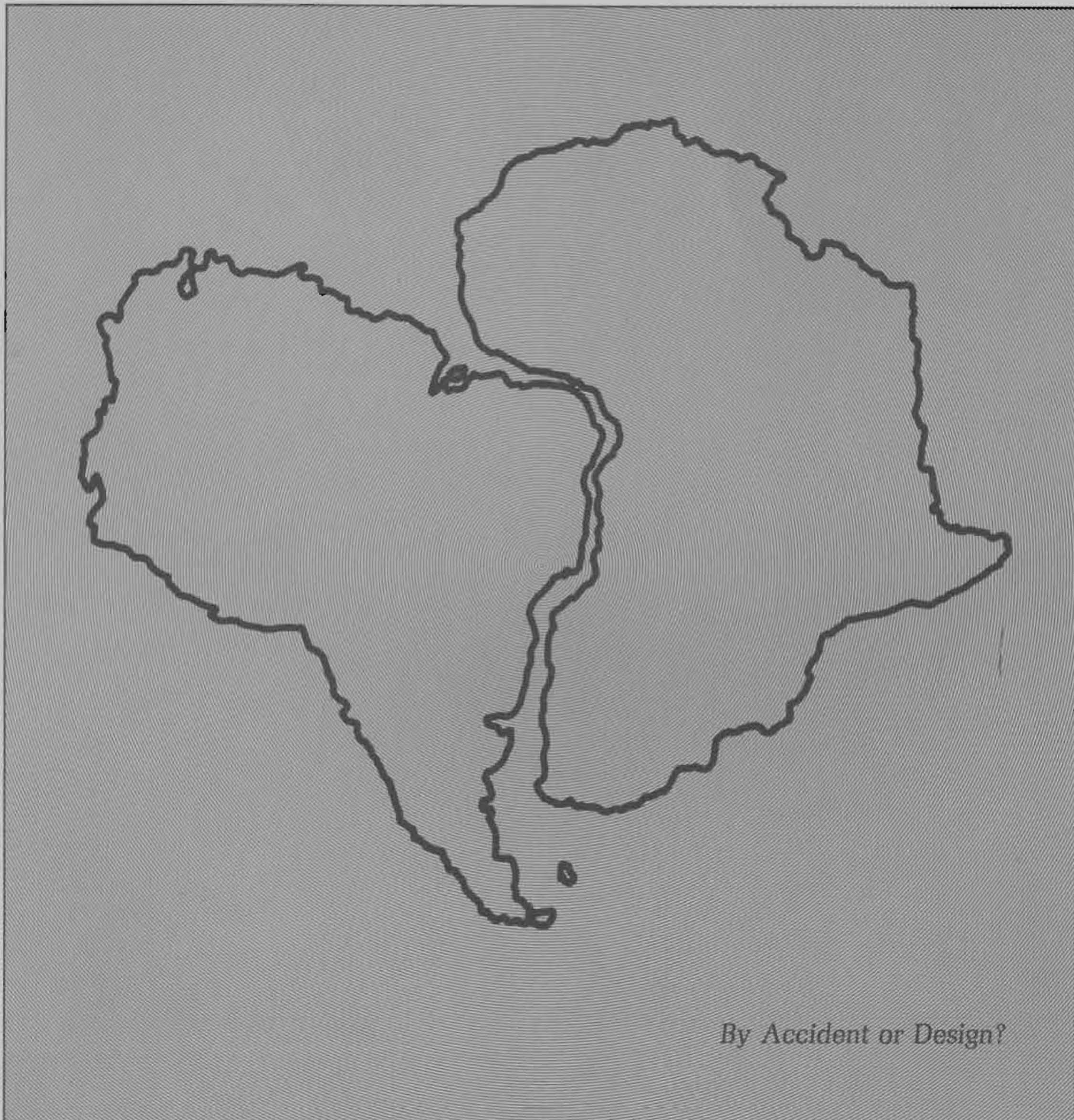
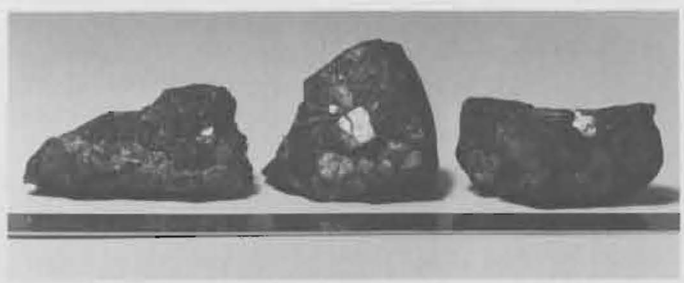
Annual Report of the Geosciences Division
1966-1967
Southwest Center for Advanced Studies



Annual Report of the Geosciences Division
1966-1967
Southwest Center for Advanced Studies

Published at Dallas, Texas, by the Southwest Center for Advanced Studies
An independent, non-profit institution chartered by the State of Texas for purposes of fundamental research and advanced education, in the public interest.
Printed in the United States of America

Contents



Diamond bearing eclogite, a gift from Mr. R.C. Versluis, a prospector from Barkely West, South Africa.

INTRODUCTION

One of the spectacular developments in earth science over the past two or three years has been the discovery by Vine and Matthews that the oceans are indeed spreading in the manner required by the hypothesis of continental drift. In essence it has been found that the magnetic anomalies on either side of the mid-Atlantic and other ocean ridges can be matched fairly precisely and show a pattern of reversed and normal fields. The pattern can be reproduced by models of the known field over the past three or four million years and thus estimates of the rate of spreading can be made. The rates are from 1 to 4 cm. per year, more or less the values proposed by the drifters.

This development has been watched with interest by the Division, for one of our first major programs, that of Drs. John W. Graham and Charles E. Helsley, was the study of the fossil magnetism of rocks. It has been clear for some ten years past that the easiest way to account for the observed directions of the magnetic field in ancient rocks was in terms of changes of the relative positions of the continents, i.e., in terms of continental drift. This new confirmation of drift will lend impetus to our own program, the central theme of which is an effort to determine as precisely as possible the relative positions of the continents in times past.

It also bears upon other parts of our program for it seems to us that the search for an understanding of the mechanism of drift is greatly dependent on increased knowledge of the properties of the upper mantle.

The study of the travel times of the seismic body waves of earthquakes begun by Drs. John R. Cleary and Anton L. Hales has been extended by Mr. Hugh A. Doyle and Dr. Hales to S waves. The ratio of the regional variations in S travel time to those in P travel time was found to be unexpectedly large. The implications of this result are that most of the difference is in the shear modulus and it has been suggested that partial melting has occurred in the upper mantle below the western United States.

Studies by Mr. Rodleigh W.E. Green and Dr. Hales of the travel times from a series of explosions in Lake Superior and comparison of these times with those from nuclear explosions in Nevada and New Mexico also show that there are major differences in upper mantle structure between parts of the western United States and the central United States.

Another method of looking at the structure of the upper mantle is through the dispersion of surface waves. Dr. Mark Landisman, in addition to pursuing his series of studies on the construction of theoretical seismograms, has collaborated with Dr. Adam Dziewonski in a program for the improvement of methods of analysis of the surface wave part of the seismogram. Mr. Selwyn Bloch and Dr. Hales have pursued a closely related investigation of methods of determining the phase velocity dispersion of the surface waves.

Dr. John S. Reitzel has completed the set of magnetic variometers begun by Dr. D. Ian Gough. During the past summer the array was set up from Nevada to the edge of the Central Plains. This study of anomalous magnetic variations is yet another way of looking at the properties of the upper mantle, in this case the electrical conductivity. It is probable that the electrical conductivity is very closely related to the temperature. It is known already from a preliminary series of observations made by Dr. Reitzel during the summer of 1966 that the anomaly found by Schmucker in New Mexico also occurs in Colorado.

The study of the inclusions in "diamond" pipes by Dr. Ian D. MacGregor and Dr. James L. Carter has continued. It is clear that this study together with the associated work on the properties of synthetic systems at high temperature and pressure will provide much needed information on the material of, and the processes of chemical fractionation in the upper mantle.

Dr. Glen H. Riley's study of the Black Hills pegmatites has shown that the phosphate materials appear to soak up strontium from the neighboring rocks. In spite of this complication, Dr. Riley has been able to establish the "age" of the pegmatites more accurately than heretofore.

Dr. Martin Halpern has started work on a new suite of Antarctic rocks. This suite was collected by Dr. F. Alton Wade of Texas Technological College during a recent expedition to Antarctica. He has also continued his studies of the ages of South American rocks and especially of the relation between South America, the Santa Arc and the Antarctic Scotia Peninsula.

Mr. William I. Manton's initial study of a suite of Lebombo rocks is complete. It raised some interesting questions with regard to the evolution of crustal rocks from the mantle and is to be extended to a new suite of rocks and other processes.

During the past year Dr. Helsley carried out seismic refraction studies in cooperation with the Scripps Institution of Oceanography from the R/V Thomas Washington. Our major effort in marine geophysics, however, was directed towards an experiment which we hope will throw light on the deposition of the Gulf Coast sediments and especially on whether these were laid down in shallow or deep water.

As the year closed the activities of the Division were extended to include micropaleontological and geochemical studies of sediments.

Anton L. Hales
Head, Geosciences Division

1. SEISMOLOGY

A. Seismic Surface Waves: Dispersion and Synthesis

Mark Landisman
Adam Dziewonski
Brian Mitchell
Robert Massé
Selwyn Bloch

The seismology group has continued its program of international co-operation, a program involving joint efforts of scientists affiliated with the Southwest Center and with institutions in Germany, Poland and Japan. Visitors from abroad have included Prof. Stephan Mueller, Director of the Geophysical Institute of the Technische Hochschule in Karlsruhe, Germany, and Dr. Dziewonski, on leave from the Polish Academy of Sciences in Warsaw, Poland. The advanced graduate students have taken oral examinations and are working on thesis projects. Several new students are expected to join the program when Dr. Landisman's survey of significant literature in theoretical and observational seismology will again be offered in the fall semester of 1967.

The sialic low-velocity channel proposed by Mueller and Landisman for the world's continents and continental margins (Mueller and Landisman, 1966 a, b) and confirmed by recent refraction studies in Germany (Fuchs and Landisman, 1966a, b) is the subject of continued study. Fundamental and higher modes of Love and Rayleigh wave propagation are being studied in Germany, southwestern North America, eastern Australia and southern Africa by Dr. Dziewonski, Mr. Bloch, Mr. Massé, Mr. Mitchell and Dr. Landisman. As might have been expected, significant variations in the velocity distributions in these areas have been found. In spite of these variations, work is proceeding in the attempt to more fully understand the nature of the propagation medium consisting of the crust and upper mantle. Two progress reports of these efforts were presented at the annual meeting of the American Geophysical Union (Dziewonski and Landisman, 1967; Bloch, Hales and Landisman, 1967), and another report was made at the Fourth International Symposium on Geophysical Theory and Computers (Landisman, Dziewonski, Massé and Satô, 1967).

The theoretical program, the result of a long and fruitful cooperative effort between Dr. Landisman and scientists of the Earthquake Research Institute of The University of Tokyo, Japan, has been concerned with the calculation and study of theoretical seismograms for realistic earth models. This fundamental effort to gain a better understanding of the basic elements which affect seismic waves traveling through the earth has produced seismograms which are extremely similar to ordinary teleseismic recordings. Notable results of this effort are the duality represented by higher modes and body waves, the effects of the core on reflected and diffracted waves, the relation of certain of the normal modes of spheroidal oscillation to Stoneley wave propagation along the core boundary, as well as the channelling of higher mode energy by Gutenberg's low-velocity channel in the upper mantle.

References

Bloch, S., A.L. Hales, and M. Landisman, "Rayleigh Wave Studies in South Africa" (abstract), Trans. Am. Geophys. U., 48 (1), p. 207, 1967.

Dziewonski, A. and M. Landisman, "Analysis of Surface Wave Dispersion Observed in Australia" (abstract), Trans. Am. Geophys. U., 48 (1), pp. 206-207, 1967.

Fuchs, K., and M. Landisman, "Results of a Re-interpretation of the N-S-Refraction Line Adelebsen–Hilders-South in West-Germany", Zeitschrift für Geophysik, 32, pp. 121-123, 1966a.

Fuchs, K. and M. Landisman, "Detailed Crustal Investigation Along a North-South Section through the Central Part of Western Germany," The Earth Beneath the Continents, Geophysical Monograph No. 10, J.S. Steinhart and T.J. Smith (Editors), American Geophysical Union, pp. 433-452, 1966b.

Landisman, M., A. Dziewonski, R. Massé and Y. Satô, "Analysis of Dispersed Seismic Waves", Fourth International Symposium on Geophysical Theory and Computers, Trieste, Italy, September 16-22, 1967.

Landisman, M. and S. Mueller, "Seismic Studies of the Earth's Crust in Continents II: Analysis of Wave Propagation in Continents and Adjacent Shelf Areas", Geophys. J.R.A.S., 10, pp.539-548, 1966b.

Landisman, M., Y. Satô and T. Usami, "Propagation of Disturbances in a Gutenberg-Bullen A′ Spherical Earth Model: Travel Times and Amplitudes of S Waves," The Earth Beneath the Continents, Geophysical Monograph No. 10, J. S. Steinhart and T. J. Smith (Editors), American Geophysical Union, Washington, D.C., pp. 482-494, 1966.

Mueller, S. and M. Landisman, "Seismic Studies of the Earth's Crust in Continents I: Evidence for a Low-Velocity Zone in the Upper part of the Lithosphere", Geophys. J.R.A.S. 10, pp. 525-538, 1966a.

Satô, Y., T. Usami, and M. Landisman, "Theoretical Seismograms of Torsional Disturbances Excited at a Focus Within a Heterogeneous Spherical Earth—Case of a Gutenberg-Bullen A′ Earth Model," Bull. Seism. Soc. Amer., in press.

Satô, Y., T. Usami and M. Landisman, "Theoretical Seismograms of Spheroidal Type on the Surface of a Gravitating Elastic Sphere, II. Case of Gutenberg-Bullen

A′ Earth Model", Bull. Earthq. Res. Inst., Tokyo Univ. 45, 1967.

Usami, T., Y. Satô and M. Landisman, "Theoretical Seismograms of Spheroidal Type on the Surface of a Heterogeneous Earth," Bull. Earthq. Res. Inst., Tokyo Univ., 43, pp. 641-660, 1965.

Usami, T., Y. Satô and M. Landisman, "Preliminary Study of the Propagation of Spheroidal Disturbances on the Surface of a Heterogeneous Spherical Earth," Geophys. J.R.A.S., 11, pp. 243-251, 1966.

