USE OF SONOBUOYS IN OCEAN EARTHQUAKE STUDIES

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Summary. U.S. Navy anti-submarine-warfare telemetering sonobuoys have recently become an important tool in the study of earthquakes at sea. Earthquake ground motion converts to sub-audio compressional waves in the water and is detected by the sonabuoy hydrophones. The frequency-modulated sonobuoy signals are monitored with commercial VHF receivers on shipboard, aircraft or land, and are recorded on f.m. magnetic tape or strip chart. Subsequent analysis of the seismic signals gives information on location and depth of the earthquake as well as direction of fault motion, stress release and other characteristics of the event. The accuracy of epicenter location is usually limited by the precision of ship navigation but may also be limited by uncertainties in sonobuoy position measured from the ship. Events large enough to be detected on land have been located with better accuracy by sonobuoys than by the land arrays.

This paper describes the techniques of using sonobuoys for earthquake research, and gives results of observations of microearthquake swarms in the Gulf of California along the extension of the San Andreas Fault.

Introduction. In order to obtain accurate hypocentral information from oceanic earthquakes, local seismograph arrays with dimensions of the same order as the size of the area and depths of events under study are necessary. Since land stations alone cannot usually meet this condition, it is necessary to find sensors capable of operating at sea and able to detect small, nearby earthquakes. Earthquakes have been detected by ships during refraction studies near active regions, while receiving hydrophones were in the water (Northrup and Raitt, 1963; Birch, 1966). The T-phase hydrophone array has been in operation for many years (see, for example, Johnson, 1966) and has detected numerous earthquakes. Raitt and Shor (Raitt, personal communication) have detected many seaquakes on hydrophones. They recognized that this type of instrument would be useful in studying microearthquakes at sea. Sonobuoys have been used for several years in seismic refraction (Hill, 1952; Hill, 1963) and seismic reflection experiments at sea (LePichon et. al., 1968; Houtz et. al., 1968). It seemed a natural extension to use this type of instrument to study earthquakes at sea. In 1970, we began experiments using U.S. Navy

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sonobuoys for local earthquake detection. These units consist of a small buoy containing an audio amplifier and VHF transmitter. A hydrophone is suspended at some present depth below the buoy. Sonobuoys can be easily deployed from a moving ship or airplane. Signals can be monitored on board or at nearby land recording sites.

Hydrophone Response. The pressure variations at the hydrophone depend upon sea state, hydrophone depth, sea bottom earthquake motion, and the elastic parameters of sub-bottom sediment and rock layers (Bradner 1962, 1963). In the present paper a simplified relation will be used to relate Richter earthquake magnitude and the pressure at the hydrophone (Reid, et. al., 1973).

$$M = \log p_{20}(\mu\text{bar}) - 2.85 - \log A_o + \log A_{20} \quad (1)$$

where M is the local magnitude; p_{20} is the pressure amplitude at a frequency of 20 Hz; A_o is the distance correction of Richter 1958; A_{20} is an additional distance correction for 20 Hz. seismic waves given by Brune and Allen, 1967.

For a M=0 at 10 km., Eqn (1) gives a peak pressure amplitude of 1.6 µbar. Since the ambient sea noise (for a sea state 2) is about 1 µbar near 20 Hz. (Wenz, 1962), M=0 at 10 km. is about the lower limit of detectability for any hydrophone system operating near that frequency. This background pressure level, 1 µbar, is equivalent to the pressure induced by .26 mµ of ground motion (at 20 Hz.). For comparison the background motion at land sites in Southern California is about 0.05 mµ for quiet sites and 0.3 mµ for noisier sites. (Brune and Allen, 1967.) Thus, the sonobuoy system (or any hydrophone system) has about an order of magnitude higher noise level than quiet land sites.

