INSTITUTE OF GEOPHYSICS and PLANETARY PHYSICS

LA JOLLA LABORATORIES
at the Scripps Institution of Oceanography, UCSD

Summary of Research Activities

JULY 1965 - JUNE 1970

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ASSOCIATE DIRECTOR'S REPORT:
WALTER H. MUNK

JULY 1965 - JUNE 1970

BUDGET AND PERSONNEL FOR THE YEARS 1967–68 AND 1969–70

Institute of Geophysics and Planetary Physics, La Jolla Laboratories

State Budgeted	Expenditures 1967-68	FTE	Expenditures 1969-70	FTE
Academic	$ 60,053	3.91	$ 77,100	3.91
Support	35,813		36,015	
Special	3,833		1,593	
	$ 99,699		$114,708	

Extramural Funds		
Research Grants & Contracts		
(a) Project	$692,243	$560,160
(b) Institutional	13,068	4,832
	$705,311	$564,992

Personnel	1967-68	1969-70
Faculty	9	9
Professional Research	11	11
Other	52	65

PHOTO ON OPPOSITE PAGE

The laboratory from the south. The Seminar Room overlooking the ocean is to the extreme left on the upper level. The rest of the upper level is occupied by offices. The laboratory wing extends southward and is accessible to trucks. A basement below the laboratory space includes a seismic and a peripheral computer center.

The building was financed half by University and half from outside sources. A statue, "Spring Stirring," by San Diego sculptor, Donal Hord, was the gift of Mr. and Mrs. Cecil Green.

INTRODUCTION

The formal decision to start a LaJolla Laboratory of the Institute of Geophysics and Planetary Physics was taken in 1960. The laboratory was dedicated late in 1964, and so the present report covers essentially the first five years of our existence.

The La Jolla Laboratory of IGPP is very closely tied to the Scripps Institution of Oceanography. The development of geophysics over the last few years has made it abundantly clear, as it should have been always, that land geophysics and ocean geophysics are part of the same subject. With the development of *plate tectonics* the emphasis in the Earth Sciences has shifted towards the seagoing work. The formation of the geophysical laboratory at the Scripps Institution was therefore a timely development.

MODE OF OPERATION

All members of the La Jolla Laboratory of IGPP have joint appointments with existing departments: Block and Lovberg with Physics; Bradner and Miles with Aerospace and Mechanical Engineering Sciences; Backus, Bullard, Eckart, Gilbert, Haubrich, Munk, Parker with the Scripps Department. James Brune and Russ Davis are entirely within the Scripps Department, but are housed at IGPP.

We also house Professor and Mrs. Burbridge, both astrophysicists, within the Department of Physics. This arrangement was made with the expectation that astrophysicists and geophysicists have much to learn from one another. To some extent this hope has been fulfilled, but the interrelation is not as close as we had hoped.

The IGPP faculty fully participates in University functions, just as their colleagues in the Liberal Arts and in the Sciences. For example, Dr. Bradner was Acting Provost of Revelle College for the academic year 1966-67, and Dr. Munk was Chairman of the UCSD Academic Senate 1968-69.

TEACHING

Since all faculty members at IGPP are also members in a teaching department, they carry out their formal course work as a part of their departmental responsibility. However, we have encouraged IGPP faculty to bring their advanced graduate students to the Institute (this is the pattern in the USSR). Accordingly, we have Scripps, Physics and AMES graduate students working next to one another, each fulfilling their departmental requirements, but all working on some aspect of understanding the planet Earth.

RESEARCH

There are no organized research activities at this laboratory other than those which individual staff members find convenient to arrange among themselves. In this sense, our work (as at many other University Institutes) differs from that in industry and government. Yet such loosely organized activity has proven quite effective.

Roughly, our research activities fall into three categories:

SOLID EARTH

Here we seemed to have moved toward a reasonably coherent effort; starting with new types of instrumentation, and ending with a better understanding of the deep earth and of earthquake mechanism (with a view towards prediction). Our activities were pioneered by Backus, Haubrich and Gilbert; the work was greatly strengthened with the arrival of Brune.

Theory. Backus and Gilbert have devoted much of their effort to the geophysical "inverse problem": given some information (such as the frequencies of the earth's normal modes) what can be learned about the distribution of density and elastic constants within the earth? (This pioneering work has earned Backus election into the National Academy of Sciences, the fourth Academy member at IGPP – La Jolla). Bullard (who comes here from Cambridge University, England, for two to three months each summer) and Parker have studied the temperature distribution within the earth from measurements of electrical potential and magnetic field.