B. S Wave Travel Times at Teleseismic Distances

Hugh A. Doyle
Anton L. Hales

In the early years of the Division Dr. Cleary and Dr. Hales studied the travel times of P waves from earthquakes to stations in North America. They found that there was a significant regional variation in the travel times, the arrivals being systematically early in the central United States, and late in parts of the western United States. Mr. Doyle and Dr. Hales extended this study to the S waves from earthquakes. They used the same methods of analysis and found a regional variation in S travel times similar to that found for P. The ratio of the S station anomalies to those for P was surprisingly high being about 3.7 instead of the expected value of somewhat less than 2. The excellent correlation of the two types of anomaly shown in Figure 1B-1 leaves no doubt that the effect is real. A paper describing the analysis has been published in the Bulletin of the Seismological Society of America.

The high value of the ratio of the S station anomalies to those for P has interesting implications. In the first place it can be shown that the observations are consistent with a model in which it is the shear modulus μ alone which varies, the incompressibility k remaining the same. In the second it follows that the temperatures at depths of the order of 100 km. in Nevada are very much higher than at similar depths in the central United States. A further conclusion reached by Dr. Hales and Mr. Doyle is that it is easier to account for the observations by partial melting than in any other way. A paper describing this second phase of the S study has been published in the Geophysical Journal of the Royal Astronomical Society.

References

Doyle, H.A. and A.L. Hales, "An Analysis of the Travel Times of S Waves to North American Stations, in the Distance Range 28° to 82°," Bull. Seism. Soc. Am., 57(4), pp. 761-771, 1967.

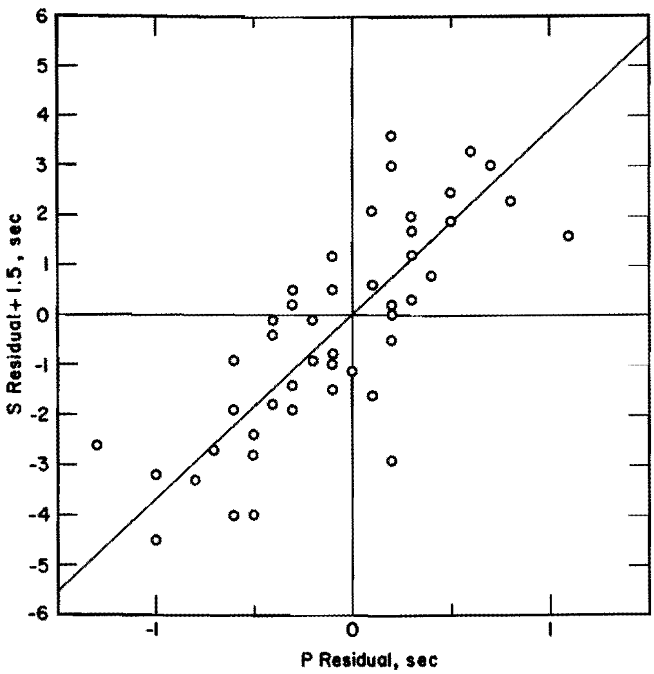


Figure 1B-1. P and S station anomalies (after Doyle and Hales, 1967)

Hales, A.L. and H.A. Doyle, "P and S Travel Time Anomalies and Their Interpretation", Geophys. J.R.A.S., 13, pp. 403-415, 1967.

C. The Early Rise Experiment

Rodleigh W.E. Green
Anton L. Hales

During July 1966, the U.S. Geological Survey Crustal Studies Branch, under ARPA sponsorship, organized a large scale seismic experiment called Early Rise. In this experiment 40 five-ton shots were fired at a single location in Lake Superior. The shots were observed by teams from a number of universities and other research laboratories. The Geosciences Division made observations at the points shown in Figure 1C-1. Good records were obtained all the way to the Texas-Mexico border as can be seen from the partial record section reproduced as Figure 1C-2. In addition observations were made of the seismic waves from a large nuclear explosion, GREELEY. The observation sites for GREELEY stretched across the central United States from Kansas to the North Carolina border. The Early Rise observations and those of GREELEY were combined with published travel times for shots at the Nevada Test Site and the GNOME explosion.

The analysis by Mr. Green and Dr. Hales confirmed that the upper mantle structures below Nevada and the Central Plains are very different. There is a marked low velocity channel at a depth of about 100 km. in Nevada, but the

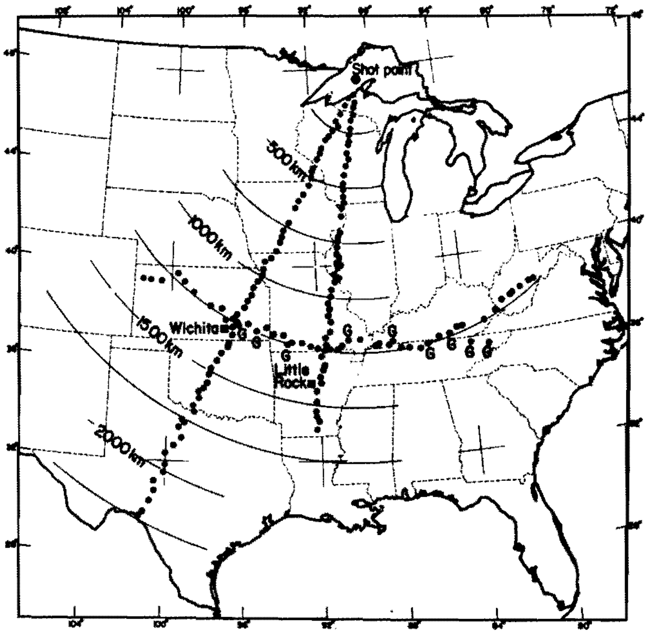


Figure 1C-1. Observation Sites for Early Rise Experiment and Nuclear Explosion GREELEY (G)

low velocity layer does not appear to exist below the Central Plains unless it is very deep or so thin and poorly defined as to be almost unobservable. The upper mantle structures of the two regions are compared in Figure 1C-3. A paper describing this work has been accepted for publication in the Bulletin of the Seismological Society of America.

Reference

Green, R.W.E. and A.L. Hales, "The Travel Times of P Waves to 30° in the Central United States and Upper Mantle Structure", Bull. Seism. Soc. Am., in press, 1968.

D. Surface Wave Studies in Southern Africa

Selwyn Bloch
Anton L. Hales

A number of new techniques have been developed for the determination of phase velocities from the digitized seismograms of pairs of stations. One of these techniques is to Fourier analyze the sum (or difference) of the two seismograms after time shifting the records to correspond to a

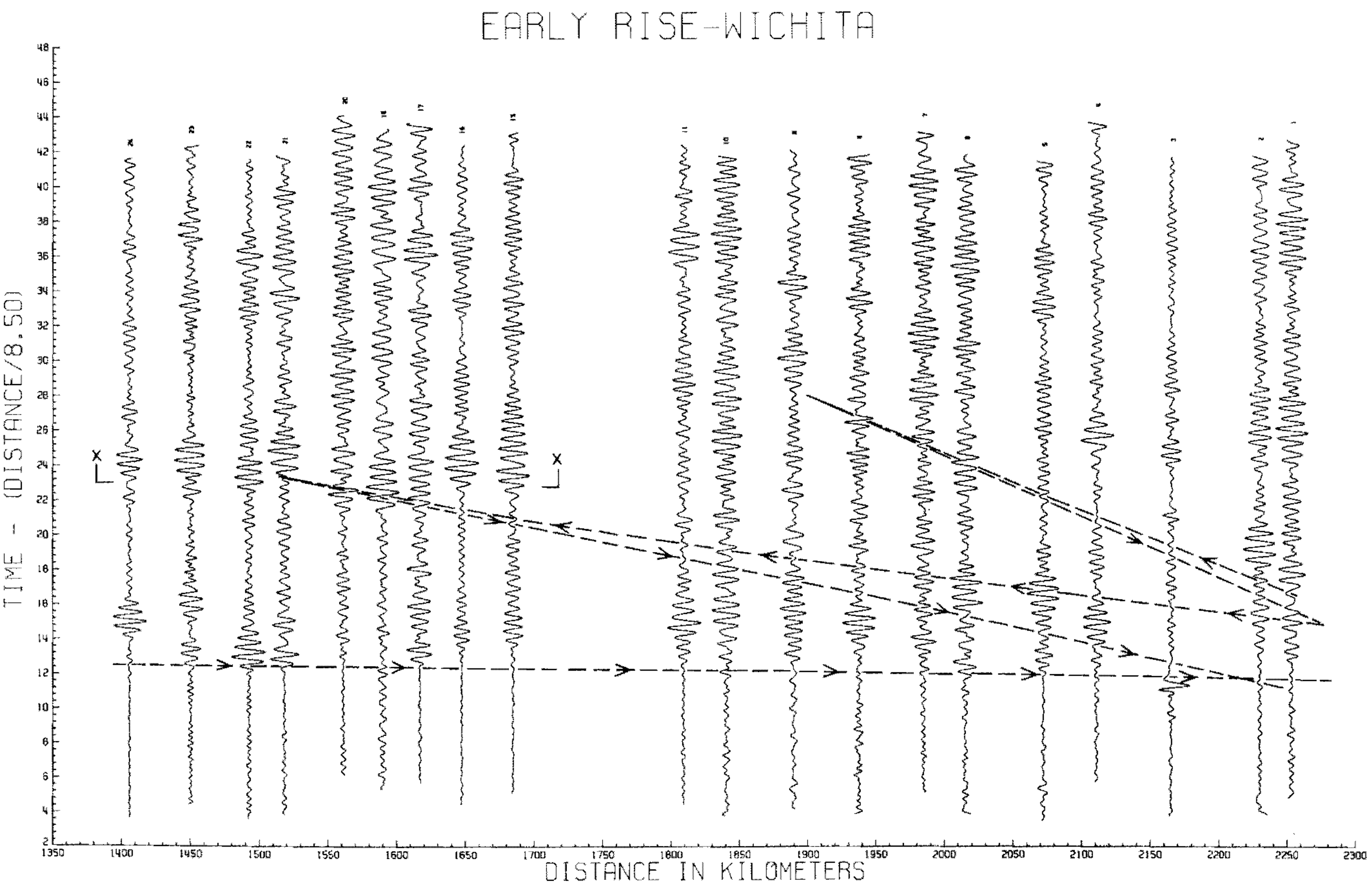


Figure 1C-2. Partial Record Section, Early Rise Experiment

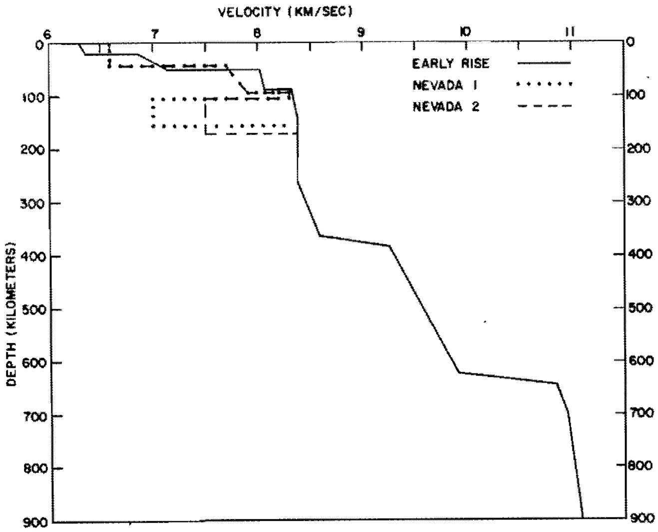


Figure 1C-3. Upper Mantle Structure Models: Nevada and Central Plains (Early Rise)

particular phase velocity. Only when the same period of both seismograms are in phase will the amplitude be a maximum (or minimum). The output is a matrix which shows the amplitude of the sum (or difference) as a function of phase velocity and period. The matrix is then contoured. Still further resolution and immunity from noise is obtained by forming the matrix of the ratio of the amplitudes of the difference and sum matrices. Another method which has proved successful is to pass both seismograms through a narrow digital filter and form the cross product of the filtered seismograms after time shifting for a particular value of the phase velocity. The output is again a matrix showing d.c. level, or average, as a function of phase velocity and period (see Figure 1D-1). Only when the periods are in phase will the d.c. level be a maximum.

Rayleigh wave phase velocities have been determined, using the techniques described above, for an array of stations centered around Johannesburg, South Africa, with a radius of approximately 200 km., and for the World Wide Network stations at Pretoria, Bulawayo and Windhoek. The Johannesburg area indicates higher shear velocities in the crust and upper mantle than those found in other shield areas, with an Sn velocity of 4.8 km/sec. This value is in good agreement with refraction studies done in the area. The World Wide Network stations indicate normal shield structure. Reliable results have been obtained for a period range of 15 to 100 secs.

The World Wide stations at Pretoria, Bulawayo and Windhoek have also been used for computing group velocities for a number of earthquakes located near Kariba Dam, Rhodesia, and one in southern Malawi, using a contouring technique developed by Drs. Landisman and Dziewonski. Fundamental and first higher mode Rayleigh and Love waves have been determined with reliable results for periods of 2-40 secs. for the fundamental mode and 2-15 sec. for the higher modes.

2. MARINE GEOPHYSICS

A. Gulf Coast Experiment

Anton L. Hales
Charles E. Helsley
Rodleigh W.E. Green
Joseph B. Nation
Selwyn Bloch

The Gulf Coast Geosyncline is one of a number of examples of basins in which sediments have been deposited to a thickness of over 10 km. It is not at all clear how such a thick body of sediments was deposited. It is easy to show that the maximum thickness of sediments should be less than two or three times the depth of the water in which they are deposited even when allowance is made for isostatic compensation. Thus one is led to speculate that the sediments of the Gulf Coast Geosyncline and perhaps similar bodies of sediments elsewhere were actually deposited in deep water, i.e., beyond the edge of the continental shelf. This hypothesis would be opposed by many geologists on the grounds that there is abundant evidence in the sediments that they were deposited in shallow water. It occurred to Drs. Helsley and Hales that determination of the velocity and thickness of the basement lying between the sediments and the Mohorovicic discontinuity would provide a valuable constraint on the possible hypotheses for the development of such a sedimentary basin.

Thus the Gulf Coast Onshore Offshore Experiment was planned in cooperation with the U.S. Coast and Geodetic Survey. A series of shots was fired along a line running roughly due south from High Island on the Texas Coast. The shots were observed at seven land stations reaching inland to Henderson and by seven sea stations, the southernmost of which was on the edge of the continental shelf.

The shooting was carried out from the U.S. Department of Commercial Fisheries vessel Geronimo under the direction of Dr. Helsley. The tending of the sea stations was carried out by the U.S.C.G.S. Ship Peirce with Dr. Hales aboard. Mr. Green, Mr. Nation and Mr. Bloch were in charge of the observations on land.

Some of the deep sea shots were well recorded far inland as is shown by the record of shot 521 at station 7 reproduced as Figure 2A-1. Shot 521 was fired 68 km south of the edge of the shelf and station 7 was not far from Nacogdoches, the distance between shot and station being 484 km. However the transmission of signal to the stations nearer the explosion was not nearly as good.