Pressure Spectrum. To determine the response of a hydrophone system to a local microearthquake signal, the spectral theory of Brune, 1970 is employed. According to his theory, the ground displacement amplitude spectrum is flat to some corner frequency, beyond which it falls off as ω^{-2}. The pressure spectrum, then, should increase as ω, reaching a peak at the corner frequency and fall as ω^{-1} at higher frequencies. Such a spectrum is plotted in Fig. 1 for a corner frequency of 20 Hz. (dashed line). Also plotted is a typical ambient noise pressure spectrum for sea state 2 from the work of Wenz, 1962 (solid line). The maximum signal-to-noise occurs at frequencies near 20 Hz. While a different corner frequency would shift the frequency at which the maximum occurs, it does, in practice, appear to be near 20 Hz. for close events.

Also shown in Fig. 1 is the earthquake pressure spectrum expected when reflection from the sea surface is taken into account. The pressure amplitude at some depth d is represented as the sum of the incident and reflected waves, i.e.,

$$p = p_i + p_r = 2p_i,\sin(d\alpha\omega) + \text{surface scattering.} \quad (2)$$

In Fig. 1, d is taken as 20 m., a common sonobuoy hydrophone depth, and the factor of two has been suppressed. The interference pattern antinode near 20 Hz. increases the signal-to-noise at 20 Hz. relative to nearby frequencies. It should be noted that the magnitude formulation of Eqn. (1) does not take the surface reflection into account. This introduces only a small (~.3 magnitude units) correction in the calculated magnitude.

The Sonobuoy System. Earthquake studies consist essentially of recording seismic signals in analog format from an array of detectors, and then determining as much as possible about the nature of the earthquake by examining the details of the analog traces: The direction of first motion (compression or rarefaction) and the relative signal amplitudes of array elements give information on the slip direction of the fault break. Signal amplitude vs. distance determines earthquake magnitude, as previously indicated. Spectral analysis of the signals gives information on the stress release of the fault break. (Brune, 1970.) The location and depth of the event is found from the relative arrival times of characteristic compressional or shear waves. Since only compressional waves often show clearly on sonobuoys, the array must consist of at least four detectors to determine the 3 spatial coordinates and origin time. If wave velocities in the sediment and rock are not known a priori, even more sonobuoys are needed. We regularly deploy as many sonobuoys as practical, up to about eight.

Each sonobuoy consists of a hydrophone and preamp hung 20 m. or 100 m. below a surface buoy with a compliant line (to decouple the hydrophone from motion of the surface buoy). The surface buoy contains sea-water batteries, an audio amplifier, and a VHF (150-170 MHz.) transmitter. The frequency response of the hydrophone-amplifier system is shown in Fig. 2 for one particular sonobuoy, the AN/SSQ-57(XN-3). The plot is taken from the sonobuoy manual, NAVAIR 16-30 SSQ5T-2. Other models do not differ much in the frequency range 10 to 100 Hz. The strip chart cut-off shown is for the multi-channel recorder often used in sonobuoy work. Other recorders have slightly different high frequency filtering, but usually do not effect the response near 20 Hz.

The sonobuoy monitoring system consists of VHF radio receivers and visible recorder. Magnetic tape is often used as well. Since the calibration of the sonobuoys is given in kHz. carrier deviation of the transmitter frequency per µbar at 440 Hz., it is necessary to calibrate each radio. The radio output circuitry was modified to allow a dc response. Detuning the radio dial a certain distance (corresponding to some frequency deviation), with a carrier present, gives a dc offset at the output. The radio-recorder signal amplitude can then be related directly to the pressure at the hydrophone. Though usually set up aboard the deploying vessel, the monitoring system may be placed on land, if a close enough site is available.

Operating and Tracking Procedures. The first major seismicity program using sonobuoys was carried out in 1972 during the HYPOGENE Expedition (Reid, et. al., 1973). The following is a discussion of operating techniques developed during HYPOGENE and subsequent expeditions. Sonobuoys have generally been deployed from ships. The simplest procedure is to deploy the buoys as the ship is steaming in some pattern. Satellite, radar or some other navigational tool will give the initial position of the sonobuoy. For a short (1 to 3 hr.) lived buoy, this position is sufficient (at least in regions where currents are not strong). If the buoy is active for a longer time, though, it either must be anchored, or its position tracked. Since sonobuoy signals are telemetered to a central receiving station on shipboard we can determine the approximate location of an event very quickly, and augment the array to surround the event. In contrast temporary land arrays usually record data at each separate seismometer; and faulty array placement is not discovered until all aftershocks have occurred.