Instrumentation. An effort has been made to develop low-frequency, low-drift broad-band instrumentation which can shed light on earth strain and earthquake mechanisms. Lovberg and Berger have developed a laser strain seismometer, lock and Moore an accelerometer, and Haubrich, a tiltmeter. The instruments have been deployed at the Institute's Camp Elliott Test Site about ten miles east of the Laboratory.

Earthquake Mechanism. This includes the work of Bradner, Brune, Haubrich, Richards and Wyss. The present emphasis is on a determination of regional stress, as it is related to earthquakes. Stations around the Gulf of California are being established jointly with the University of Mexico. Some offshore measurements are included in the program.

GEOPHYSICAL FLUID DYNAMICS

This group under the general leadership of John Miles includes Davis, Eckart and Garrett. They have studied a wide variety of problems applicable to both atmosphere and oceans.

ABYSSAL OCEANOGRAPHY

Munk and Snodgrass with Dormer and Wimbush have been working on various aspects of deep-sea measurements, including the study of deep-sea tides.

FACILITIES

The laboratory is housed in a redwood building north of Scripps Pier, overlooking the ocean. The cost was $20.90 per assignable square foot, including some built-in furniture. Ground access is provided at each of the four levels. All laboratories are open to truck access.

A field testing station at Camp Elliott provides space for testing seismic instruments, and has a general purpose digital data logging system. We are negotiating for some land at Pinyon Flat, two and a half hours from the Institute, for a permanent field site. This site is ideally located for a geophysical observatory to monitor earthquakes in all of Southern California.

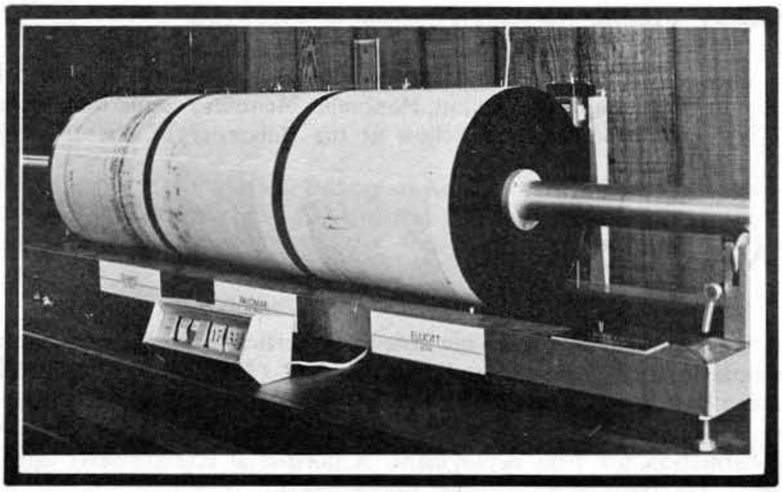

Figure 1. Seismic Recording Unit at entrance to Institute of Geophysics and Planetary Physics building. Earth movements are telemetered from Cal Tech stations; GLAMIS (East of Salton Sea) and Palomar (near Observatory) and UCSD station CAMP ELLIOTT (12 miles east of La Jolla). Instantaneous recording of earth motions by this array of stations allows immediate location and magnitude determination for earthquakes. This aids in planning field experiments to record aftershocks and to measure free oscillations of the earth.

GEORGE E. BACKUS, *Professor Geophysics*

Ph.D., University of Chicago; member of Phi Beta Kappa, Sigma Xi, American Academy of Arts and Sciences, New York Academy of Science, National Academy of Sciences; fellow, American Geophysical Union, John Simon Guggenheim Memorial Foundation

GEOPHYSICAL INVERSE PROBLEMS

Seismic research has included a potential representation of tangent tensor fields on spheroids, a geometrical representation of arbitrary fourth order elastic tensors, and a catalog of all possible forms of small anisotropy in the upper mantle. Seismic research with F. Gilbert has included a general formulation of geophysical inverse problems, accounting for errors of observation and the finite resolving power of the data; numerical applications have been made to the earth's elastic-gravitational normal modes. Geomagnetic research has included a method for finding all motions of the core capable of explaining the secular variation at time scales for which the core is nearly a perfect conductor, and an investigation of the extent to which observations of the magnitude of the external geomagnetic field determine that field.

BARRY BLOCK, *Associate Professor of Geophysics*

Ph.D., Massachusetts Institute of Technology; American Physical Society; American Geophysical Union; Honorable Mention – American Association of Physics Teachers, 1965; Visiting Fellow at the University of Maryland for one month, 1970.

ACCELEROMETER

A wide-band, tidal to seismic frequency vertical accelerometer has been developed which is of simple internal geometry and has low drift (10^{-9} g/day). Earth tidal measurements have been taken over the past year. Earth normal modes have been recorded from about 5-90 cph earthquakes as small as magnitude 6 (20 db signal to noise ratio). Several more of instruments are under construction for field deployment. A horizontal accelerometer using the vertical design and its associated technology is under development.