The experiment was not as complete as had been planned due partly to some minor technical difficulties in the shooting, but mainly because almost all the buoys went adrift during a severe storm and valuable time was spent in searching for them.

The records from the experiment have been digitized and will be computer processed. At this preliminary stage of the analysis it seems that the crust below the sediments is in fact thin, but whether it is thin enough to be called an oceanic crust is still to be determined.

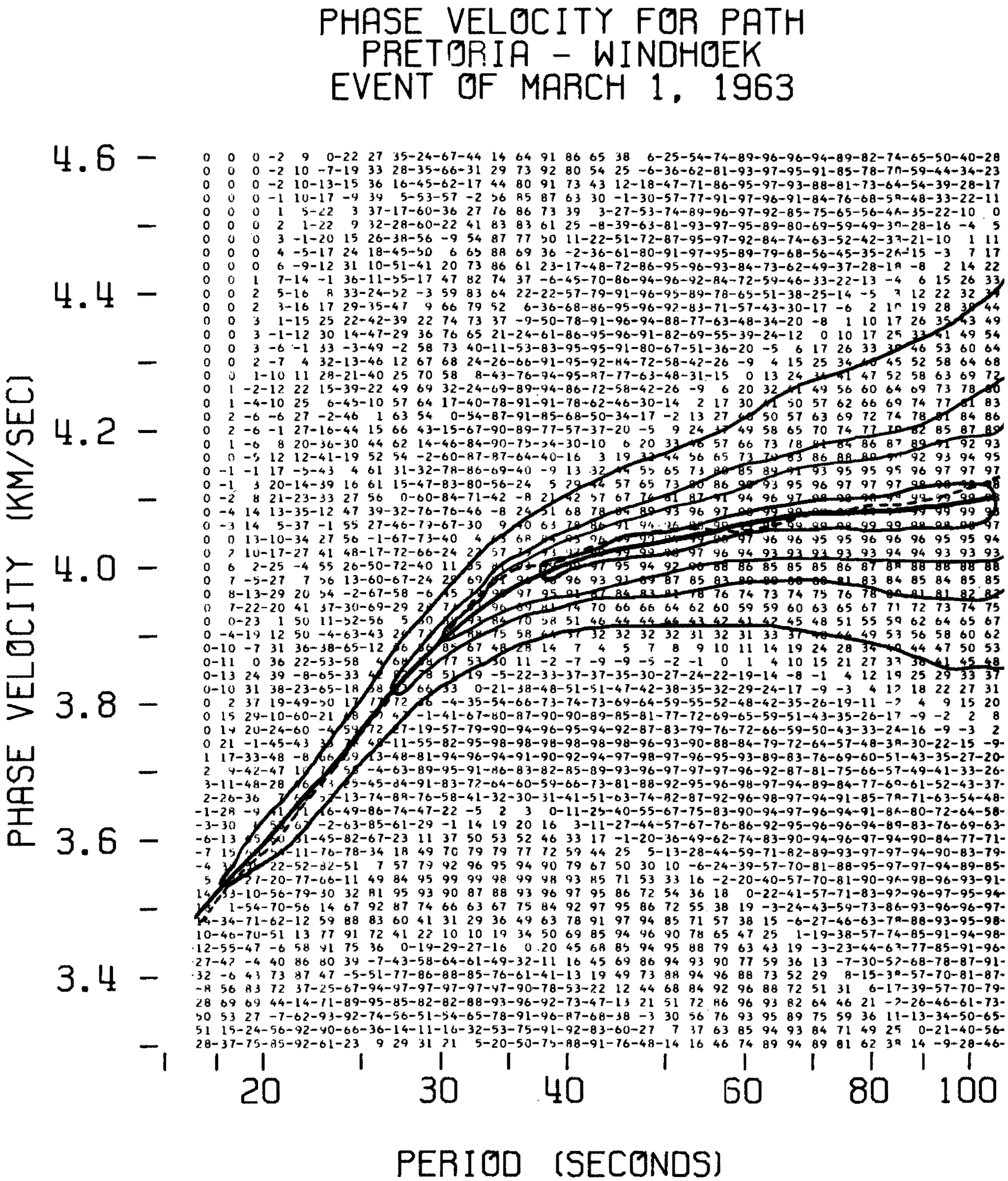


Figure 1D-1. Phase velocity contour diagram resulting from cross-multiplication process. Values within the matrix are d.c. levels, normalized such that the maximum has a value of 99. Additional phase velocity determinations at whole wavelength separations have positive values; ±1/2 wavelength separations have negative values; ±1/4 and ±3/4 wavelength separations are the zeros between them. The dashed line is the phase velocity obtained by taking phase differences from the Fourier analysis of time-variant filtered seismograms.

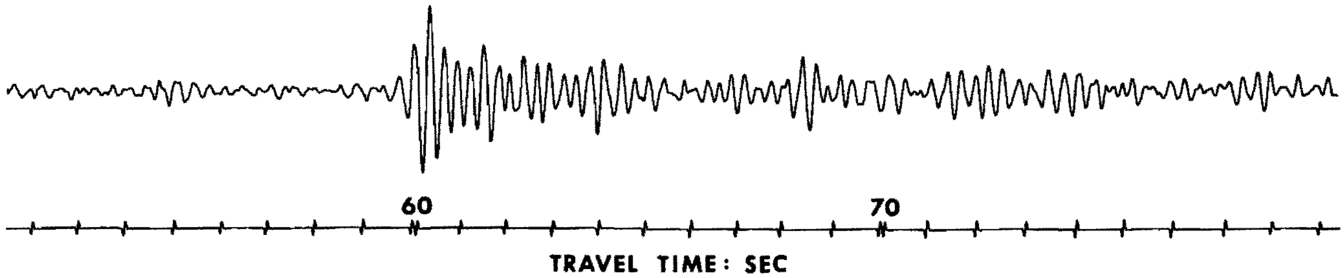


Figure 2A-1. Record of Shot 521 at Station 7, Gulf Coast Onshore Offshore Experiment

B. Measurements in the Gulf of Mexico: The Mississippi Delta–DeSoto Canyon Area

John J. Dowling

In June 1966, more than 1,000 miles of reflection profile data was taken off the Mississippi River Delta and over the west side of Desoto Canyon. The portions of the data that have been interpreted are indicated in Figure 2B-1.

Section AB (Figure 2B-2) crosses the Sigsbee Scarp and reveals the presence of north dip of the sediments at the foot of the Scarp. This north dip may be a local feature. On the other hand it may be an indication of a more gen-

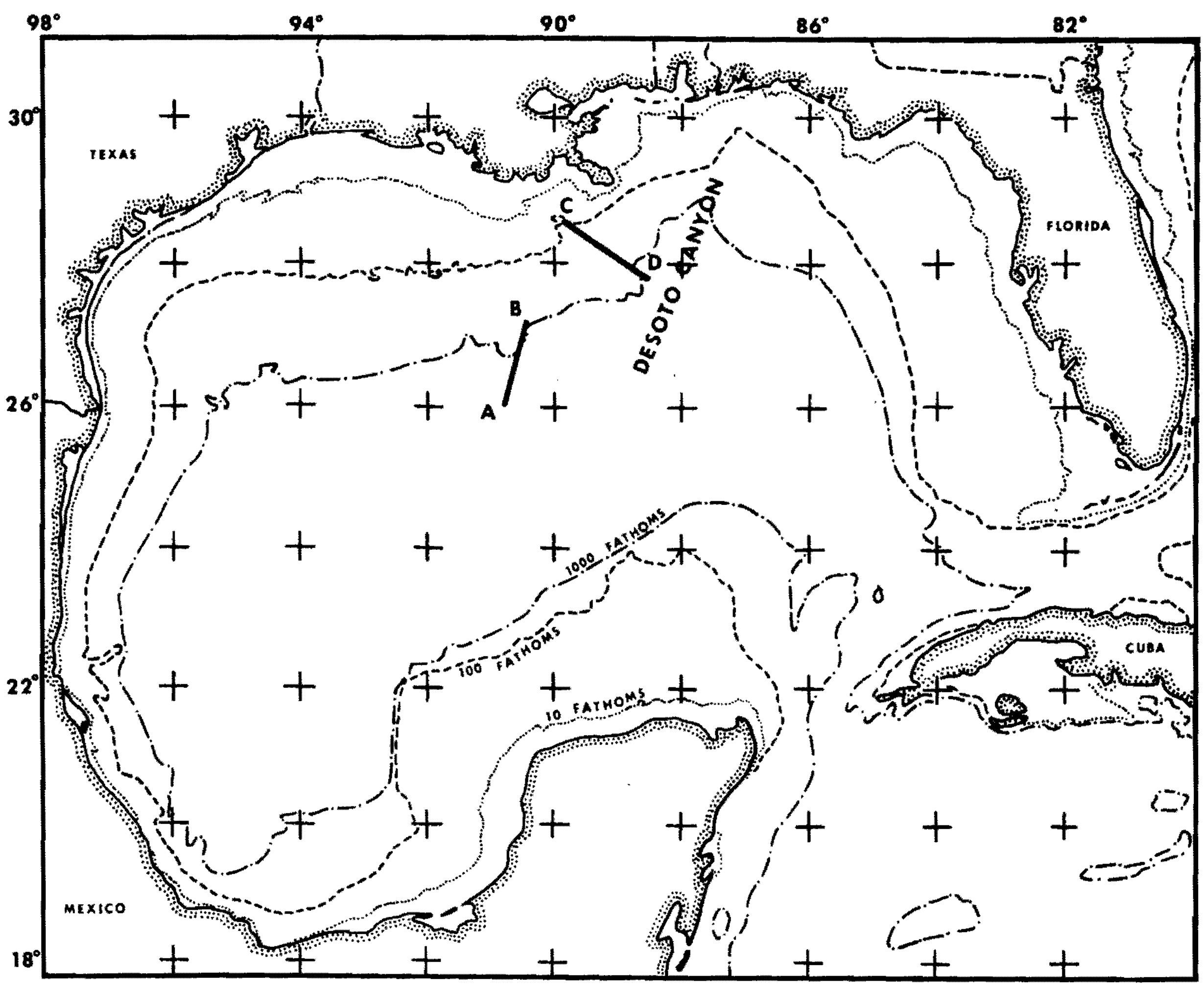


Figure 2B-1. Reflection Profile Areas in the Gulf of Mexico eral structural feature associated with the Scarp itself. This can be interpreted as reverse drag on the down-thrown side of a normal fault. According to Hamblin (1965), this reverse drag is caused by normal movement along a curved fault plane and is illustrated in Figure 2B-3. This interpretation of the data along AB would also provide for the fault not penetrating the basement, a condition which is imposed by the lack of any pronounced magnetic anomaly near the edge of the Scarp. Further investigation of the sediments at the base of the Scarp will be made in order to establish whether this reverse dip is present all along the Scarp edge.

Section CD (Figure 2B-4) across the west flank of DeSoto Canyon shows a large structure interpreted as normal faulting down-thrown into the canyon.

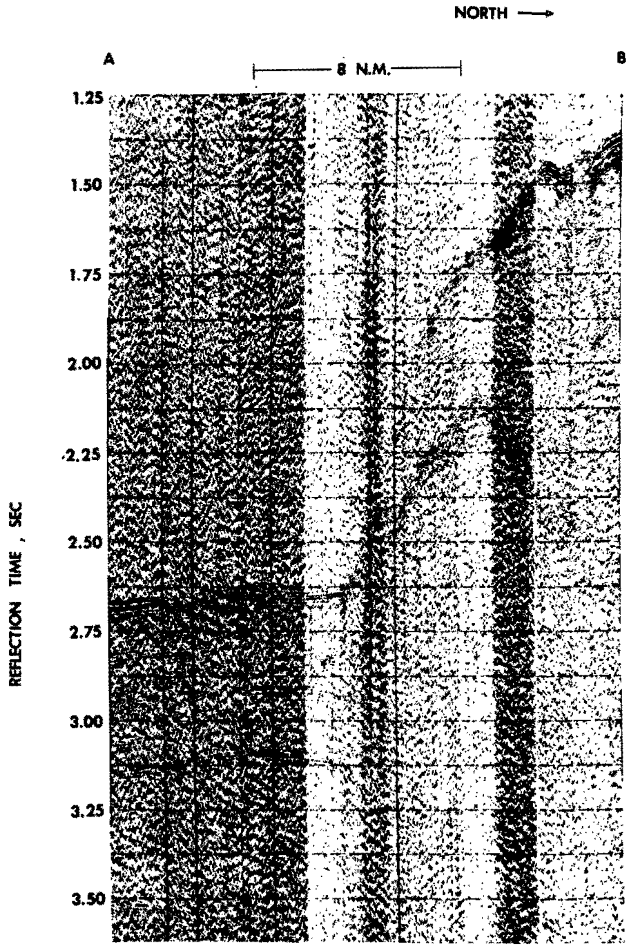


Figure 2B-2. Section AB, Across Sigsbee Scarp.

<u>Reference</u>

Hamblin, W.K., "Origin of 'Reverse Drag' on the Down-thrown side of Normal Faults", <u>Bull. Geol. Soc. Am.</u>, <u>76</u>(10), pp. 1145-1164, 1965.

C. Measurements in the Gulf of Mexico: The Southwestern Part of the Gulf

John J. Dowling
(with D.A. Fahlquist, Texas A&M University)

In the fall of 1965 three refraction profiles were taken in the southwestern part of the Gulf of Mexico in cooperation with Texas A&M University aboard the R/V Alaminos. The locations of the profiles are shown as an inset in Figure 2C-1. They are designated 65-A-M-3, 65-A-M-4 and 65-A-M-5. The data were analyzed at Texas A&M by Dr. Davis A. Fahlquist and Mr. Henri Swolfs. The results of the interpretation are shown in Figure 2C-1 along with other data from the literature.

