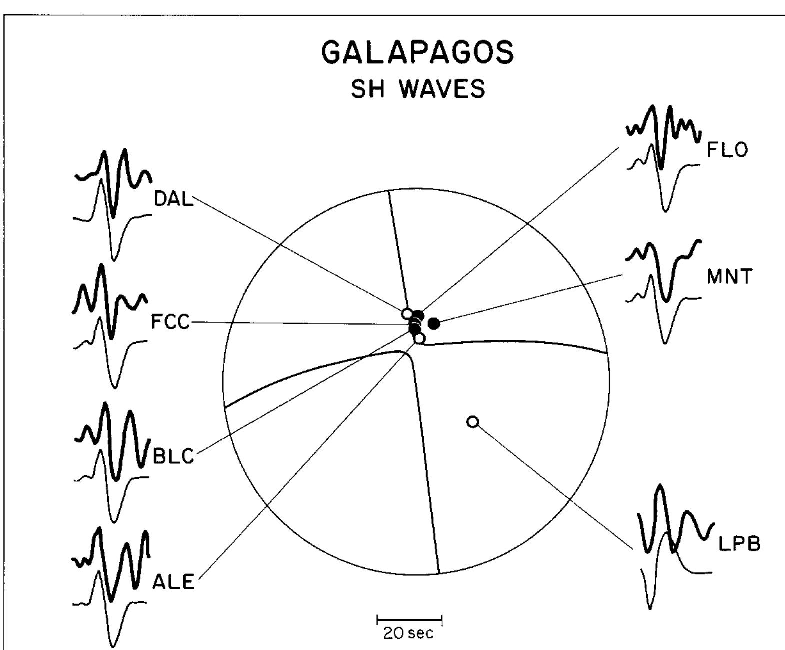

FIG. 8. The observed and calculated SH waveforms are shown as they distribute around the lower hemisphere nodal pattern. Stations ALE and DAL lie directly on the mode but nearby stations do not.

found from the waveform modeling to be about 6 sec. An average moment for one of the 21 events was 8×10^{24} dyne-cm. The graphic relationship between time function duration, moment, and stress drop of Helmberger and Johnson (1977) shows that the stress drops were of the order of 1 bar. Finally, a typical M_S for the events was 5.0. The $M_S - M_0$ relationship from Kanamori and Anderson (1976) again indicates a stress drop about of 1 bar. The implication would seem to be that there are few asperities present to either cause high stress concentrations or to cause deflections of the fault plane in this type of oceanic crust. The fact that the Galapagos events occurred in a swarm does not necessarily mean that regions of variable strength were present. It is just as likely that the occurrence of the first event stressed the location of the second. This second region initially absorbed the stress but then fatigued and failed (Scholz, 1968). If the fatique time was fairly

TABLE 2
SEISMIC MOMENT DATA

Date	Origin Time (h m)	M_S	M_b	M_0 (dyne-cm × 10^{25}) ALQ	BKS	DUG	FLO	ATL	Average
6/12/68	22 21	5.1	4.8	0.82	—	—	—	0.54	0.68
6/13/68	7 34	5.2	5.3	1.04	1.03	1.21	0.56	0.84	0.94
	15 45	5.0	4.8	0.67	0.68	0.64	0.37	—	0.59
	21 39	5.0	4.7	0.74	0.68	0.50	0.30	0.46	0.54
6/14/68	4 09	5.1	4.6	1.19	1.23	1.00	0.67	1.07	1.03
	10 40	5.0	4.7	0.89	0.96	0.89	—	0.76	0.86
	16 24	4.9	4.9	0.82	—	—	0.48	0.69	0.66
	22 27	5.1	5.2	1.19	1.30	1.28	0.67	1.03	1.09
6/15/68	4 20	5.1	5.4	1.19	1.30	1.12	0.67	0.99	1.05
	13 15	4.8	5.2	1.19	0.68	1.12	—	0.76	0.94
	17 40	4.9	5.0	1.00	0.96	1.07	0.52	0.76	0.86
	21 25	4.8	5.2	0.59	0.62	0.64	0.30	0.54	0.54
6/16/68	0 31	4.8	5.0	0.67	0.61	0.71	0.37	0.57	0.59
	3 47	4.9	4.9	0.89	0.89	0.93	0.48	0.69	0.78
	7 13	4.9	4.9	0.74	0.82	0.85	0.44	0.61	0.69
	10 12	4.8	4.6	0.59	0.62	0.64	0.30	0.38	0.51
	13 00	4.8	4.7	0.67	0.62	0.71	0.37	0.46	0.57
	16 20	4.8	4.7	0.74	0.75	0.71	0.41	0.69	0.66
6/17/68	2 15	4.8	4.5	0.63	0.68	0.71	0.37	0.54	0.59
	4 28	4.8	4.5	0.74	0.62	0.64	0.33	0.46	0.56
	14 55	4.8	4.9	0.85	0.69	0.73	0.37	0.63	0.65
									Total 1.5×10^{26} dyne-cm

constant it would help to explain some of the periodicities of the swarm that have been difficult to model until now.