HUGH BRADNER, *Research Physicist; Professor of Engineering Physics and Geophysics*

Ph.D., California Institute of Technology; member of Seismological Society of America, American Geophysical Union, New York Academy of Sciences; Fellow, American Physical Society

SEISMIC GEOPHYSICS

Ocean-bottom seismic background studies were extended to include coherence between a bottom instrument and a midwater swallow float instrument. Energy is contained in several definable organpipe modes. Mid-ocean seismic background can be characterized by local ocean waveguide modes, driven by a broad non-white forcing function.

Measurements of crustal displacements from earthquakes were made with the Nordsieck pendulous gyro. During approximately one year of operation only one earthquake produced oscillation larger than background.

A program has been started on measuring pressures and accelerations in the near field of oceanic earthquakes. This work is of interest for determining epicenter characteristics and locations (with Dr. Brune) and the effects of earthquakes on structures in the ocean (with Professor Isaacs).

JAMES N. BRUNE, *Professor of Geophysics*

Ph.D., Columbia University; Seismological Society of America – President, 1970; Vice President, 1969; Board of Directors, 1967-72; American Geophysical Union, New York Academy of Sciences.

EARTHQUAKE MECHANISMS

The spectra of earthquakes are being studied in detail to recover source parameters; in particular stress and source dimensions. If stress can be estimated from spectra of earthquakes then small earthquakes might be used to map stress and thus determine the areas of greatest seismic hazard. Once our laser strain meter is operating in a tectonically active area it is hoped that the pattern of strain build-up along the San Andreas fault may be better understood and this may help to understand the pattern of stress indicated from the spectra of seismic waves.

Discrimination and identification of underground nuclear explosions: The Block-Moore accelerometer is being used to study seismic waves generated by earthquakes and explosions. Since the instrument is believed to be quieter than any other instrument for the wave periods of interest, it may be possible to extend the current discrimination techniques to lower magnitudes.

SIR EDWARD BULLARD, *Professor of Geophysics*

Ph.D., Cambridge; Sc.D., Cambridge; Sedgwick Prize (1936); Fellow, Royal Society (1941); Hughes Medal, Royal Society (1953); Foreign Honorary Member, American Academy of Arts and Sciences; Chree Medal of the Physical Society (1956); Day Medal, GSA (1959); Foreign Member, National Academy of Sciences; Agassiz Medal, NAS (1965); Gold Medal, Royal Astronomical Society (1965); Wollaston Medal, Geological Society of London (1967); Vetlesen Prize (1968); Foreign member American Philosophical Society (1969).

PLATE TECTONICS

THE EARTH'S MAGNETIC FIELD

If the continents around the Atlantic were once joined together then it should be possible to fit the pieces together again. An objective method of doing this on a computer was devised. The resulting fit was better than could reasonably have been expected and, with the hardening of opinion in favor of the hypothesis of Continental Drift, has been extensively used by others studying many aspects of the problem. Continental Drift has now become part of Plate Tectonics and has developed connexions with most branches of geology and geophysics. The whole subject was reviewed in a Bakerian Lecture to the Royal Society and at much greater length in the published version of the lecture. At present the main problems seem to lie in the relation of plate tectonics to continental geology and to the history of *inland seas*.

In geomagnetism some progress has been made in understanding the difficulties of the dynamo theory of the origin of the field. Substantial work has also been done in the quite different topic of electromagnetic induction in the earth by natural magnetic variations. The theory of induction in the oceans has been studied in collaboration with Dr. R.L. Parker and a review written. On the experimental side, extensive measurements have been made by graduate students in the British Isles, remarkable anomalies exist and some progress has been made in their interpretation.

DOUGLAS R. CALDWELL, *Assistant Research Geophysicist, Currently Assistant Professor, Department of Oceanography, Oregon State University*

Ph.D., University of Chicago.

DEEP SEA OCEAN CURRENTS

Transducers using the hot wire principle were developed and used with the Deep Sea Tide Capsules to measure ocean bottom currents. Studies were made of the instabilities of the laminar Ekman boundary layer and of mean profiles and turbulent spectra of the turbulent Ekman layer. The theoretically predicted multiple-valued heat flow for finite-amplitude instability of a fluid layer heated from below was found. Measurements of the thermal expansion coefficient for sea water under pressure, using the Rayleigh-Benard instability, showed that the traditional form of the equation of state predicts this quantity better than more recent formulations.

FLORENCE OGLEBAY DORMER, *Programmer*

M.A., Syracuse University

BOOM TIME SERIES ANALYSIS SYSTEM

The BOOM computer programming system for time series analysis is the successor to the BOMM system and is named for its authors: E.C. Bullard, F. Oglebay Dormer and W.H. Munk. It is written for the CDC 3600 computer.