A mantle velocity of 8.1 km./sec. was measured in the Campeche Basin. The depth to the M-discontinuity increases from 16 km. beneath the Campeche Basin to a minimum of 23 km. under the Mexican continental slope. The "oceanic" crustal layer, velocity 6.7 to 6.9 km./sec., thickens from 3.5 km. to 9.5 km. in the direction of the

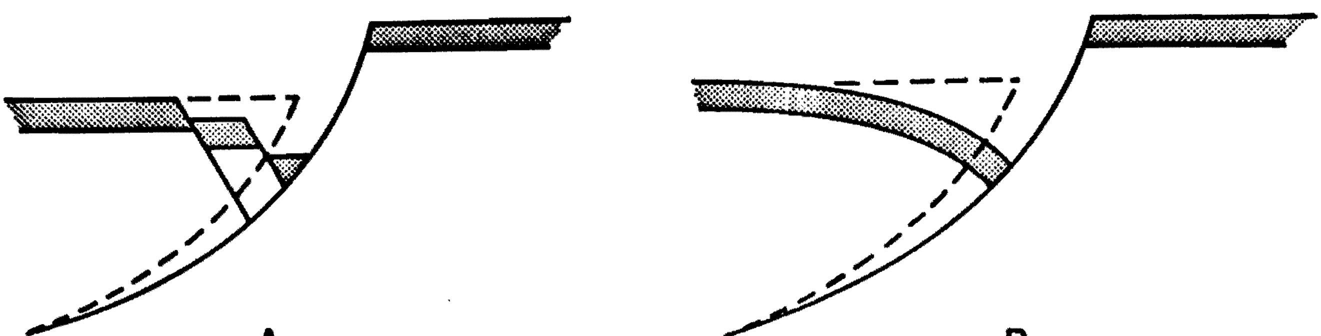


Figure 2B-3. Diagrams illustrating the mechanism by which reverse drag may be produced. Normal movement along a curved fault plane would tend to pull the blocks apart as well as displace them vertically. Subsidence to fill the incipient gap may develop antithetic faults (A) or reverse drag (B) after Hamblin (1965).

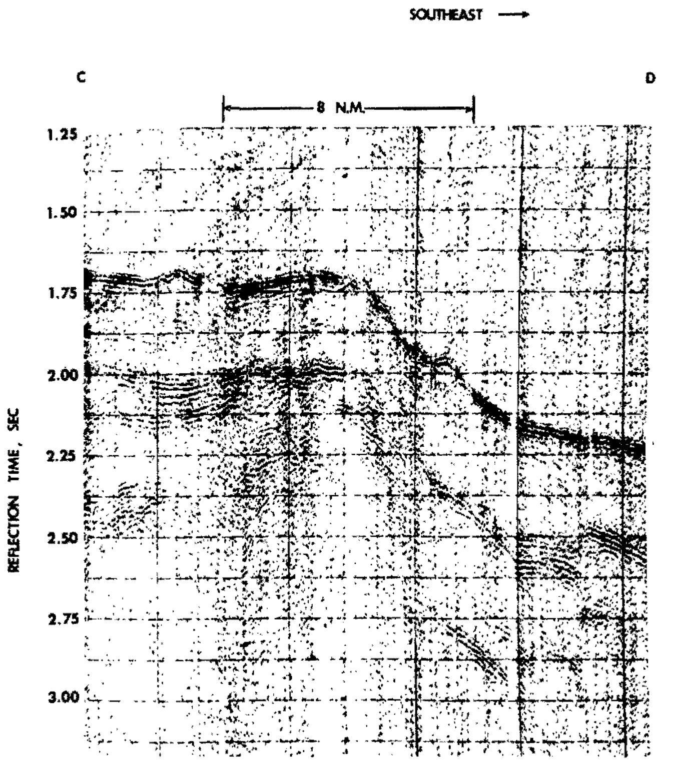


Figure 2B-4. Section CD, Across West Flank of DeSoto Canyon

Mexican coast. This layer is overlain by 8 to 12 km. of sediments with velocities ranging from 2.0 to 4.5 km./sec.

Reference

Fahlquist, D.A., H.S. Swolfs and J.J. Dowling, "Seismic Refraction Studies in the Southwestern Gulf of Mexico" (Abstract), Trans. Am. Geophys. U., 48(1), p. 128, 1967.

D. East Coast Onshore Offshore Experiment

John J. Dowling

During June and July 1965, a series of seismic refraction experiments was conducted on the east coast of the United States. As part of these experiments two lines of instrumented, observing buoys were anchored on the continental shelf between Cape Hatteras and Cape Fear (Figure 2D-1). One line of buoys, AB, extended from the shore line across the shelf to the 100 fathom depth contour. The other line, CD, was placed parallel to and near the edge of the shelf. Charges varying in size from 20 lbs. to 10 tons were fired along both lines.

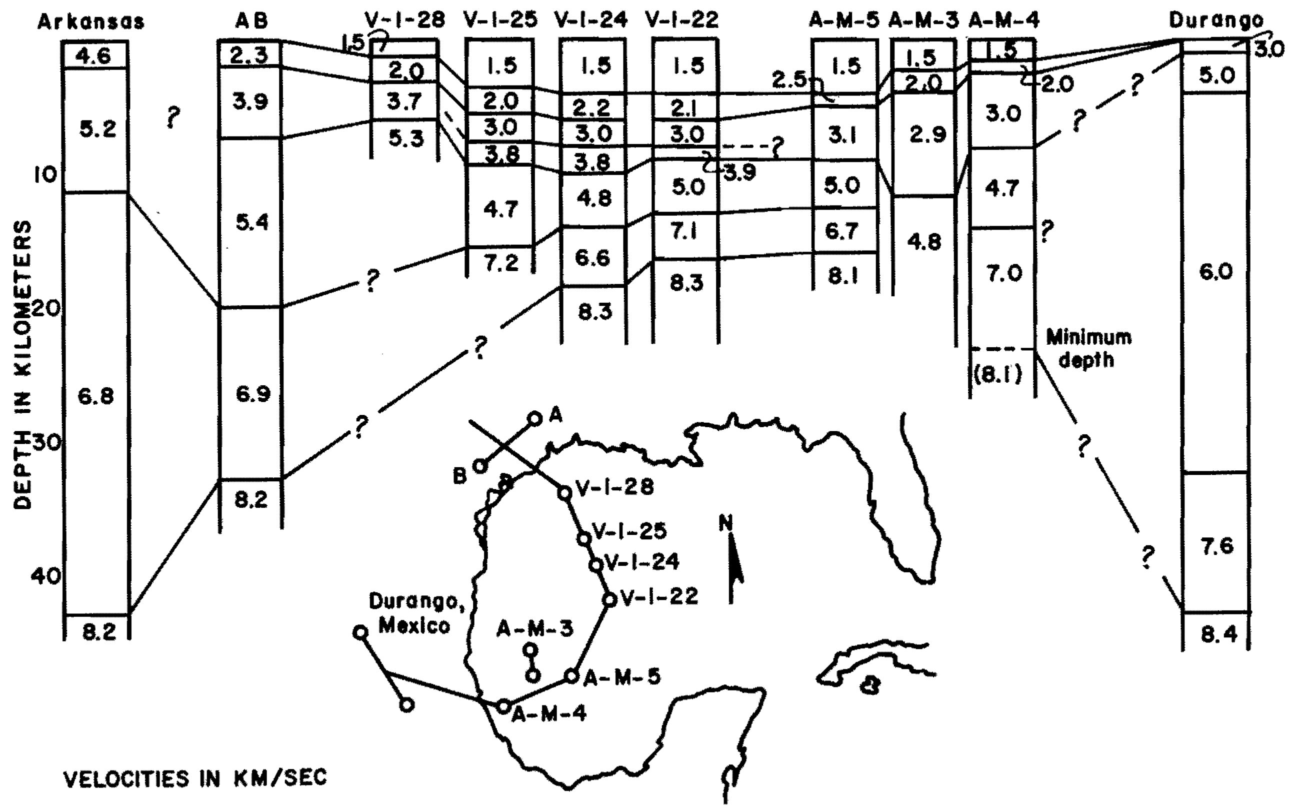


Figure 2C-1. Refraction Profiles and Crustal Section in Southwestern Gulf of Mexico

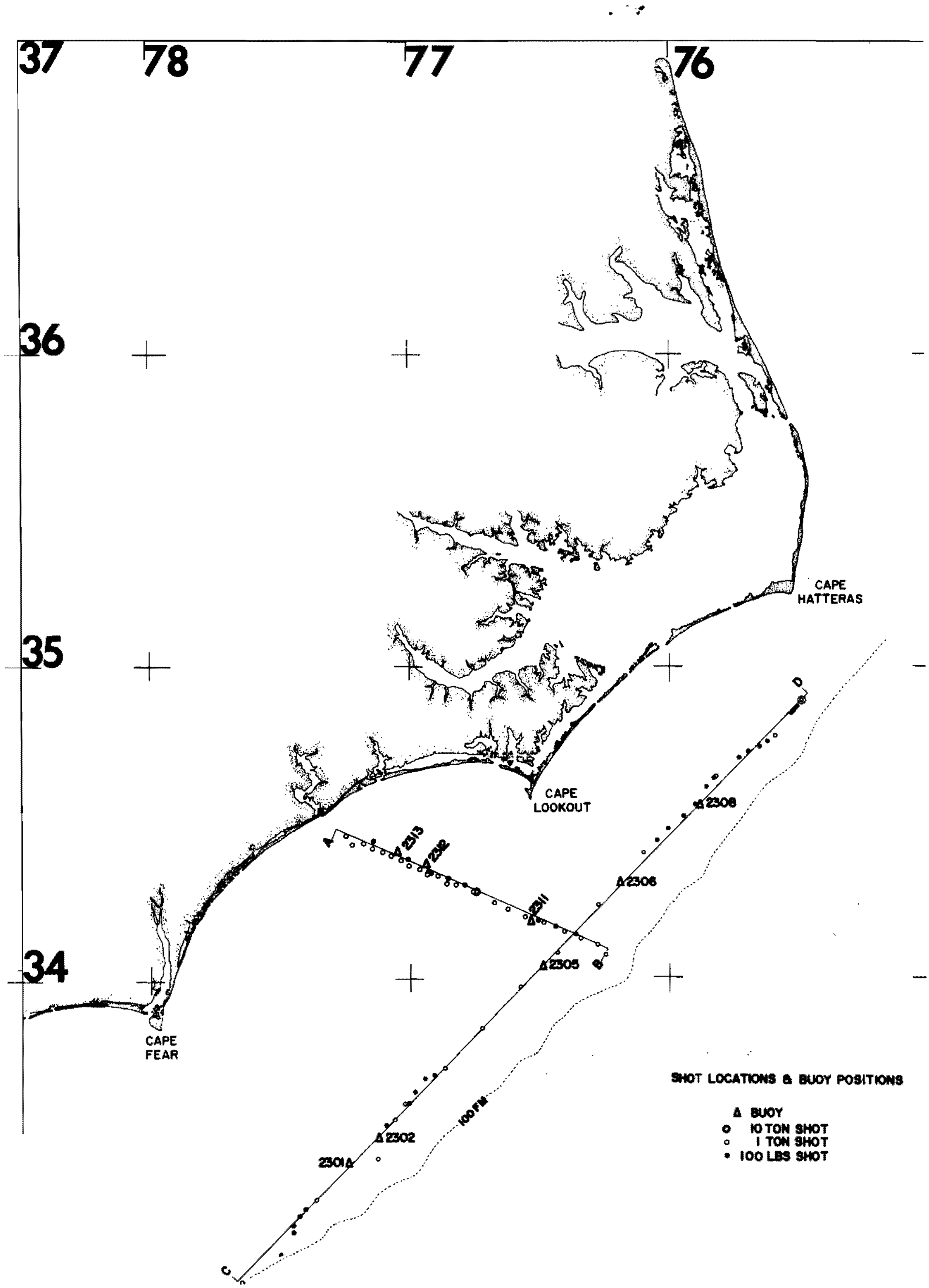


Figure 2D-1. Shot Locations and Buoy Positions for East Coast Onshore Offshore Experiment

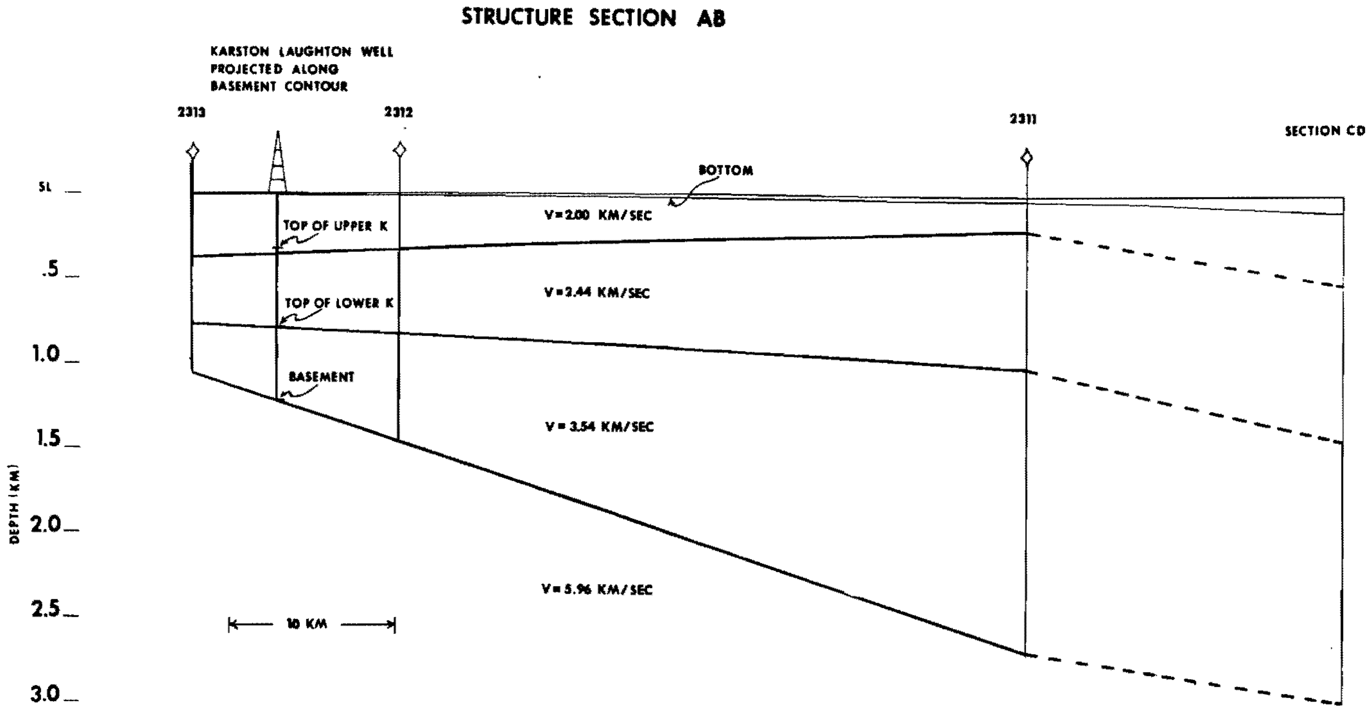


Figure 2D-2. Structure Section AB, Between Cape Fear and Cape Lookout

A statistical method of analysis was applied to the data which yielded layer thicknesses and velocities as well as estimates of the errors of these quantities. Onshore well correlations by Maher (1965) and Denison, et al., (1967) afforded the opportunity to relate the seismic layers with geologic units. Under the assumption that layer 5 (5.90 km./sec.) is the top of the crystalline basement, layer 1 (2.00 km./sec.) was correlated with Miocene sediments.