Even allowing for the fact that the fault plane was very consistent, it is still remarkable that so many of the fine details of the coda reproduced from event to event. This strongly suggests that the multitudinous arrivals of the coda are caused by the propagation of the seismic waves through the intricate velocity structure between source and station. It is unlikely that they could be caused for instance by continued radiation from the source. The sensitivity of the coda to perturbations in source location is difficult to assess because the epicenters are poorly known. On the one hand, the ISC locations show the swarm to be over 100 km in length, but on the other, Filson *et al.* (1973) argue that the ISC locations were very unreliable, and all of the events could have occurred on tiny Fernandina. If the source region was very small it is not too surprising that the coda reproduced as well as it did.

Conclusions

The clearest result of this study is that a different interpretation of the relationship between the Fernandina collapse and Galapagos swarms than the one previously proposed is possible. The long-period body wave data is consistent with the majority of the seismic energy being radiated by ordinary extensional shear faulting at about 14-km depth rather than by the dropping caldera block. We propose that both phenomena were part of the same multi-faceted tectonic event, although the exact cause and effect relationship is hard to determine.

The reproducing character of the Galapagos events appears to reflect the stable, low stress drop failure mode of that section of the oceanic crust. It is stilll very unusual, however, that even the fine details of the coda did not change from event to event. Although a fault plane solution for the swarm has been determined from the body wave data, it is difficult to easily relate the solution to the tectonics of the region because they are complex, and the event locations are poorly known.

Acknowledgments

This report has been improved substantially by the careful reviews and helpful comments of Lynn R. Sykes and Klaus H. Jacob. The work has been supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by the Air Force Office of Scientific Research under Contract F49620-79-C-0021.

References

Allendinger, R. W. and F. Riis (1979). The Galapagos rift at 86°W: 1. Regional morphological and structural analysis, *J. Geophys. Res.* **84,** 6379–5389.

Burdick, L. J. (1977). Broad-band seismic studies of body waves, *Ph.D. Thesis,* California Institute of Technology, Pasadena, California.

Burdick, L. J. and G. R. Mellman (1976). Inversion of the body waves of the Borrego mountain earthquake to the source mechanism, *Bull. Seism. Soc. Am.* **66,** 1485–1499.

Filson, J., T. Simkin, and L.-K. Leu (1973). Seismicity of a caldera collapse: Galapagos Islands 1968, *J. Geophys. Res.* **78,** 8591–8622.

Filson, J. and T. Simkin (1975). Application of a stochastic model to a volcanic earthquake swarm, *Bull. Seism. Soc. Am.* **65,** 351–357.

Helmberger, D. V. and L. R. Johnson (1977). Source parameters of moderate size earthquakes and the importance of receiver crustal structure in interpreting observations of local earthquakes, *Bull. Seism. Soc. Am.* **67,** 301–313.

Helmberger, D. V. and L. J. Burdick (1979). Synthetic seismograms, *Ann. Rev. Earth Planet. Sci.* **7,** 417–442.

Hey, R., G. L. Johnson, and A. Lowrie (1977). Recent plate motions in the Galapagos area, *Bull. Geol. Soc. Am.* **88,** 1385–1403.

Johnson, C. E. and D. M. Hadley (1976). Tectonic implications of the Brawley earthquake swarm, Imperial Valley, California, January 1975, *Bull. Seism. Soc. Am.* **66,** 1133–1144.

Kanamori, H. and D. L. Anderson (1975). Theoretical basis of some empirical relations in seismology, *Bull. Seism. Soc. Am.* **65,** 1073–1095.

Kanamori, H. and G. S. Stewart (1976). Mode of strain release along the Gibbs fracture zone, mid-Atlantic ridge, *Phys. Earth Planet. Interiors* **11,** 312–332.

Kanamori, H. and G. S. Stewart (1978). Seismological aspects of the Guatamala earthquake, *J. Geophys. Res.* **83,** 3421–3434.

Langston, C. A. (1978). The February 9, 1971 San Fernando earthquake: a study of source finiteness in teleseismic body waves, *Bull. Seism. Soc. Am.* **68,** 1–30.

Langston, C. A. and D. V. Helmberger (1975). A procedure for modeling shallow dislocation sources, *Geophys. J.* **42,** 117–130.

Langston, C. A. and R. Butler (1976). Focal mechanism of the August 1, 1975 Oroville earthquake, *Bull. Seism. Soc. Am.* **66,** 1111–1120.

McKenzie, D. (1972). Active tectonics of the Mediterranean region, *Geophys. J.* **30,** 109–185.

Scholz, C. H. (1968). Microfractures, aftershocks, and seismicity, *Bull. Seism. Soc. Am.* **58,** 1117–1130.

Simkin, T. and K. A. Howard (1970). Caldera collapse in the Galapagos Islands, *Science* **196,** 429–437.
Sykes, L. R. (1970). Earthquake swarms and sea-floor spreading, *J. Geophys. Res.* **75,** 6598–6611.
van Andel, T. H., G. R. Heath, B. T. Malfait, D. F. Heinricks, and J. I. Ewing (1971). Tectonics of the Panama Basin, eastern equatorial Pacific, *Bull. Geol. Soc. Am.* **82,** 1489–1508.

CIRES
University of Colorado
Boulder, Colorado 80302 (K.K.)

Lamont-Doherty Geological Observatory of Columbia University
Palisades, New York 10964 (L.J.B.)

Manuscript received January 23, 1980