The system like its predecessor, is a user-oriented set of routines designed in such a way as to make a reasonably simple language which is well related to the operations performed. In devising the system the main objectives were to enable a wide variety of data formats to be accepted without recoding, to allow gross errors to be removed automatically from the data, to provide considerable variety of arithmetic operations and leave the user free to choose the order in which they are applied, and to allow further processes to be easily incorporated into the system.

The basic features which make BOOM superior to BOMM are: 1) the language of BOOM is an extension of Fortran, 2) BOOM is designed to operate on merged or multiplexed time series, 3) BOOM makes use of the interrupt and asynchronous input/output features of the CDC 3600, 4) a dynamic memory allocation scheme makes more efficient use of computer memory, and 5) the fast Fourier transform is incorporated into BOOM. The set of BOOM statements for studying the tides has been redesigned to take advantage of the merger series feature of BOOM.

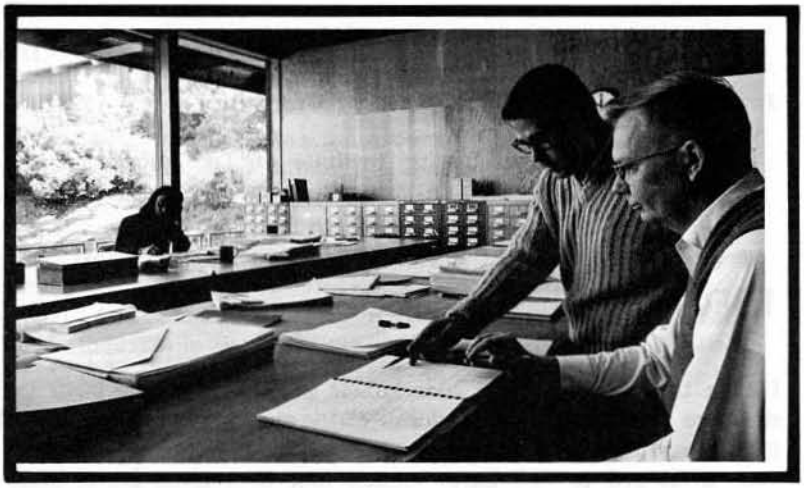

Figure 2. Geotape Room. The preparation area for a library of magnetic tapes, called geotapes. Recorded in a prescribed format, the geotapes contain geophysical time series together with legends describing the series.

CARL ECKART, *Professor of Geophysics*

Ph.D., Princeton University; Member of American Association for Advancement of Sciences, Acoustical Society of America, National Academy of Sciences, Sigma Xi; Guggenheim Fellow; Alexander Agassiz Medal (National Academy of Sciences)

For the past three years, the principal project has been the development of systematic equations for geophysical hydrodynamics, and their solution in special cases (barotropic, solenoidal, and adiabatic approximations). It has been possible to cast these equations into a form analogous to the beta plane equations, thus making it possible to use rectangular coordinates and avoid the complexities of the spherical geometry.

CHRISTOPHER J. R. GARRETT, *Assistant Research Geophysicist*

Ph.D., University of Cambridge

FLUID DYNAMICS

Two theoretical problems of ocean engineering have been studied. The first concerns the excitation of oscillations in bottomless harbours of artificial islands; the results also led to a reevaluation of theories of the excitation of oscillations in ordinary harbours. The second concerns wave forces exerted on a circular dock. Work was also completed on a theory of cross waves, half-frequency water waves at right angles to wavemakers first observed by Faraday in 1831 and hitherto unexplained.

J. FREEMAN GILBERT, *Professor of Geophysics*

Ph.D., Massachusetts Institute of Technology; member of Seismological Society, Geophysical Union, Sigma Xi, American Academy of Arts and Sciences, Society of Exploration Geophysicists.

THEORETICAL SEISMOLOGY

During the past five years considerable progress has been made in the determination of Earth structure from the normal modes of elastic-gravitational vibration of the Earth. Perturbations due to Earth rotation and ellipticity of figure are now theoretically well understood. Methods have been developed to find Earth models that fit a given set of data, and to determine localized averages of Earth structure. The identification of normal mode eigenfrequencies has been improved by using relative excitation amplitudes for a known fault plane solution.

Some progress has been made in the application of the Cagniard de Hoop method to radially stratified media.