Layer 2 (2.44–2.67 km./sec.) was correlated with the top of the Upper Cretaceous. The top of layer 3 (3.43–3.76 km./sec.) was correlated with the top of the Lower

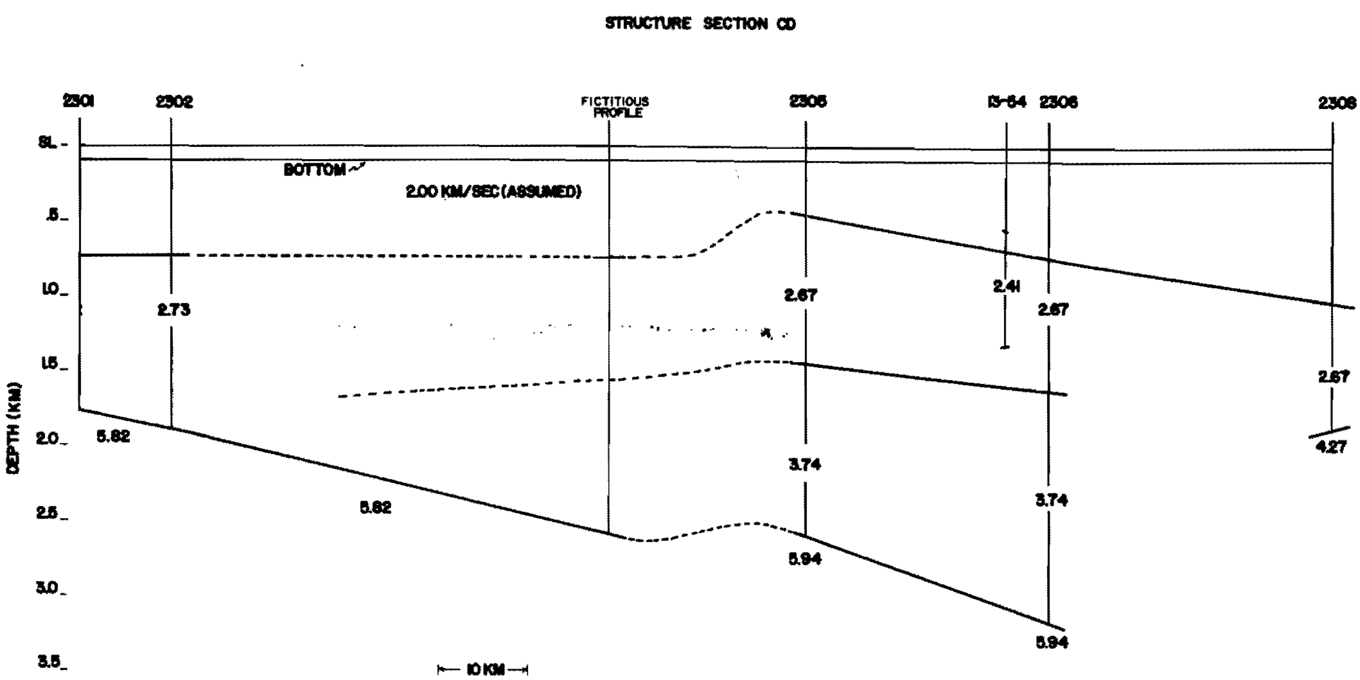


Figure 2D-3. Section CD, Parallel to Shelf Edge

Cretaceous. Structure sections along the two lines are shown in Figures 2D-2 and 2D-3. The Karston Laughton well shown on section AB (Figure 2D-2) has been projected along the basement contours from its position on Cape Lookout.

Section AB, across the shelf, indicates no large basement structure parallel to the shelf edge. The magnetic anomalies described by Drake, et al., (1955) paralleling the shelf edge must, therefore, be caused by some sub-basement structure. This lends support to the same interpretation of similar magnetic anomalies north of Cape Hatteras given by King, et al. (1961).

Section CD (Figure 2D-3) shows a structure on the basement surface near the middle of the line which strikes across the shelf. This structure, which extends up through the top of layer 2, can be interpreted as a high angle reverse fault of Upper Cretaceous–Paleocene age.

References

Denison, R.E., H.P. Raveling and J.J. Rouse (1967), "Age and Descriptions of Subsurface Basement Rocks, Pamlico and Albermarle Sound Areas, North Carolina," Am. Assoc. Petrol. Geologists Bull. (51), pp. 268-272.

Dowling, J.J., "Seismic Observations on the Continental Shelf between Cape Hatteras and Cape Fear during the East Coast Onshore-Offshore Experiment (ECOOE), (Abstract), Trans. Amer. Geophys. U., 48(1), p. 127, 1967.

Drake, C.L., J. Heirtzler and J. Hirshman (1963), "Magnetic Anomalies off Eastern North America," Jour. Geophys. Res. (68), pp. 5259-5275.

King, E.R., I. Zietz, and W.J. Dempsey (1961), "The Significance of a Group of Aeromagnetic Profiles off the Eastern Coast of North America, U.S. Geological Survey Professional Paper 424-D, pp. 299-303.

Maher, J.C. (1965), "Correlations of Subsurface Mesozoic and Cenozoic Rocks Along the Atlantic Coast," Am. Assoc. Petrol. Geologists Special Publication, 18p.

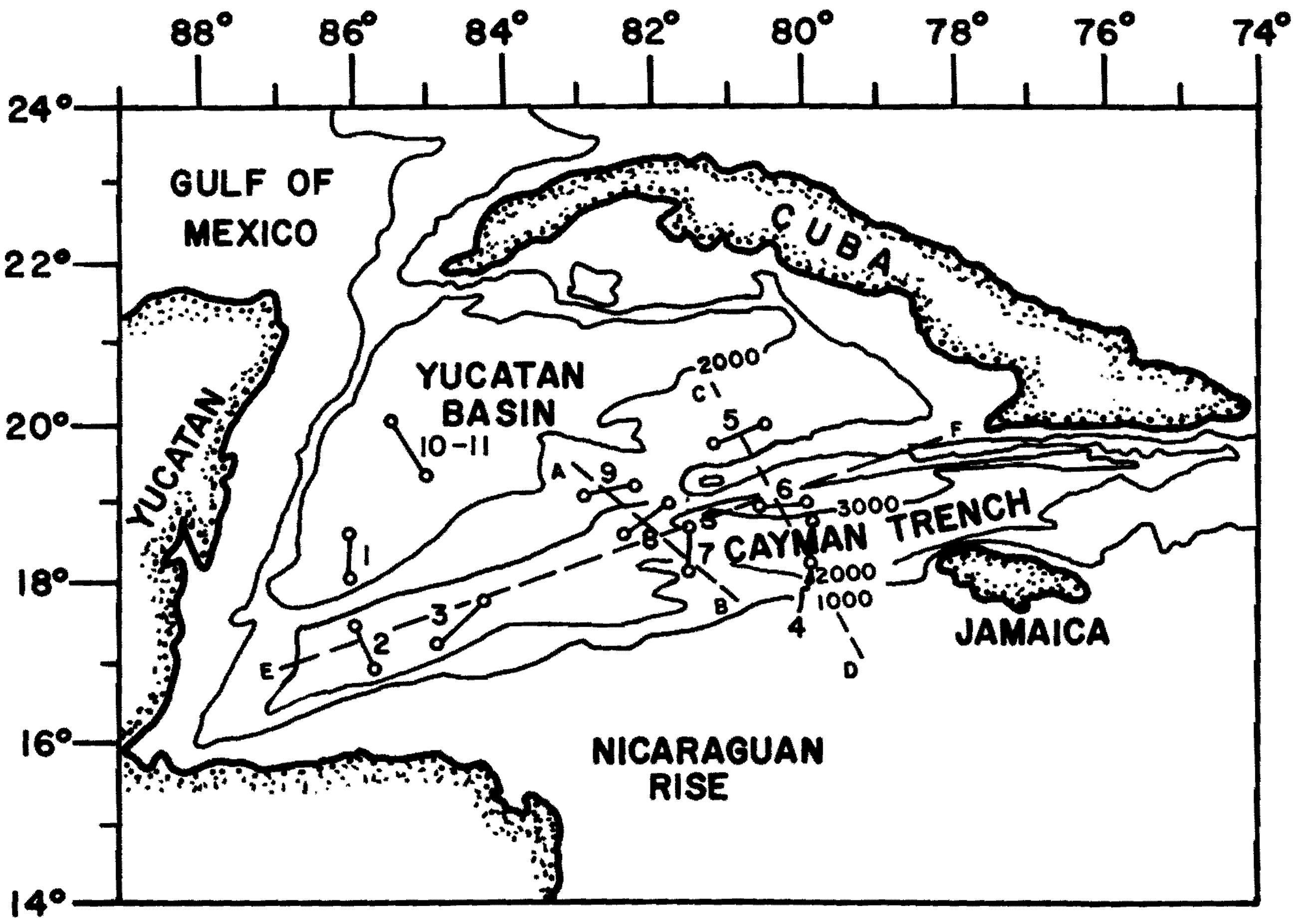


Figure 2E-1. Western Caribbean Survey Area

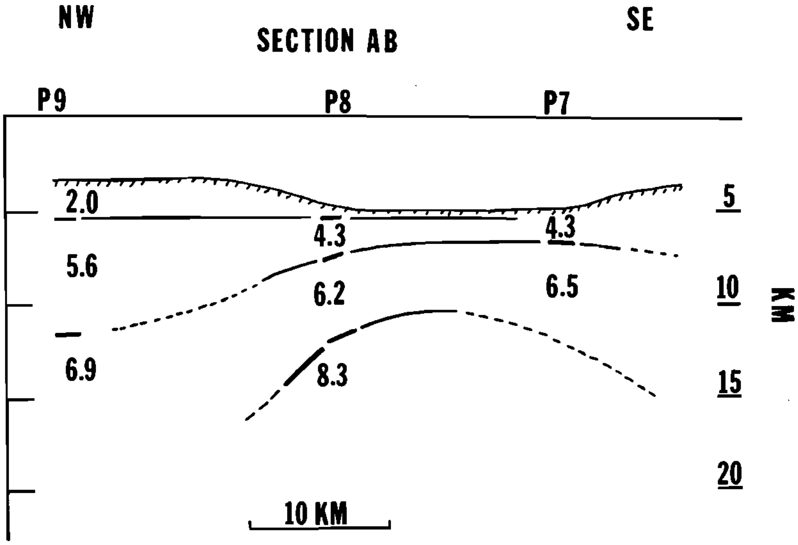


Figure 2E-2. Section AB, Crossing Cayman Trough

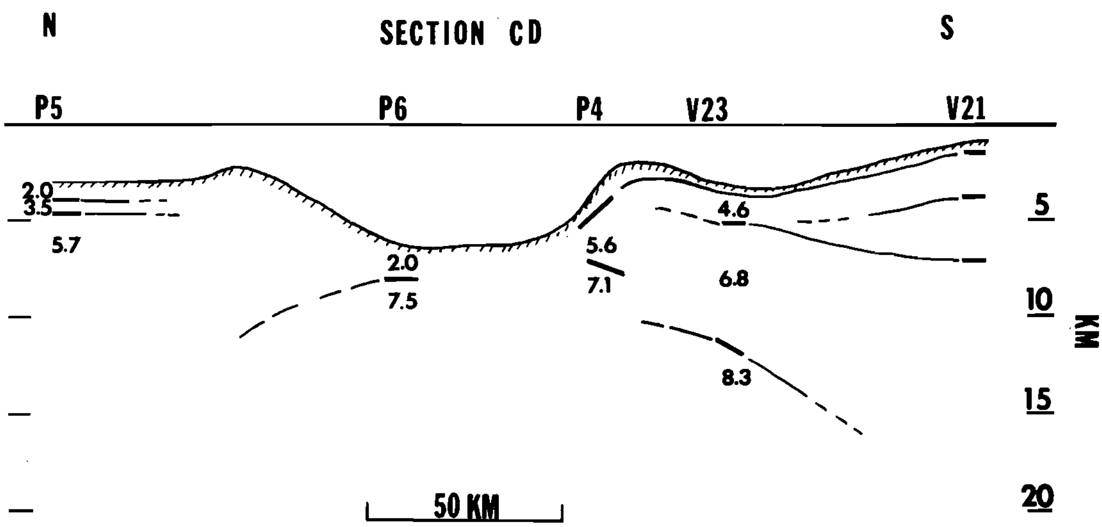


Figure 2E-3. Section CD, Crossing Cayman Trough

E. Measurements in the Western Caribbean

John J. Dowling

In January of 1965 a geophysical survey of the Yucatan Basin, Cayman Ridge and Cayman Trough was made jointly by scientists from Texas A&M and the Southwest Center for Advanced Studies. Ten seismic refraction profiles were observed in this area (Figure 2E-1).

Based on this data, three structure cross sections were made (Figure 2E-1). Sections AB (Figure 2E-2) and CD (Figure 2E-3) are perpendicular to the strike of the Trough and section EF is along the strike of the deepest part of the Trough.

Sections AB and CD confirm and extend westward the crustal structure east of Grand Cayman island as described by Ewing, Antoine and Ewing (1960). North of the Trough, under the Cayman-Misteriosa Ridge, the crust is thick (>20 km) and the crust-mantle boundary is deep (>22 km). Within the Trough the crust is thin (<5 km) and the mantle is less than 10 km below sea level. To the south, beneath the Nicaraguan Rise, the crust thickens (>25 km) and the mantle may be as deep as 30 km.