Several sonobuoys were anchored near Guaymas, Sonora, Mexico during HYPOGENE (Brune, et. al., 1973). This was a time consuming process and had limited success. In particular, noise resulting from tidal current flow past the hydrophone considerably reduced system sensitivity for part of each day. Free-floating sonobuoys were found to be much quieter.

Two methods have been used to track the position of free-floating sonobuoys. The first employs small sound sources, such as an air gun or explosives. As the ship steams around and in the array, the explosions are set off and the signals received at each sonobuoy are recorded. Knowing the origin time and location of each source, and the arrival time of the direct pressure wave at the buoy, a distance to the sonobuoy can be calculated. With several of these ranging shots, the average position of the buoy during the shooting period can be determined. In some instances, the direct wave can be refracted down, away from the buoy, and no such arrival seen at the sonobuoy. When this occurs, the time of arrival of the wave reflected at the ocean bottom is used to determine distance. This is a common technique in seismic refraction work, and was used successfully during HYPOGENE to locate free drifting sonobuoys.

For the second tracking method, a small (6 to 15 ft.) spar buoy, with one or two radar corner reflectors fixed to the top, is connected to each sonobuoy via a 10 to 20 ft. line. Whenever the ship is within radar range of the buoys, then, the position of the buoy relative to the ship can easily be determined. For work accomplished during the past three years, the maximum range at which the radar reflectors could be detected was rarely 10 km. and at times was only 2 km. Nevertheless, this technique has some advantages over the explosion method. An air gun system or explosives do not have to be aboard; only a radar is necessary to determine the buoy locations relative to the ship. The tracking operation can be carried out at any time; the ship need not be underway. The position is determined with a single reading, while at least three separate explosive shots are required. Also, the radar technique can be carried out in the presence of high seismicity, when knowledge of buoy positions is most critical but an arrival from a shot may be lost in a natural event. One disadvantage is that the system cannot be deployed while the ship is underway. Stopping the ship does decrease accuracy in navigation (especially if only satellite navigation is used) since errors can accumulate in the dead-reckoning position. In addition, the ship usually stays in the area to retrieve the radar reflector spars. This time consuming operation is not necessary when no radar reflectors are used. Radar transponders have evident advantages over corner reflectors but we have not been able to afford them.

Generally, the positions of the buoys relative to the ship can be determined with an accuracy of about 0.1 km. for radar fixing and 0.3 km. or so with the explosive method. The largest sources of error in the latter are usually lack of knowledge of the velocity structure in the upper ocean, and the necessity to average the position over the time required to shoot several well-spaced shots. The absolute buoy locations, however, can be determined only as accurately as the ship's location. All navigation techniques used, satellite, radar, and LORAN have limitations and inherent sources of error. The best system would use some combination of these as well as bathymetric navigation to determine the ship's position as accurately as possible relative to the fault features. Ideally, one would like to know the sonobuoy locations to about .1 km. For various reasons, this accuracy has not been achieved. During most of the field work in the Gulf of California, navigation has been solely by radar or sextant. The large distances to targets (up to 100 km.), poor azimuth distribution of useable targets, and erroneous positioning of the targets on the available charts, introduces possible errors as large as 4 km. Such errors can make interpretation of results difficult. Navigation errors have, in fact, been the largest source of error in epicentral determinations for the studies discussed in this paper. Nevertheless, epicenter locations by sonobuoys have shown less scatter than locations from teleseismic land stations.

The standard Navy sonobuoys were designed to be dropped from an airplane. We have used this technique in several studies (e.g., Bradner and Brune, 1974). Short life sonobuoys are usually used, since they will drift after deployment and no easy tracking method is available for use from a civilian plane. The signals are usually recorded with a system aboard the plane.