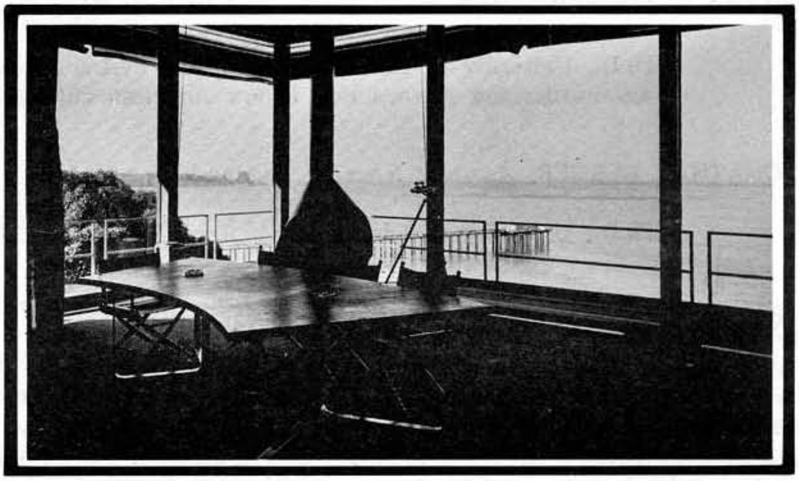

Figure 3. View from the IGPP Conference Room Overlooking the Scripps Institution of Oceanography Pier and the La Jolla Cove.

RICHARD A. HAUBRICH, *Professor of Geophysics*

Ph.D., University of Wisconsin, American Geophysical Union; Society of Exploration Geophysicists; Geological Society of America; European Society of Exploration Geophysicists; Royal Astronomical Society; Society of the Sigma Xi; Seismological Society of America.

SEISMIC STUDIES AND EARTHQUAKE RESEARCH

The continuous background motion of the earth's surface has been studied using data collected from LASA, a large seismic array located in eastern Montana. The frequency, velocity and direction characteristics of the ground motion was determined in the frequency band from 0.04 to 0.5 Hz. Sources of the seismic waves were found to be storm waves near coast lines and the wake of large storms at sea. Seismic background below 0.04 Hz was also studied using data from special low noise, low frequency seismometers. Atmospheric pressure variations acting locally on the ground appear to be responsible for the background seismic motion in this band. The statistical properties of the occurrence of earthquakes in time have been studied. The relationship between earthquake occurrence and latitude changes has been investigated; no significant correlations have been found.

RALPH H. LOVBERG, *Professor of Physics and Research Physicist*

Ph.D., University of Minnesota; American Physical Society; American Institute of Aeronautics and Astronautics; Fellow American Physical Society.

JONATHAN BERGER, *Assistant Research Geophysicist*

Ph.D., University of California, San Diego

STUDIES OF THE EARTH'S STRAIN FIELD

A laser interferometric strain meter of high sensitivity and exceptional long-term stability has been developed and deployed at the Elliott Geophysical Observatory. This instrument, which is a surface installation, has a digital output that is flat from D.C. to 1 MHz. Studies are currently underway involving correlations between strain, tilt and vertical displacement due to earth tides, ocean and atmospheric loading, earthquakes and nuclear detonations. Long term strains associated with regional tectonic activity are routinely monitored for studies of fault movements and earthquake mechanisms with a long term goal of earthquake prediction. The deployment of a second geophysical observatory in the region of the active San Jacinto and San Andreas fault systems is planned. This observatory will include a three axis laser strain meter, long baseline tiltmeters, quartz accelerometers of the Block-Moore design, a microbarograph array, as well as a set of standard seismic instruments. An on-line computer will control a digital recording system allowing real time data reduction of the various geophysical outputs.

JOHN W. MILES, *Professor of Applied Mechanics and Geophysics; Chairman, Aerospace and Mechanical Engineering Sciences Department*

Ph.D., California Institute of Technology; Fulbright Fellow, (U.K.), 1969; Fellow, AIAA.

ACOUSTIC AND ELECTROMAGNETIC DIFFRACTION THEORY; SUPERSONIC AERODYNAMICS, ESPECIALLY NONSTATIONARY PROCESSES: WATER WAVES: ELASTIC WAVE PROPAGATION; HYDRODYNAMIC STABILITY

Recent research has concerned hydrodynamic stability, water waves and elastic waves, with special reference to meteorology and oceanography (generation of ocean waves by wind). Research will continue in the area of fluid mechanics, as applied to problems of meteorological and oceanographic interest, and is currently on lee waves in rotating and stratified flows, tsunami response of harbors and bays, and diffraction of swell.

ROBERT D. MOORE, *Assistant Professor of Applied Electrophysics; Assistant Research Geophysicist*

Ph.D., Princeton University; Sigma Xi

SEISMIC INSTRUMENTATION DEVELOPMENT

Early work was concerned with modifying a pair of La Coste gravimeters for earth tide recording. Work has been and still is being done with these instruments studying tidal loading phenomena (in conjunction with W.E. Farrell). Development of a quartz-spring accelerometer of novel design has been successfully completed (with Barry Block). This instrument has recorded earth normal mode activity from medium size earthquakes (with Barry Block and Jay Dratler). The existing quartz instrument, now in full-time operation at our Camp Elliott field site has been adapted for use in studying the possibility of nuclear test detection using long period (40 sec) waves as a discriminant to distinguish bombs from earthquakes.