Section EF (Figure 2E-4), along the strike, shows that the thin crust, shallow mantle of the deep trough is a continu-

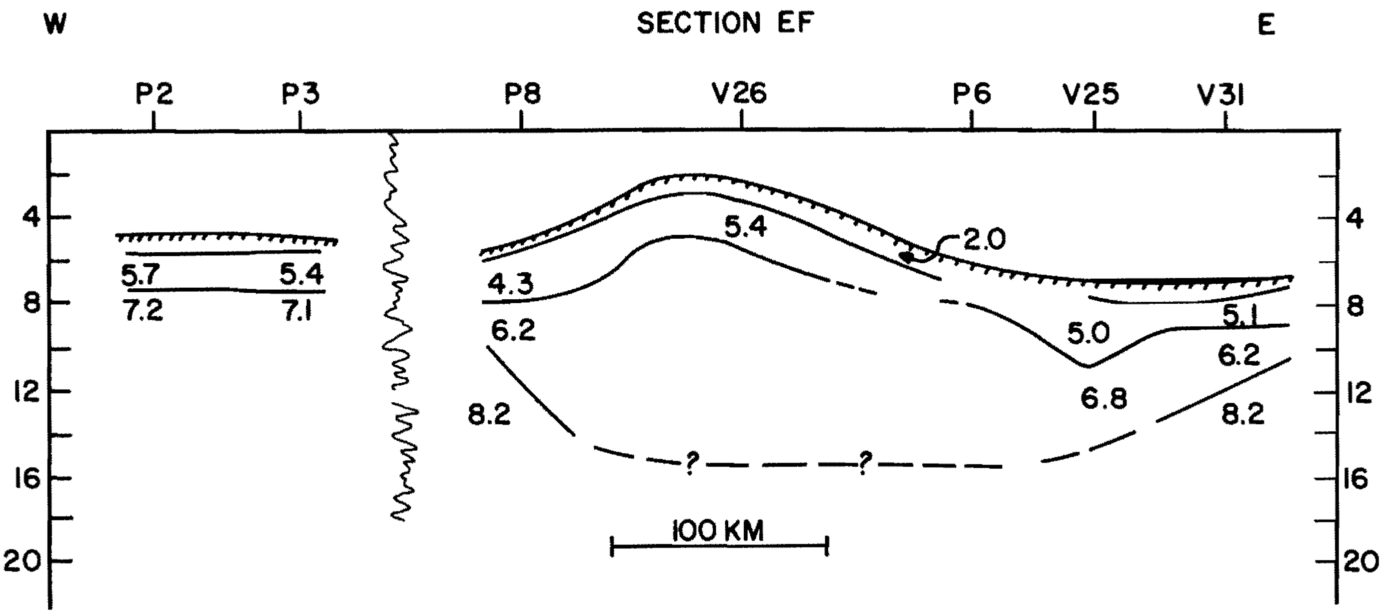


Figure 2E-4. Section EF, Along Deepest Portion of Cayman Trough

ous feature as far west as 83° (P8). Two profiles placed near Honduras continental shelf at the extreme west end of the Trough (Figure 2E-1) were not especially good profiles but provide the vital piece of information that there are high velocities at shallow depths as far west as 86° thus inviting the speculation of extension into Central America.

3. EXPERIMENTAL PETROLOGY

A. Stability Fields of Garnet- and Spinel-Peridotites

Ian D. MacGregor

Rocks with an ultramafic composition may occur as three main facies, which are characteristic of the mineral assemblages shown in Figure 3A-1.

The minerals within each assemblage may, for a specific composition, only coexist at equilibrium within well defined stability limits. Previous experimental work has shown that the assemblages 1, 2 and 3 are stable at successively higher pressures.

The general reaction defining the boundary between the spinel- and garnet-peridotites is one in which pyroxene reacts with spinel to give garnet plus olivine. For the four-component system CaO-MgO-Al_2O_3-SiO_2 the reactions shown in Figure 3A-2 are applicable.

Because of the addition of other components such as Fe^{++}, Mn, Co and Ni which commonly substitute for Mg, K and Na which substitute for Ca and Cr and Fe^{+++} which may substitute for Al, the above reactions become more complex in nature. Although the above reactions have been defined for simple three- and four-component systems the effect of other components, important in rock systems, has not previously been determined, and there arises the problem of applying the experimental data to field occurrences. A possible way out of this dilemma, for a specific geological situation or petrographic rock type, is to run an experiment on natural mineral assemblages. This has been done for a suite of ultramafic nodules from the Kilbourne Hole basalt, New Mexico.

Experimental work on the four-component system CaO-MgO-Al_2O_3-SiO_2 indicates that variations of the CaO/MgO ratio of the assemblage make significant differences in the pressure at which the spinel-peridotite converts to a garnet-peridotite (MacGregor, 1965). However, for all compositions with CaO/MgO ratios, such that both ortho- and clinopyroxene are present as phases, the reaction boundary between the two peridotite types is univariant and for a specific temperature the boundary occurs at the same pressure (MacGregor, 1965).

Using this result the natural assemblage has been treated as a four-component system, in which olivine, orthopyroxene, clinopyroxene and spinel are assigned as components. Any specific reaction assemblage composition which has a composition such that it lies within the four-phase volume olivine + orthopyroxene + clinopyroxene + spinel will react to the high pressure assemblage, olivine + orthopyroxene + clinopyroxene + garnet, at the same pressure for a specific temperature. Variations of the orthopyroxene:clinopyroxene ratio should not seriously affect the reaction boundary. With this in mind a set of compositions was made up using analyzed coexisting sets of ortho-

MINERAL ASSEMBLAGE	ROCK NAME
(1) OLIVINE + ORTHOPYROXENE ± CLINOPYROXENE ± PLAGIOCLASE	PLAGIOCLASE PERIDOTITE OR LHERZOLITE
(2) OLIVINE + ORTHOPYROXENE ± CLINOPYROXENE ± SPINEL	SPINEL PERIDOTITE OR LHERZOLITE
(3) OLIVINE + ORTHOPYROXENE ± CLINOPYROXENE ± GARNET	GARNET PERIDOTITE OR LHERZOLITE

Figure 3A-1. Ultramafic Mineral Assemblages

pyroxene, clinopyroxene and spinel from olivine nodules from the Kilbourne Hole basalt. The compositions chosen cover a very wide range of that found for these ultramafic minerals, and may be plotted against a differentiation index such as the mole per cent fayalite to show that they belong to a cognate suite of fractionally derived residues or precipitates. The bulk chemistry of the reaction assemblages, using a molecular ratio of 5 orthopyroxene to 3 clinopyroxene which lies close to an average model ratio for the Kilbourne Hole samples, while still lying within the solvus, is shown in Table 3A-I.

The chemistry of the reaction assemblage is presented to show that there is no systematic variation of SiO_2, TiO_2, FeO, MgO, CaO, NiO, MnO and Na_2O. Systematic variations are only noted for the three trivalent oxides Al_2O_3, Cr_2O_3 and Fe_2O_3 and may be reflected in the trivalent oxide ratios at the bottom of the table. Although changes of the fayalite content of the coexisting olivine vary systematically with the trivalent oxides, this is not reflected in the FeO/FeO + MgO ratio. Thus the major chemical variation in the suite of reactants is in the trivalent oxides, and one may suspect that variations in the

(1) $$\underset{\text{ORTHOPYROXENE}}{2x\,Mg_2Si_2O_6} + \underset{\text{SPINEL}}{x\,MgAl_2O_4} \rightleftharpoons \underset{\text{OLIVINE}}{x\,Mg_2SiO_4} + \underset{\text{GARNET}}{x\,Mg_3Al_2Si_3O_{12}}$$

(2) $$\underset{\text{DIOPSIDE}}{2y\,CaMgSi_2O_6} + \underset{\text{SPINEL}}{y\,MgAl_2O_4} \rightleftharpoons \underset{\text{OLIVINE}}{y\,Mg_2SiO_4} + \underset{\text{GARNET}}{y\,Ca_2MgAl_2Si_3O_{12}}$$

(3) $$\underset{\text{ORTHOPYROXENE}}{2x\,Mg_2Si_2O_6} + \underset{\text{CLINOPYROXENE}}{2y\,CaMgSi_2O_6} + \underset{\text{SPINEL}}{(x+y)\,MgAl_2O_4} \rightleftharpoons \underset{\text{OLIVINE}}{(x+y)\,Mg_2SiO_4} + \underset{\text{GARNET}}{\left\{\begin{matrix}(x+y/3)Mg_3Al_2Si_3O_{12}\\(2y/3)\,Ca_3Al_2Si_3O_{12}\end{matrix}\right.}$$

Figure 3A-2. Reactions Defining Boundary Between Spinel- and Garnet-Peridotites and Lherzolites

SAMPLE OXIDE	104	2	109	89	129	114
SiO_2	39.82	39.55	40.19	40.01	37.70	40.17
Al_2O_3	20.77	18.96	17.38	14.13	12.80	7.96
TiO_3	0.85	0.27	0.21	0.11	0.19	0.21
Cr_2O_3	0.81	2.87	3.69	7.21	11.02	12.35
FeO	5.51	6.10	5.64	6.15	6.52	4.92
Fe_2O_3	0.40	1.11	1.32	1.32	2.21	3.48
MgO	25.29	25.32	24.95	24.50	23.94	25.16
CaO	5.86	5.27	5.85	5.80	5.10	6.04
NiO	0.13	0.14	0.14	0.11	0.08	0.10
MnO	0.10	0.09	0.09	0.15	0.06	0.09
Na_2O	0.42	0.46	0.48	0.46	0.27	0.35
TOTAL	99.96	100.14	99.94	100.04	99.99	100.83
FeO/FeO + MgO	17.89	19.14	18.17	20.06	21.40	16.3
$Al_2O_3/\Sigma R_2O_3$	94.50	82.60	77.62	62.36	49.10	33.4
$Cr_2O_3/\Sigma R_2O_3$	3.69	12.50	16.48	31.81	42.30	51.9
$Fe_2O_3/\Sigma R_2O_3$	1.82	4.80	5.90	5.83	8.40	14.6
Mol. % Fa in olivine (coexisting)	12.0	10.1	9.4	9.8	8.2	7.2

TABLE 3A-I. CHEMISTRY OF REACTION ASSEMBLAGE USED IN EXPERIMENTS

$$(5\ Mg_2Si_2O_6 + 3\ CaMgSi_2O_6 + 4\ MgAl_2O_4 \rightleftharpoons 4\ Mg_2SiO_4 + Ca_3Mg_9Al_8Si_{12}O_{48})$$

pressures and temperatures at which the reaction occurs will be related to the ratios of these oxides.

Figure 3A-3 shows a pressure-composition section at 1200°C. It may be seen that the ratios of the trivalent oxides to their sum vary systematically with pressure. Increasing Al_2O_3 decreases the pressure of reaction, while increasing Cr_2O_3 and Fe_2O_3 increases the reaction pressure, Cr_2O_3 having a more profound effect than Fe_2O_3. There is no systematic variation with the FeO/FeO + MgO ratio, or for that matter with any other component. Thus within the range of compositional variation of four-phase ultramafic rocks it appears that the trivalent ions, which occupy a combination of tetrahedral and octahedral lattice sites, are the critical compositional variables defining the relative stability of spinel and garnet.

A pressure-temperature section of the same results (Figure 3A-4) indicates the wide range of pressure over which the reaction may occur. Reaction assemblages from typical garnet-lherzolites from kimberlite occurrences have a range of $Al_2O_3/\Sigma R_2O_3$ ratios from 85 to 90. The primary anhydrous Lizard assemblage has an $Al_2O_3/\Sigma R_2O_3$ ratio of approximately 90. Both these sets of rocks would have a reaction boundary similar to that for the lower pressure curves. Ito and Kennedy's determination of this reaction for a

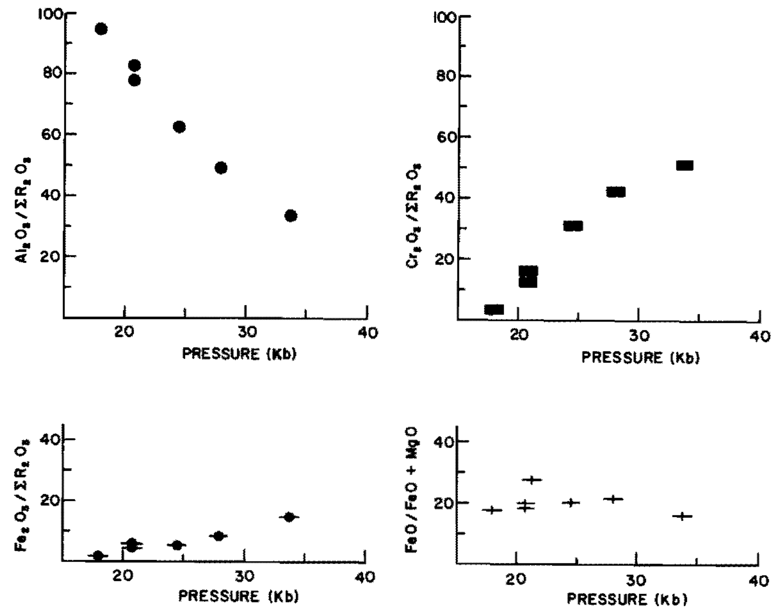


Figure 3A-3. Pressure-Composition Section at 1200°C

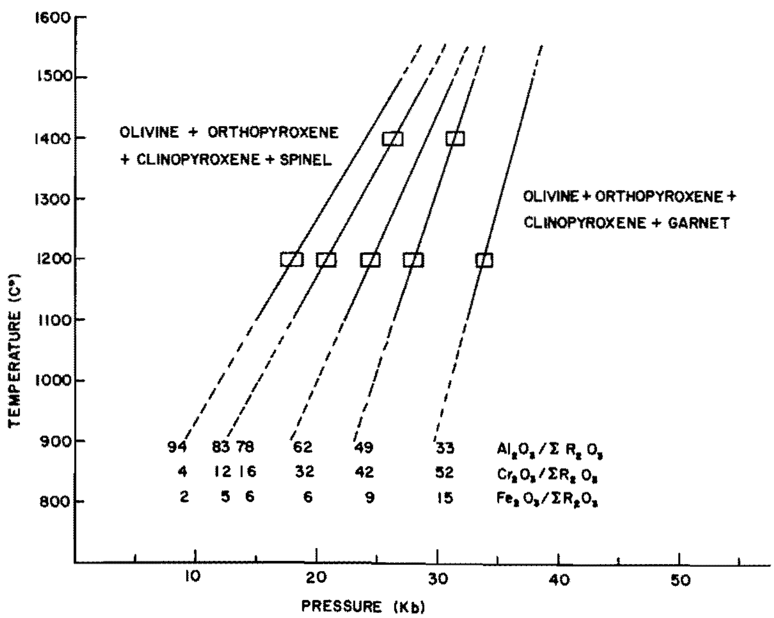


Figure 3A-4. Pressure-Temperature Section garnet-lherzolite falls very close to the lowest reaction boundary shown in the figure. Similarly the boundary for the four-component system CaO-MgO-Al_2O_3-SiO_2, which has an $Al_2O_3/\Sigma R_2O_3$ ratio of 100, coincides approximately with the lowest boundary curve. In contrast the spinel peridotites from Alpine occurrences generally have low $Al_2O_3/\Sigma R_2O_3$ ratios, varying from 10 to 40 which suggest reaction boundaries extending to even higher pressures than those shown in the figure. Indeed reaction boundaries for the Ca-poor, diopside-free harzburgitic assemblages probably extend to even higher pressures. The data well illustrates that the composition of the ultramafic rock, in particular the ratio of the trivalent oxides, must be specified prior to predictions of the temperature and pressure at which that rock converts from a spinel- to a garnet-bearing assemblage.