Types of Experiments. There are, in general, two types of seismic experiments which involve temporary stations. For seismicity surveys, the stations operate for some length of time with the hope that some significant activity will be present. Locations of active faults, source depths and some source mechanism information can be examined without waiting for a large earthquake sequence to occur in the region of interest. The experiment may last several days or weeks before sufficient information is available for thorough analysis. For example, the seismicity work of Brune and Allen, 1967, was carried out over periods of from two days to one year per site.

The second type of experiment takes advantage of aftershocks of a large earthquake or the time duration of an earthquake swarm, and the ability to respond quickly, before the activity dies away. Some activity is almost guaranteed, depending on the size of the largest event and the delay in setting up the stations. The events located give the length, depth, and orientation of the ruptured region. Some information on source mechanism and stresses involved is sometimes available, if the recording technique allows determination of the direction of first motion, or spectral analysis of the recorded signals.

For various reasons, sonobuoys are better suited for the aftershock or swarm study than for seismicity. The cost and operating life of each buoy, as well as their tendency to drift away from the fault zone, limit their abilities to measure seismicity for any length of time. During swarms and aftershock sequences, however, the data density is usually high enough to offset the cost and effort of sonobuoy arrays. The major advantage of using sonobuoys for an aftershock or swarm study is that they can be deployed and monitored from almost any vessel.

Observations in the Gulf of California. We will describe one series of observations in the Gulf of California to illustrate the value of sonobuoys. Geological, seismic, gravity, and magnetic surveys of the Gulf of California region have developed a general concensus regarding its history and present structure. (See for example Shepard 1950, Hamilton 1961, Phillips 1964, Harrison and Mather 1964, Runsak et. al., 1964, Sykes 1967, 1968, 1970, Moore 1973, Karig 1971, Henyey and Bischoff 1973, Bischoff and Henyey 1974, Sharman 1974).

The present Gulf has probably grown from a proto-gulf (a back-arc marginal sea) during the past 4 million years. The long Baja California peninsula rides on the Pacific plate and thus moves in a general northwesterly direction with respect to the American continent. The land of California west of the San Andreas Fault appears to be similarly riding on the Pacific plate, but the tectonics of the Gulf has been thought to be much simpler than the multi-faulted and lifted California region. We are attempting to improve our understanding of the San Andreas fault by studying its extension in the Gulf.

The bathymetry and suggested fault pattern of the central Gulf is shown in Fig. 3. A long transform fault connects the Sal si Puedes Basin with the Guaymas Basin. The San Pedro Martyr Basin may represent a short spreading center segment. The Guaymas Basin consists of two well defined grabens (Sharman, 1974), sites of crustal formation. The

Carmen Basin appears to have a small spreading-center type offset of the transform fault extending south from the Guaymas Basin.

During our first extensive, six week, cruise using sonobuoys an average of 3 discrete earthquakes per day were detected, in addition to six large microearthquake swarms. The discrete events compare well with active portions of the San Andreas fault system. However swarms of up to 1000 small events lasting up to a few days are not observed along the San Andreas fault. Fig. 4 shows a sample of seismograms from a swarm of 1000 events recorded during an eight hour period in the northern Guaymas Basin trough. The largest event of the swarm had a local magnitude of less than about 2.0. None of the events were recorded at a permanent seismograph station at Guaymas, 120 km. distance.

Of the 1000 events, 28 were selected from a four-hour sample for accurate location. No swarm events had a significantly different arrival pattern than these 28. Arrival times were measured to 0.2 sec. accuracy and event coordinates were determined by triangulation assuming a uniform velocity below the sea floor. All of the located events were shallower than 2 km. into the crust. All epicenters lay within a 3 km. by 2 km. area, trending approximately parallel to the spreading center trough of the northern Guaymas Basin and lying beneath the northern wall of this trough. A fault plane solution from first motions was not possible, though such solutions have been obtained on other earthquakes; we would expect the Guaymas Basin swarms to be associated with either normal faulting or magma movement near the wall of the spreading center. The seismic activity during the swarm was not constant; there were several clusters of earthquakes. A sample autocovariance of the seismic time series shows that the swarm was not a random series of events.