A self-contained version of the quartz instrument for underwater operation is being developed.

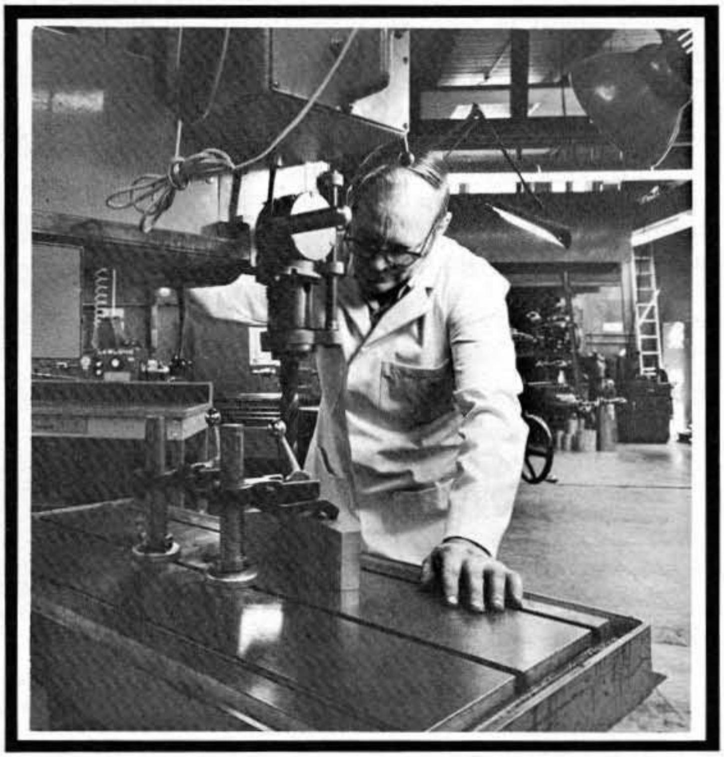

Figure 4. Machine Shop. Research work at the La Jolla Laboratories of IGPP is facilitated by a well equipped shop.

WALTER H. MUNK, *Associate Director (IGPP/UCSD); Director, La Jolla Laboratories; Professor of Geophysics*

Ph.D., University of California; member of National Academy of Sciences; American Academy of Arts and Sciences, American Philosophical Society; Leopoldina; Sverdrup Gold Medal, American Meteorological Society; American Geological Society; Gold Medal of the Royal Astronomical Society.

FRANK E. SNODGRASS, *Research Engineer*

D.Sc. Flinders University of South Australia; M.S.E.E., University of California, Berkeley.

TIDES

A free-falling capsule has been developed which is dropped from shipboard, records on computer-compatible tape, and is recalled to the surface by acoustic command from a vessel. Over 50 drops exceeding 2 km. in depth have been made, and many of the records exceed one month in duration. The work has been done off California and between Australia and Antarctica. On the basis of these observations, the behavior of the tides in the deep sea has been discussed. The implications of tidal effects on the history of the Earth-Moon system is being studied.

BENTHIC BOUNDARY LAYER

The flow in the lowest 10 m of the ocean has been studied by direct observation, and by application of boundary layer theory (with Mark Wimbush).

INTERNAL WAVES

A study of internal waves of tidal and inertial frequencies has led to some theoretical criteria for the coherence scale of motion in the sea (with Norman Phillips).