In Figure 3A-5 the data are summarized in a more general perspective. The range of pressures over which different groups of ultramafic rocks may be expected to convert from the low pressure spinel- to the high pressure garnet-peridotite is shown. In general the more primitive compositions such as Ringwood and Green's pyrolite, the primary Lizard composition, and garnet lherzolites from diamondiferous kimberlite pipes, have a reaction boundary that lies at the lowest pressure range. The spinel-peridotite nodules from basaltic lavas have a wide compositional range, with the reaction occurring at increasingly higher pressures for the more refractory Cr_2O_3-rich assemblages. Alpine peridotites, which generally represent a more highly differentiated sequence than the nodule suites, have compositions which indicate reaction boundaries that overlap the nodular samples and extend to considerably higher pressures. This conclusion would be reinforced for the Ca-poor, diopside-free spinel-harzburgites, which convert to the higher density assemblage at higher pressures than the two pyroxene assemblages. Superimposed on this P-T section are an average oceanic and Precambrian shield geotherm and a lherzolite solidus determined by Ito and Kennedy (1967).

Apart from the obvious conclusion that the pressure and temperature at which the reaction

$$\text{pyroxene} + \text{spinel} \rightleftharpoons \text{garnet} + \text{olivine}$$

occurs are critically dependent on composition, a few more specific comments may be made:

(1). Firstly, relating these results to the distribution of natural ultramafic rocks in geological occurrences, we note that the large Alpine spinel-peridotites commonly found in the cores of old mountain belts generally have high

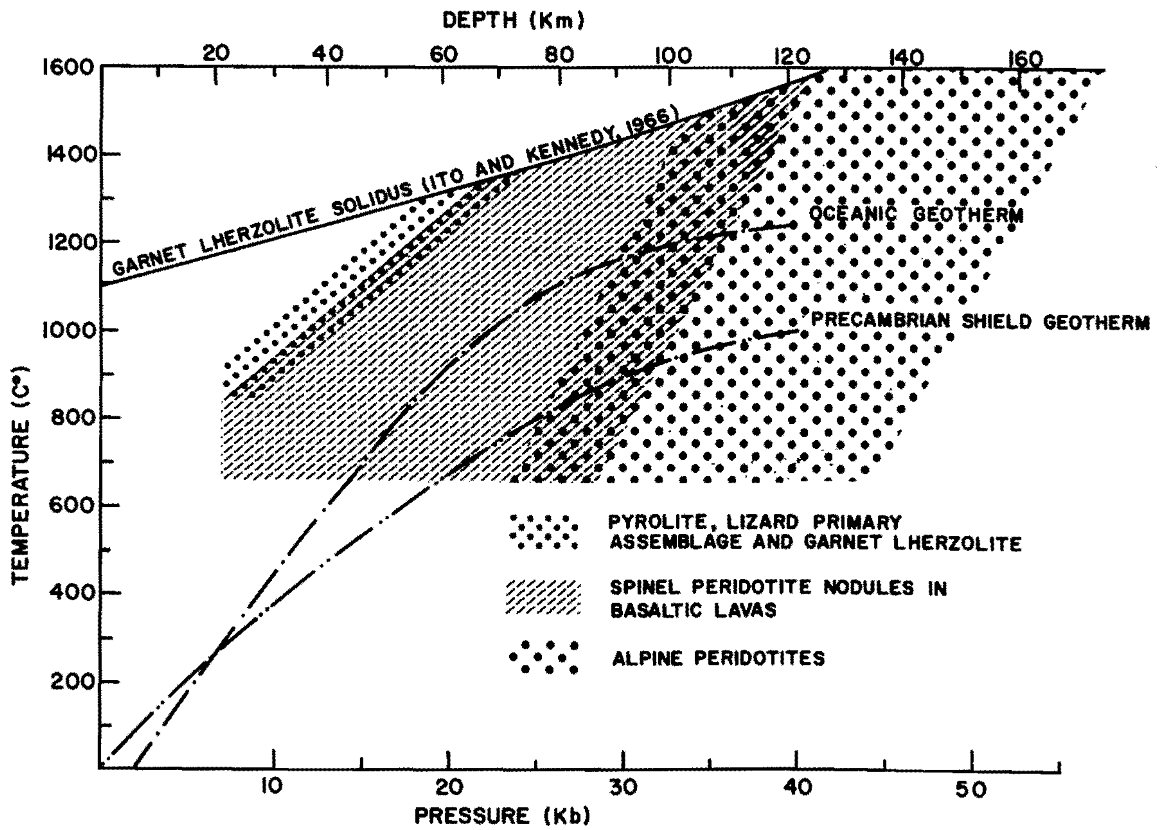


Figure 3A-5. Conversion Pressure Ranges, Spinel- to Garnet-Peridotites

$Cr_2O_3/\Sigma R_2O_3$ ratios. They would be expected to lie within the spinel-peridotite stability field down to depths of approximately 80 and 95 km. beneath average shield and oceanic regions, respectively. Garnet-peridotites in high grade metamorphic terraines such as the Norwegian Caledonides have low $Cr_2O_3/\Sigma R_2O_3$ ratios which place them within the garnet peridotite stability field. It should be pointed out that in the same metamorphic terrain ultramafic rocks with different $Cr_2O_3/\Sigma R_2O_3$ ratios may coexist stably as spinel and garnet peridotites. Garnet-peridotite nodules from kimberlite pipes have $Cr_2O_3/\Sigma R_2O_3$ ratios which place them well within the garnet stability field for both oceanic and shield geotherms. The high temperature peridotites such as the Lizard generally have low $Cr_2O_3/\Sigma R_2O_3$ ratios, and a high pressure garnet-peridotite assemblage may be expected. However, the evidence of local high temperatures well above the normal geothermal gradients, and, in the Lizard, the presence of plagioclase-peridotites, indicate conditions of final equilibration to the lower pressure side of the Cr_2O_3-poorest assemblages.

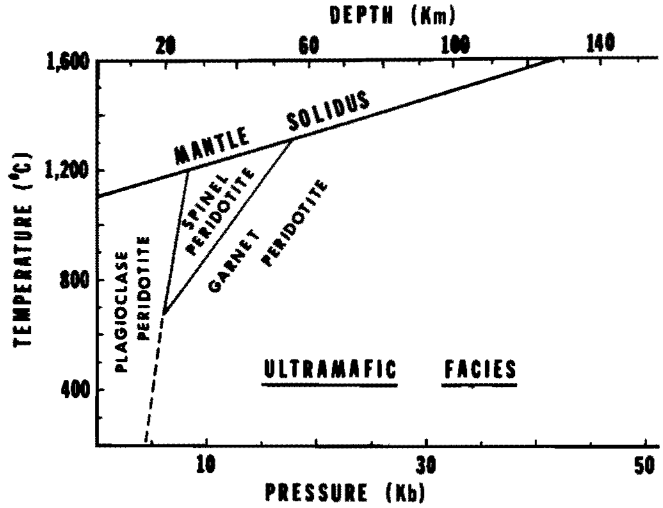


Figure 3A-6. Pressure-Temperature Section of Ultramafic Facies

The data from the Kilbourne Hole basalt allow the specific conclusion that this suite of cognate spinel-peridotites represents a final equilibration at depths less than 55 km. If they are cumulates from a basaltic liquid this represents the maximum depth of the magma chamber. The absence of plagioclase-peridotites in the suite allows the use of the reaction, anorthite + forsterite $\rightleftharpoons$ pyroxene + spinel, to place an upper limit on the depth of final equilibration of these nodules (Figure 3A-6). For the four-component system CaO-MgO-Al_2O_3-SiO_2 Kushiro and Yoder (1966) indicate that the anorthite + forsterite reaction intersects the spinel- to garnet-peridotite boundary curve at an invariant point at approximately 670°C. and 6 kilobars (Figure 3A-6). Thus, the intersection of these boundaries severely limits the stability field of the spinel-peridotites. Kushiro and Yoder's results indicate that the four-phase spinel-peridotites have formed at pressures in excess of approximately 25 kilobars. This information agrees well with the result with natural minerals and suggests that, if the Kilbourne Hole nodules are in fact a cumulate suite, the magma chamber in which these rocks have formed lies in the depth zone 25 to 55 km.

(2). A second area to which these data apply is the question as to whether seismic discontinuities in the lower crust and upper mantle are related to phase changes from the lower density spinel to the higher density garnet-peridotite.

Depending on one's choice of composition a wide variety of possible results may ensue. To make any prediction of the present phase distribution we need a far more sophisticated knowledge of the compositional distribution of the upper mantle than is presently available.

Two interesting points which emerge are as follows: Firstly, it is possible that seismic discontinuities in the upper mantle may be related to small compositional variations within the overall ultramafic composition. Secondly, if we assume that the crust has evolved from the mantle beneath it, we may expect an increasingly more refractory mantle both in depth and time. This would result on the average in an increase of the stability field of the spinel-peridotites to greater depths with time.

B. Mafic and Ultramafic Inclusions as Indicators of the Depth of Origin of Basaltic Magmas

Ian D. MacGregor

The mafic and ultramafic nodules commonly found in basaltic lavas supply useful information on the history of that lava. The rock types found as nodules in a single basalt represent a set of solidus or subsolidus phase assemblages which have formed within well-defined limits of temperature and pressure. These sets of assemblages may be thought of in the same sense as metamorphic facies.

Experimental data for the system CaO-MgO-Al_2O_3-SiO_2 (Kushiro and Yoder, 1966; Fawcett and Yoder, 1966; Boyd and England, 1963; Davis and Boyd, 1966; MacGregor, 1964 and 1965) allow a useful summary (Table 3B-I and Figures 3B-1, 3B-2 and 3B-3) of the sets of mafic and ultramafic phase assemblages, or facies, which may stably coexist at different temperatures and pressures. For both mafic and ultramafic compositions the facies may be divided into three main categories characteristic of the phase assemblage for the commonest mafic and ultramafic compositions. For mafic compositions these may be divided into the gabbro, pyroxenite or garnet granulite and eclogite facies (Table 3B-I); for ultramafic compositions approximately corresponding divisions may be made into the plagioclase-, spinel- and garnet-peridotite facies, respectively (Table 3B-I and Figures 3B-1, 3B-2 and 3B-3).

TABLE 3B-I

ULTRAMAFIC COMPOSITIONS		MAFIC COMPOSITIONS		RANGE OF STABILITY AT SOLIDUS TEMPERATURE (Kb ± 2)
PHASE ASSEMBLAGE	FACIES	PHASE ASSEMBLAGE	FACIES	
Fo + EN_{ss} + Di_{ss} + An Fo + Di_{ss} + An + Ak Fo + An + Ak + Sp	PLAGIOCLASE PERIDOTITE	Fo + En_{ss} + Di_{ss} + An Fo + Di_{ss} + An + Ak Fo + An + Ak + Sp	GABRO	0 – 3
Fo +.En_{ss} + Di_{ss} + An Fo + Di_{ss} + An + Sp		Fo + En_{ss} + Di_{ss} + An Fo + Di_{ss} + An + Sp		3
Fo + En_{ss} + Di_{ss} + An Fo + En_{ss} + An + Sp Fo + Di_{ss} + An + Sp		Fo + En_{ss} + Di_{ss} + An Fo + En_{ss} + An + Sp Fo + Di_{ss} + An + Sp		3 – 8
Fo + En_{ss} + Di_{ss} + Sp Fo + Di_{ss} + Me + Sp	SPINEL PERIDOTITE	Di_{ss} + En_{ss} + Sp + An	PYROXENITE GARNET GRANULITE	8 – 15
Fo + En_{ss} + Di_{ss} + Sp Fo + Di_{ss} + Me + Sp		Di_{ss} + En_{ss} + Gt + An Di_{ss} + En_{ss} + Gt + Sp Di_{ss} + Gt + Sp + An		15 – 17.5
Fo + En_{ss} + Di_{ss} + Sp Fo + Di_{ss} + Me + Sp		Di_{ss} + En_{ss} + Gt + Sp Di_{ss} + Gt + Sp + An		17.5 – 18
Fo + En_{ss} + Di_{ss} + Gt Fo + En_{ss} + Gt_{ss} + Sp Fo + Di_{ss} + Gt_{ss} + Sp	GARNET PERIDOTITE	Di_{ss} + En_{ss} + Gt + Qz Di_{ss} + Gt_{ss} + Sp + An	ECLOGITE	18 – 30
Fo + En_{ss} + Di_{ss} + Gt Fo + En_{ss} + Gt_{ss} Fo + Di_{ss} + Gt_{ss} + Sp		Di_{ss} + En_{ss} + Gt + Qz Di_{ss} + Gt_{ss} + Sp + An Fo + Gt_{ss} + Sp		30 – 35
Fo + En_{ss} + Di_{ss} + Gt_{ss}		Di_{ss} + En_{ss} + Gt + Qz Di_{ss} + Gt_{ss} + Sp Fo + Gt_{ss} + Sp		55 –

Table 3B-I. Possible sets of phase assemblages, for mafic and ultramafic compositions in the system CaO-MgO-Al_2O_3-SiO_2, that may stably coexist at solidus temperatures. (Ak-akermanite; An-anorthite; Co-cordierite; Di_{ss}-diopside solid solution; En_{ss}-enstatite solution; Fo-forsterite; Gt_{ss}-garnet solid solution; Qt-quartz, coesite; Sp-spinel. Except where garnet is of fixed composition (Gt) two and three phase combinations of any four phase assemblage are stable).

The distribution of the different mafic and ultramafic facies is shown in pressure-temperature diagrams of Figures 3B-4 and 3A-6. Since the nodules are solidus or subsolidus assemblages, their high temperature stability limit is defined by the mantle solidus (Ito and Kennedy, 1967). Figures 3B-4 and 3A-6 illustrate the possible temperature-pressure regimes from which the included nodules of different facies, and hence by inference, the host magma, may have been derived. Thus, if a host magma were so kind as to contain cognate nodules from its source region, plus a representative suite of readily identifiable, accidental inclusions torn from the walls of the transport pipe, it should be

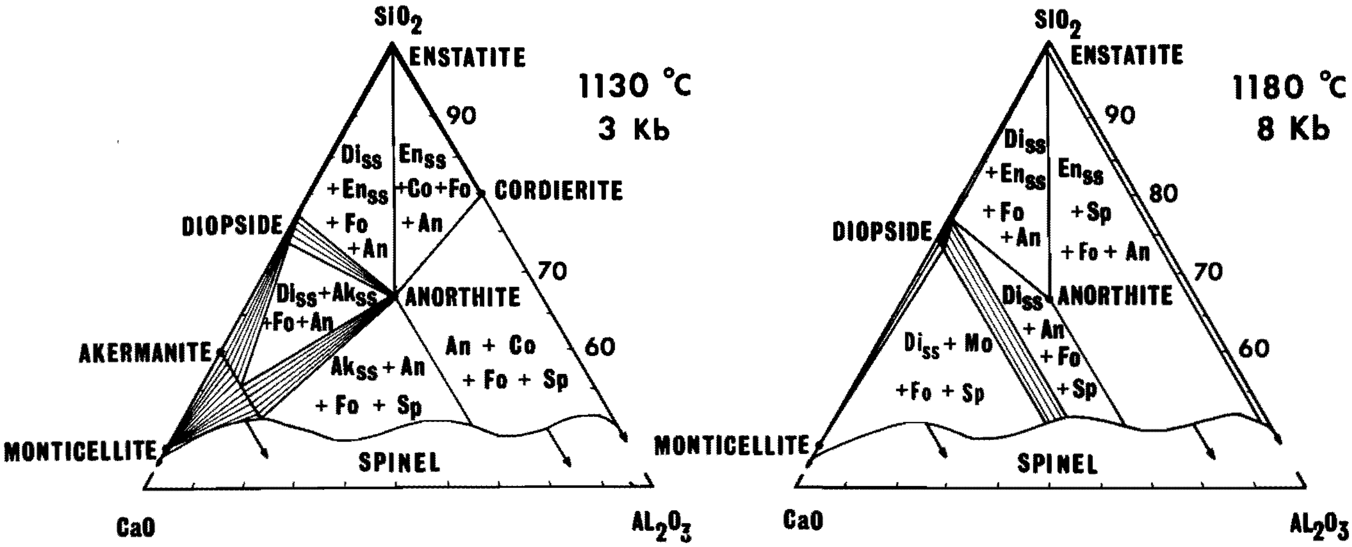


Figure 3B-1. Plagioclase-Peridotite Facies

possible to plot, within limits, the depth of origin and path of migration of that benevolent magma. Such an ideal case seldom occurs in nature. There are, however, three hypothetical cases which may be examined.