On the basis of Guaymas Basin observations the Gulf appeared to be perhaps a simple structure. Subsequent observations of other swarms in the Gulf have shown that the structure is not simple, but nevertheless less complex than fault systems of California.

Conclusions. We have discussed the use of sonobuoys for earthquake studies and have briefly summarized some observations in the Gulf of California to illustrate their utility. Sonobuoys can be effectively used to record earthquakes that are poorly determined or even undetectable by land stations. In spite of difficulties in position-fixing they give earthquake locations with accuracy comparable to land arrays. By studying microearthquake swarms we have been able to examine regions in finer detail. In particular we note that the tectonics of the northern Gulf of California is apparently quite complicated although not on such a large scale as represented by the Transverse Ranges of Southern California. In order to untangle the northern Gulf, and completely determine its relation with the active faulting of Baja California and Southern California, accurate epicenters obtained over an extended period of time are necessary. This study has begun (Lomnitz, et. al., 1970, Brune, et.al., 1975) but the data is not yet sufficient to provide accurate fault delineation.

References

F. Birch, “An earthquake recorded at sea,” Bull. Seismol. Soc. Am., vol. 56, pp. 361-366; 1966.

J. Bischoff and T. Henyey, “Tectonic elements of the central part of the Gulf of California,” Bull. Geol. Soc. Am., vol. 85, pp. 1893-1904; 1974.

H. Bradner, “Pressure variations accompanying a plane wave propagated along the ocean bottom,” J. Geophys. Res., vol. 67, pp. 3631-3633; 1962.

H. Bradner, “Probing sea-bottom sediments with microseismic noise,” J. Geophys. Res., vol. 68, pp. 1788-1791; 1963.

H. Bradner and J. Brune, “The use of sonobuoys in determining hypocenters of aftershocks of the February 21, 1973 Pt. Mugu earthquake,” Bull. Seismol. Soc. Am., vol. 64, pp. 99-101; 1974.

J. Brune, “Tectonic stress and spectra of seismic shear waves from earthquakes,” J. Geophys. Res., vol. 75, pp. 4997-5009; 1970.

J. Brune, C. Allen, F. Lehner, C. Lomnitz, F. Mooser, “Permanent seismograph station around the Gulf of California,” (in preparation); 1975.

J. Brune and C. Allen, “A micro-earthquake survey of the San Andreas Fault system in Southern California,” Bull. Seismol.,Soc. Am., vol. 57, pp. 277-296; 1967.

J. Brune, S. De la Cruz, H. Bradner, C. Villegas, I. Reid, M. Reichle, A. Nava, M. Lozada and P. Silva, “Earthquakes in the Gulf of California using land based recordings of moored hydrophone arrays,” Geofisica Internacional, vol. 12, pp. 201-212; 1973.

W. Hamilton, “Origin of the Gulf of California,” Bull. Geol. Soc. Am., vol. 72, pp. 1307-1318; 1961.

J. Harrison and S. Mather, “Gravity anomalies in the Gulf of California in Marine Geology of the Gulf of California - A Symposium,” Am. Assoc. Petroleum Geol., Mem. 3, pp. 76-89; 1964.

M. Hill, “Seismic refraction shooting in an area of the Eastern Atlantic,” Phil. Trans. Roy. Soc. London, vol. A244, pp. 561-596; 1952.

M. Hill, "Single Ship Seismic Refraction Shooting" in The Sea, vol. 3, The Earth Beneath the Sea, M. Hill, ed., J. Wiley and Sons; 1963.

T. Henyey and J. Bischoff, "Tectonic elements of the Gulf of California I Northern Province," Bull. Geol. Soc. Am., vol. 84, p. 315; 1973.

R. Houtz, J. Ewing, and X. LePichon, "Velocity of deep-sea sediments from sonobuoy data," J. Geophys. Res., vol. 73, pp. 2614-2642; 1968.

R. Johnson, "Routine location of T-phase sources in the Pacific," Bull. Seismol. Soc. Am., vol. 56, pp. 109-118.

D. Karig, "Origin and development of marginal basins in the Western Pacific," J. Geophys. Res., vol. 76, pp. 2542-2561, 1971.