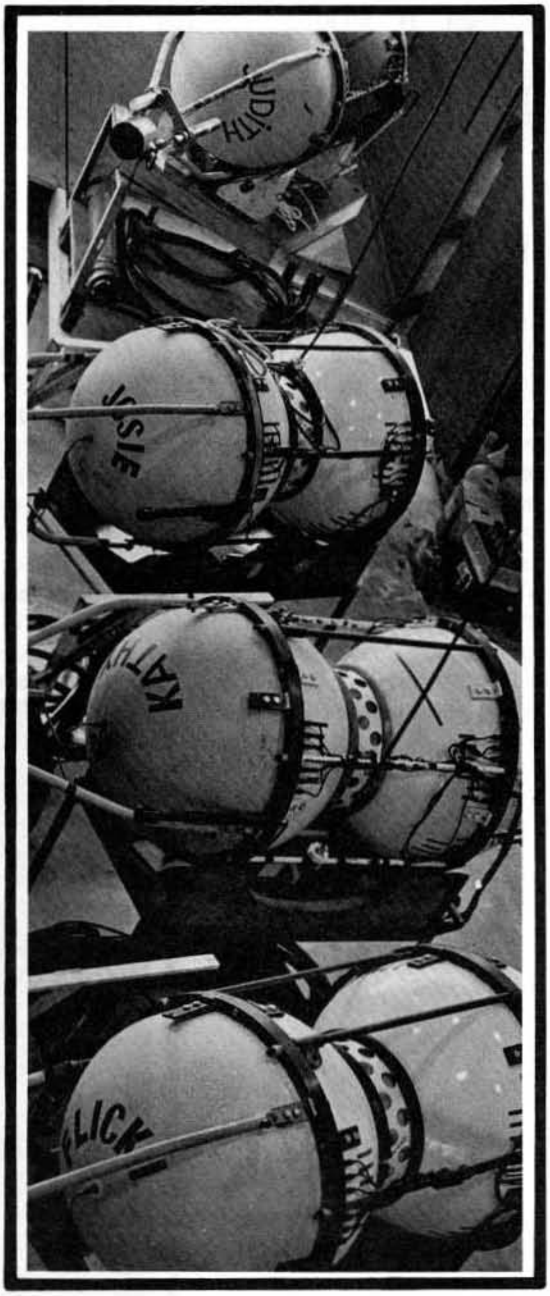

Figure 5. Four Deep Sea Tide Capsules Lined up in the La Jolla Laboratory.

SURFACE WAVES

Bragg scattering of e.m. waves from the sea surface has yielded information on the saturation constant of the wave spectrum (with William Nierenberg).

ROBERT L. PARKER, *Assistant Professor of Geophysics*

Ph.D., Downing College, Cambridge, England; Cambridge University Tape Recording Society; Cambridge University Musical Club; Sloan Foundation Fellowship (1969-1971).

ELECTROMAGNETIC INDUCTION IN THE SEA

It has been known experimentally for some time that the oceans cause a modification to the magnetic fluctuations observed near the coast, but how much of the modification is due to the water and how much to a difference in the conductivity 50 km. beneath the surface is not known. Calculations have been made concerning the effect of an ocean above, with a constant structure under the continent of the land. The nature of the equations forces one to consider very large areas of ocean even when a knowledge of the electric currents is required in quite a small area. Thus, as a first step, computer programs have been written to find the currents in the complete global system of the oceans. Then when a local problem needs attention the global solution can be used as a starting point.

The inversion techniques of Gilbert and Backus have been applied to a theoretical study of the electrical conductivity deep within the earth, say 200 km. – 2000 km. in depth. It is possible to give specific recommendations to the experimentalists on the type of data that determines the structure.

PAUL G. RICHARDS, *Assistant Research Geophysicist*

Ph.D., California Institute of Technology; Member of Seismological Society of America; American Geophysical Union; Society of Exploration Geophysicists

SEISMOLOGY

The theory of seismic body waves has been extended to investigate departures from classical ray theory. Accomplishments include the development of a complete system of potentials for studying elastic displacements in spherically symmetric media; the prediction, in realistic Earth models, of amplitude and phase-slowness (for P, SV, SH) near the core shadow boundary; and the deduction, from published seismic reflection data, that there must be transition regions in the mantle where velocities change by several percent over less than 3 or 4 vertical kilometers.

MARK A. WIMBUSH, *Assistant Research Geophysicist*

Ph.D., University of California, San Diego

THE BENTHIC BOUNDARY LAYER

Using the deep sea recording capsule developed by Frank Snodgrass, the dynamical and thermal structure of the abyssal boundary layer has been studied. Mean profiles and spectra of current and temperature were measured in the bottom few metres of the deep sea. Results were consistent with theoretical expectations, except that no significant mean current veering was found.

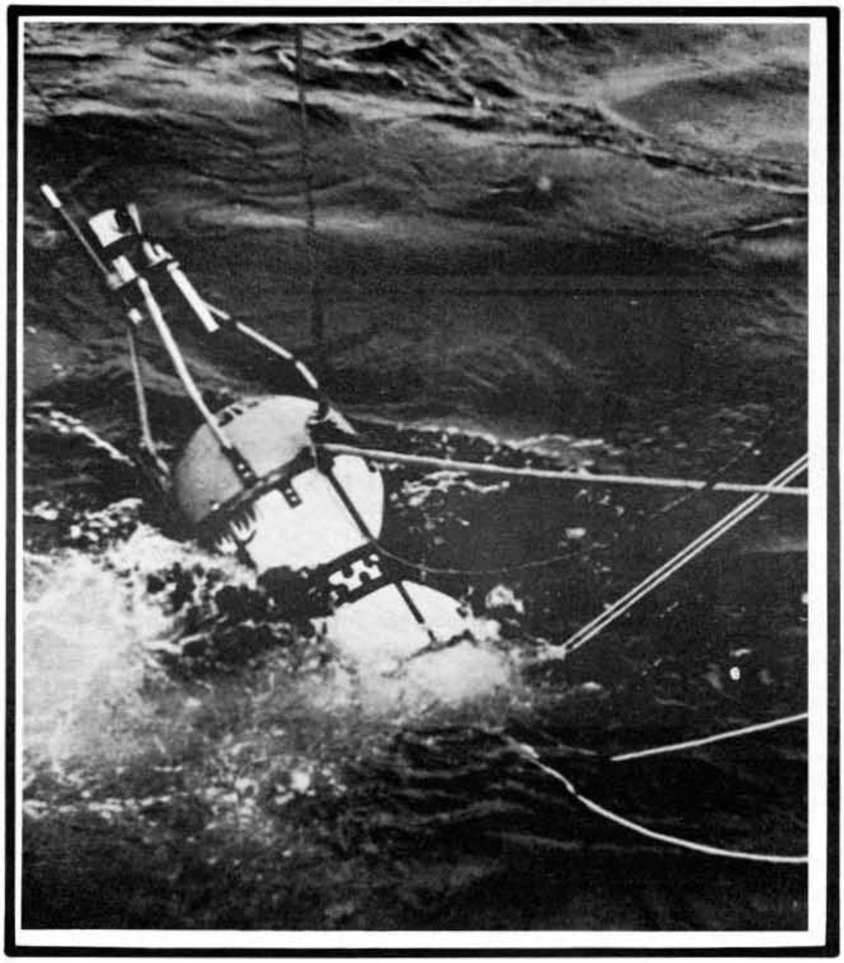

Figure 6. Launching the Deep Sea Tide Capsule, JOSIE.

MAX WYSS, *Assistant Research Geophysicist*

Ph.D., California Institute of Technology; Seismological Society of America; American Geophysical Union, American Association for the Advancement of Science.

EARTHQUAKE MECHANISM

Earthquake source parameters are estimated from seismic amplitude spectra. The seismic moment, radiated energy and apparent average stress is determined for approximately 300 earthquakes, magnitude 1 to 6, in the Western United States. The compiled apparent average stress map of Southern California together with the known seismicity furnished, at the present time, the best information for the assessment of the likelihood of an earthquake in a particular region.

For a number of small earthquakes the fault dimension, dislocation and stress drop is estimated using a theoretical source model. It is shown that earthquakes of magnitude 1 to 5 have typically 10 times larger source dimensions than nuclear explosions of equal magnitude. A comparison of nuclear explosions on Amchitka with earthquakes in that region shows that not only the excitation of long period surface waves but also the excitation of long period P-waves is a good discriminator.

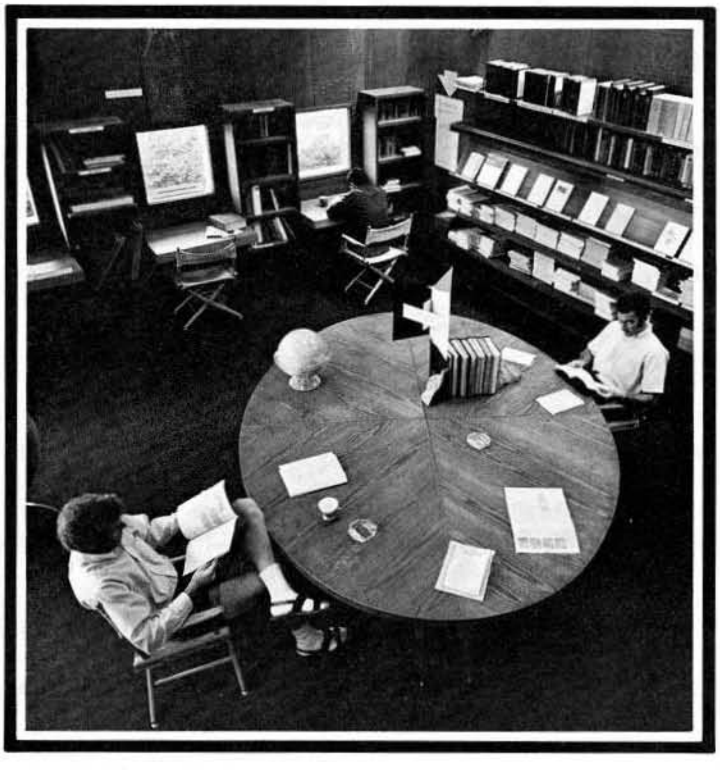

Figure 7. Reading Room. The library of journals and selected references is made possible by a contribution from the Westinghouse Corporation.

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