X. LePichon, J. Ewing, and R. Houtz, "Deep-sea sediment velocity determination made while reflection profiling," J. Geophys. Res., vol. 73, pp. 2597-2614; 1968.

C. Lomnitz, F. Mooser, C. Allen, J. Brune and W. Thatcher, "Seismicity and tectonics of the Northern Gulf of California Region, Mexico, preliminary results," Geofisica Internacional, vol. 10, pp. 31-48; 1970.

D. Moore, "Plate edge deformation and crustal growth, Gulf of California structural province," Bull. Geol. Soc. Am., vol. 84, pp. 1883-1906; 1973.

J. Northrup and R. Raitt, "Seaquakes in the Flores Sea," Bull. Seismol. Soc. Am., vol. 53, pp. 577-583; 1963.

R. Phillips, "Seismic refraction studies in the Gulf of California in Marine Geology of the Gulf of California - A Symposium," Am. Assoc. Petroleum Geol., Mem. 3, pp. 90-121; 1964.

I. Reid, M. Reichle, J. Brune and H. Bradner, "Microearthquake studies using sonobuoys: Preliminary results from the Gulf of California," Geophys. J. Roy. Astr. Soc., vol. 34, pp. 365-379; 1973.

G. Rusnak, R. Fisher, and F. Shepard, "Bathymetry and faults of the Gulf of California in Marine Geology of the Gulf of California - A Symposium," Am. Assoc. Petroleum Geol., Mem. 3, pp. 59-75; 1964.

G. Sharman, “The Gulf of California, A changing plate edge,” Abstr. in EOS, vol. 55, p. 1188; 1974.

F. Shepard, “Submarine topography of the Gulf of California, pt. 3 of the E.W. Scripps cruise to the Gulf of California,” Geol. Soc. Am., Mem. 43, 32 pp; 1950.

L. Sykes, “Mechanics of earthquakes and nature of faulting on mid-ocean ridges,” J. Geophys. Res., vol. 72, pp. 2131-2153; 1967.

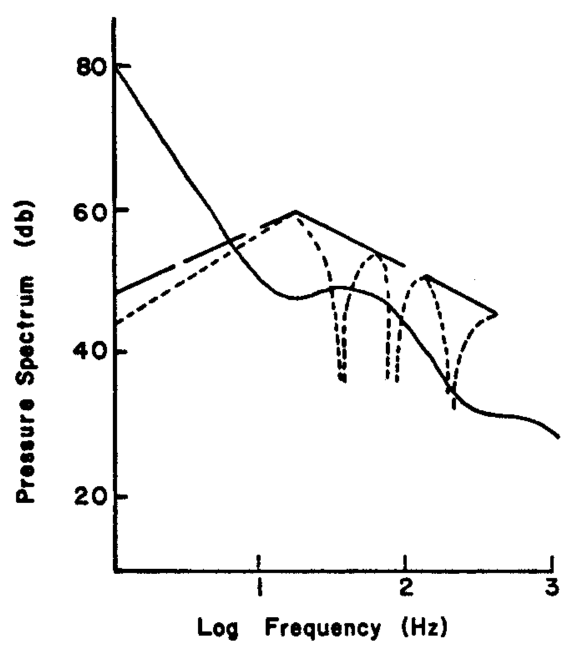
L. Sykes, “Seismological Evidence for Transform Faults, Sea-Floor Spreading and Continental Drift in Proceedings of NASA Symposium, History of the Earth’s Crust,” R.A. Phinney, ed., Princeton University Press; 1968.

L. Sykes, “Earthquake swarms and sea-floor spreading,” J. Geophys. Res., vol. 75, pp. 6598-6611; 1970.

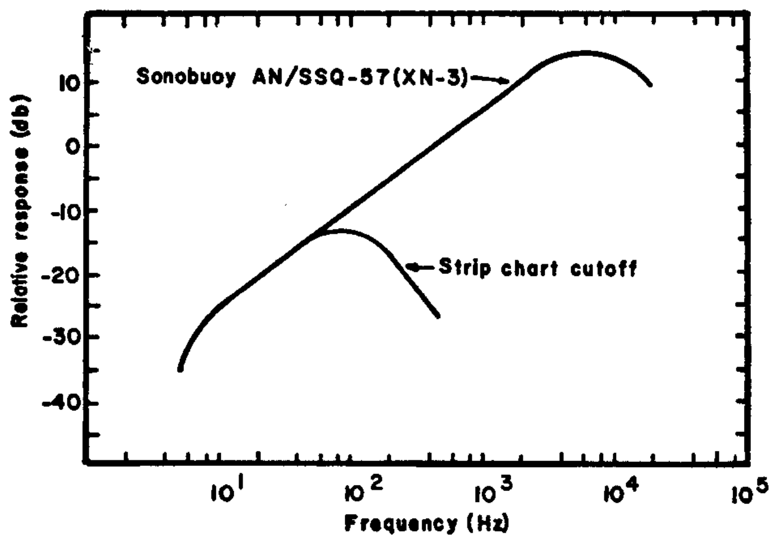
R. Tatham and J. Savino, “Faulting mechanisms for two oceanic earthquake swarms,” J. Geophys. Res., vol. 79, pp. 2643-2652; 1974.

W. Thatcher and J. Brune, “Seismic study of an oceanic earthquake swam in the Gulf of California,” Geophys. J. Roy. Astr. Soc., vol. 22, p. 473; 1971,

G. Weny, .Acoustic ambient noise in the ocean: Spectra and sources,” J. Acous. Soc. Am., vol. 34, pp. 1936-1956; 1962.



Earthquake Pressure Spectrum



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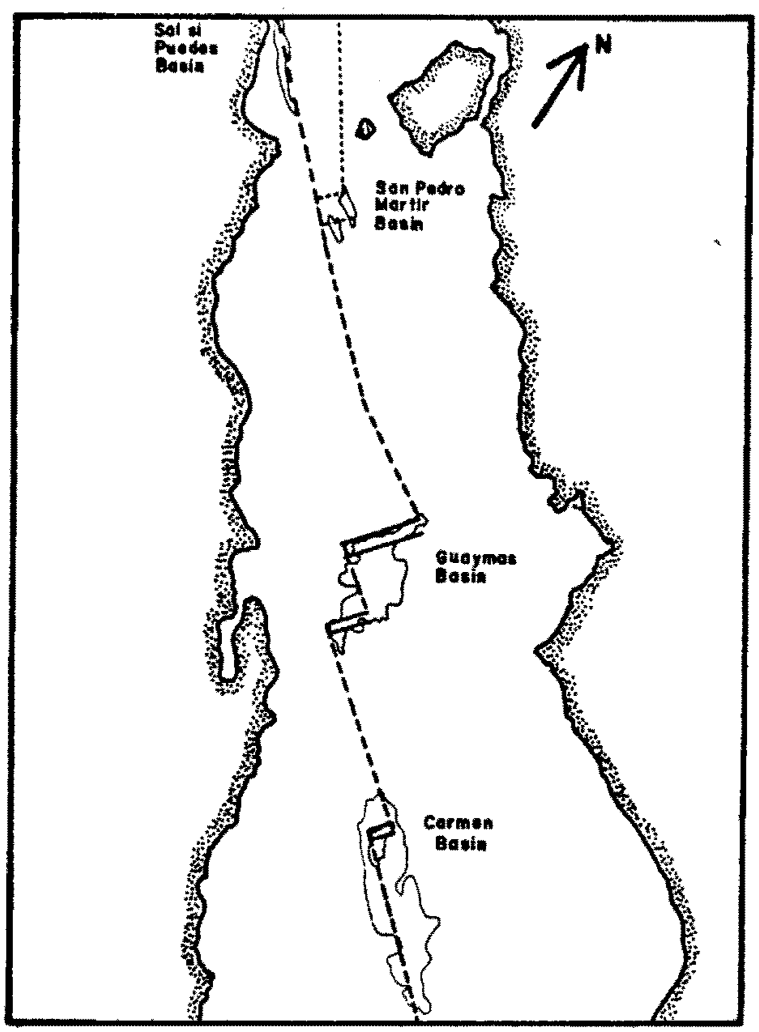
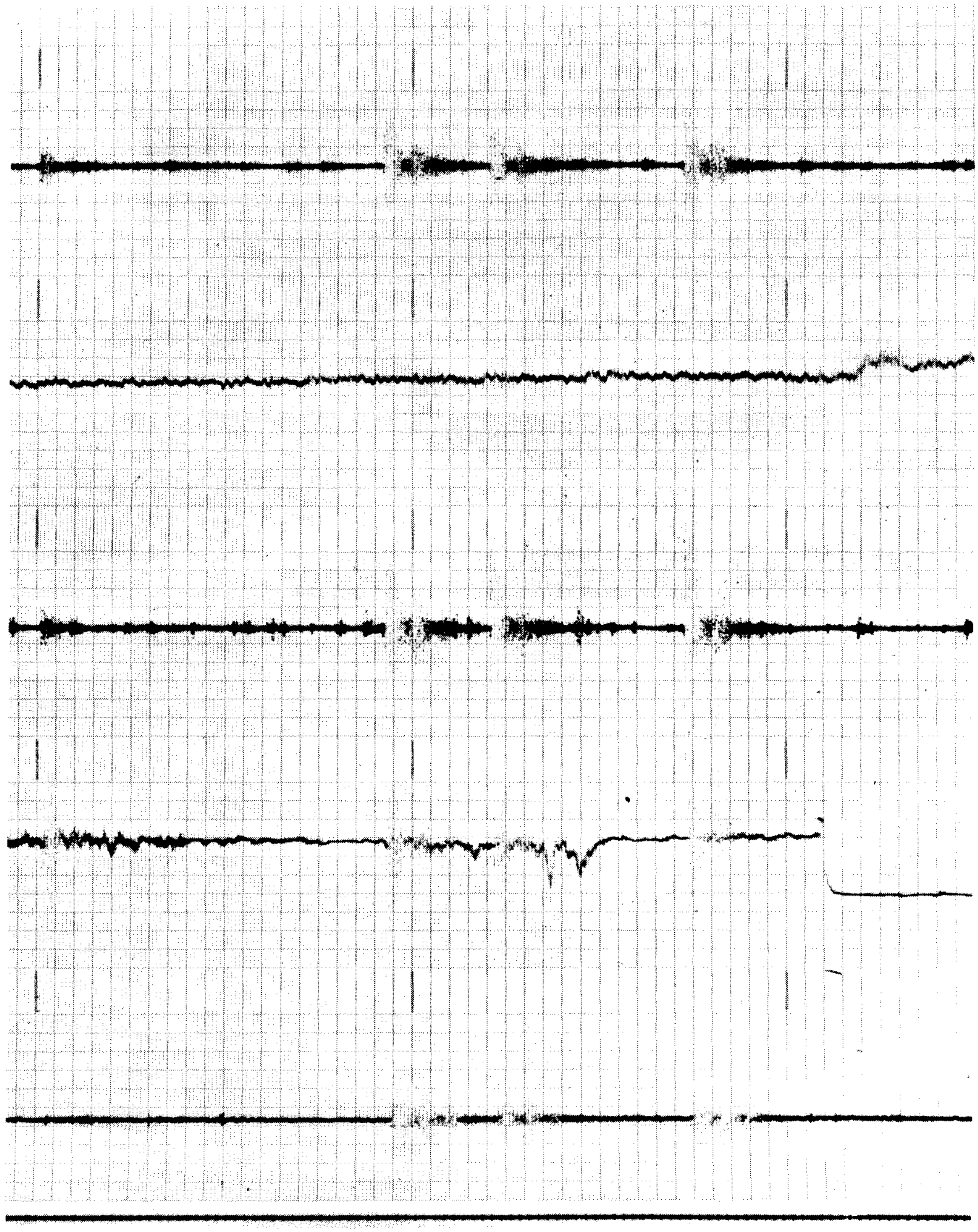


Gulf of California, Central Part



Earthquake Swarm