The first case assumes that the nodules have formed at the magma source in equilibrium with the liquid. Should the nodules continue to re-equilibrate with the liquid during its upward passage, they would disappear by reaction with the liquid or react to give only the lowest pressure facies. Since this is not observed, we can assume that complete re-equilibration does not always occur. When there is partial re-equilibration of the whole nodule assemblage with the liquid or with the changing physical conditions, the nodules would take on the characteristics of a facies representing a minimum pressure or depth above which the magma was formed. If no re-equilibration occurs, then the nodules are truly cognate and directly represent the physical conditions of the source region.

A second case is one in which the crystal products have continued to precipitate from the magma during its upward passage. A minimum depth of origin would therefore be indicated.

The third case assumes that the nodules are entirely accidental and have not equilibrated with the liquid. The magma migrates to the surface along the mantle solidus but passes through rocks lying along the ambient geothermal gradient. Other than indicating that the magma has traversed some path through the stability fields of the included nodules, the nodules supply little information on the depth of magma generation. However, a knowledge of the equilibrium temperature and pressure of the nodules may supply information on the geothermal gradient prevailing at the time of extrusion.

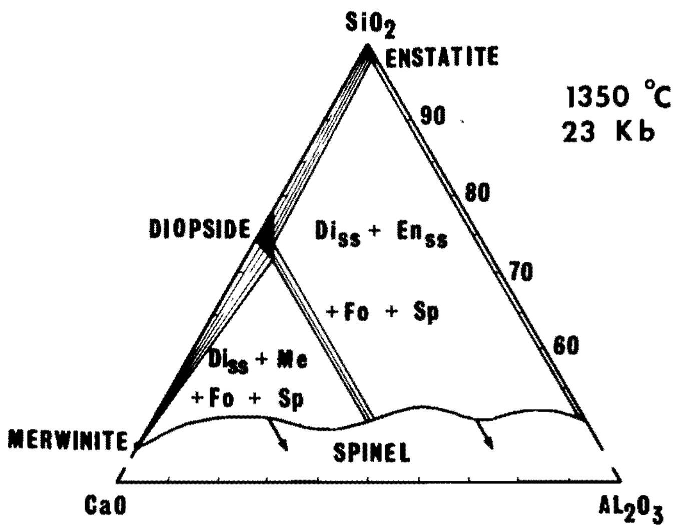


Figure 3B-2. Spinel-Peridotite Facies

It is obvious from the above discussion that the nature and history of the nodules must be clearly understood before any interpretation of the depth of magma generation can be made. In addition, it should be noted that the virtual absence of nodules from certain lava types (Forbes and Kuno, 1965) possibly restricts their usefulness to a limited population of lava types.

A survey of the literature allows the following broad generalizations to be made:

(1). Mafic and ultramafic nodules are rarely found in tholeiitic basaltic rocks. However, when present, the nodules fall either in the gabbro-, pyroxenite- or plagioclase-peridotite facies.

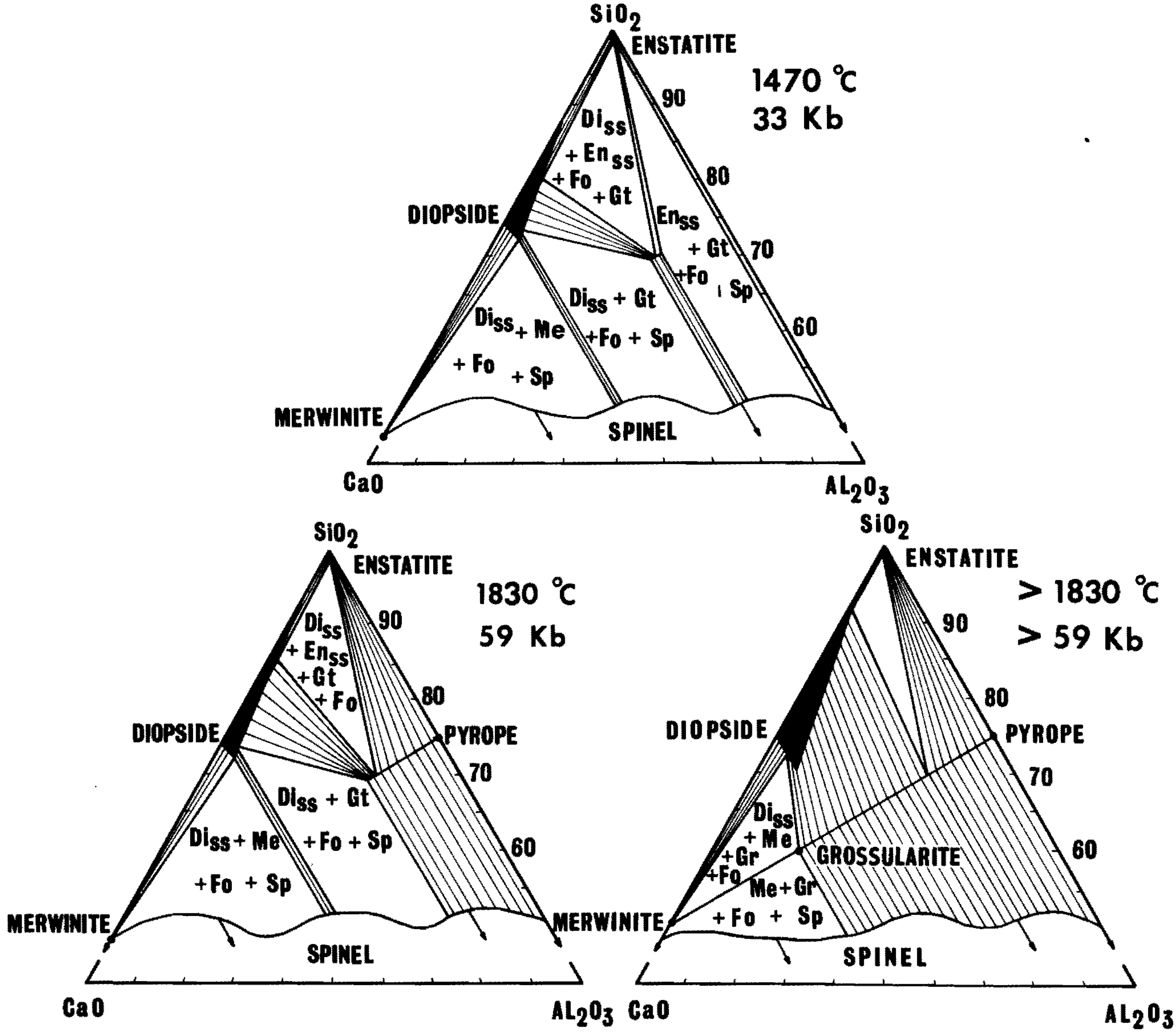


Figure 3B-3. Garnet-Peridotite Facies

(2). Host lavas of alkali olivine basalt affinity have nodules in the gabbro-, pyroxenite-, spinel-peridotite, and occasionally eclogite, facies as their included assemblage.

(3). Nephelinitic basalts or tuffs characteristically contain nodules in the spinel-peridotite, eclogite and, occasionally, garnet-peridotite facies.

(4). Kimberlitic basalts have abundant nodules which are generally restricted to the garnet-peridotite and eclogite facies.

The nodule assemblage in the different basaltic magma types suggests that in general the tholeiitic basalts, alkali olivine basalts, nephelinitic basalts and kimberlitic basalts have either originated at successively greater depths or passed through mantle rocks lying in stability fields at successively greater pressures or lower temperatures. The assumptions that the nodules are truly of cognate origin, have formed in the source region and are truly representative of all the magma types, lead to the relationships presented in Table 3B-II. If they are cognate, but have formed during the upward passage of the magma with the higher pressure assemblages either dropping out of, or reacting with, the magma, then the nodules indicate a minimum depth range above which the magma has originated. If the nodules are accidental and representative of the traverse to the surface, minimum depths of origin may also be established.

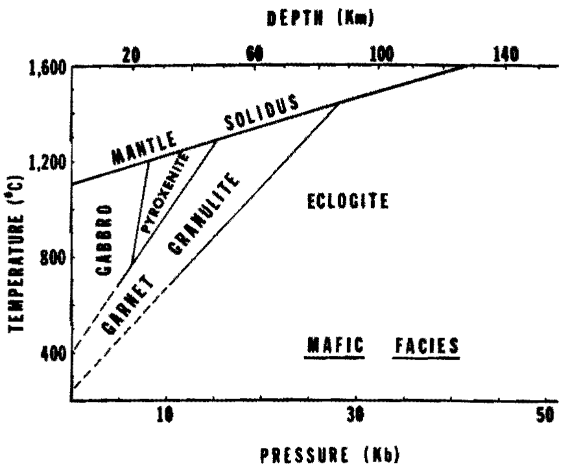


Figure 3B-4. Pressure-Temperature Section of Mafic Facies

Although it is not possible to state categorically that the depth classification in Table 3B-II is established, the present data, though limited, suggest that in general, the sequence of basalt types (tholeiite, alkali olivine, nepheline to kimberlite) is derived by processes taking place at successively greater depths. At present, Table 3B-II should be viewed more as a working model than as a final interpretation. It must be emphasized that each individual set of nodules should be very carefully analyzed before it can be interpreted in the light of this model. It appears that by regarding the included nodules as members of subsolidus assemblages which belong to distinct facies having well-defined stability limits, it is possible to get much useful information on the evolution of the basalt magma.

Apart from the fact that accidental nodules supply some samples of the upper mantle, an appreciation of the temperature and pressure at which the nodules have formed, can give useful information on fossil geothermal gradients. This is particularly the case if it is possible to identify the equilibrium temperature and pressure of each nodule.

An example of the manifestation of these principles is perhaps to be seen in the following two examples. Regionally, the nodules from the stable Precambrian Shields fall in the garnet-peridotite or eclogite facies; ultramafic and mafic nodules in basaltic rocks of the tectonically active southwestern United States characteristically fall in the spinel-peridotite, gabbro or pyroxenite facies. If these nodules are regarded as cognate samples, then it is possible to place an upper limit of 23°C. per km. on the geothermal gradient beneath the Precambrian Shields at the time of kimberlitic magma extrusion; similarly, an upper limit of

MAGMA TYPE	INCLUDED NODULE ASSEMBLAGE	GENERALIZED FACIES		STABILITY RANGE (KILOBARS) AT SOLIDUS TEMPERATURE	PROBABLE DEPTH (KILOMETERS) OF ORIGIN
		ULTRAMAFIC	MAFIC		
THOLEIITE BASALT	GABBRO PYROXENITE PLAGIOLASE-PERIDOTITE	PLAGIOCLASE-PERIDOTITE	GABBRO	0 - 15	0 - 50
ALKALI OLIVINE BASALT	GABBRO PYROXENITE SPINEL-PERIDOTITE ECLOGITE	SPINEL-PERIDOTITE	PYROXENITE GARNET-GRANULITE	8 - 25	25 - 75
NEPHELINE BASALT KIMBERLITE BASALT	SPINEL-PERIDOTITE ECLOGITE GARNET-PERIDOTITE	GARNET-PERIDOTITE	ECLOGITE	18 - 55	60 - 180

TABLE 3B-II.

45°C. per km. and lower limit of 23°C. per km. may be assigned to the geothermal gradient of the tectonically active southwestern United States. Careful selection of nodule suites across other regional structures such as the large thrust faults dipping beneath Island Arc structures (Benioff, 1954; Plafker, 1967; Oliver and Isacks, 1967) may allow useful conclusions as to the regional changes in the geothermal gradients and possibly the attitude of the thrust plane itself. Such information would be critical in evaluating the current hypothesis of ocean floor spreading.

References

Benioff, H., "Orogenesis and Deep Crustal Structure—Additional Evidence from Seismology", Bull. Geol. Soc. Amer., 65, pp.385-400, 1954.

Boyd, F.R., and J.L. England, "Some Effects of Pressure on Phase Relationships in the System $MgO-Al_2O_3-SiO_2$," Ann. Rep. Dir., Geophys. Lab., Carnegie Inst., Wash., Year Book 62, pp. 121-124, 1963.

Davis, B.T.C., and F.R. Boyd, "The System $Mg_2Si_2O_6-CaMgSi_2O_6$ and its Bearing on the Origin of Kimberlite", J. Geophys. Res., 71, pp. 3567-3576, 1966.

Fawcett, J.J., and H.S. Yoder, "Phase Relationships of Chlorites in the System $MgO-Al_2O_3-SiO_2-H_2O$," Amer. Min., 51, pp. 353-380, 1966.

Forbes, R.F., and H. Kuno, "The Regional Petrology of Peridotite Inclusions and Basaltic Host Rocks", Upper Mantle Symposium, New Dehli, ed. Smith, C.H., and T. Songenfrei, pp. 161-179, 1965.

Ito, K., and G.C. Kennedy, "Melting and Phase Relations in a Natural Peridotite to 40 kb.," Trans. Am. Geophys. Union, 48, p. 256 (abs), 1967.

Kushiro, I., and H.S. Yoder, "Anorthite-Forsterite and Anorthite-Enstatite Reactions and Their Bearing on the Basalt-Eclogite Transformation", Jour. Pet., 7, pp. 337-362, 1966.

MacGregor, I.D., "Stability Fields of Spinel and Garnet Peridotites in the Synthetic System $MgO-CaO-Al_2O_3-SiO_2$", Ann. Rep. Dir., Geophys. Lab., Carnegie Inst., Wash., Year Book 64, pp. 126-134, 1965.

MacGregor, I.D., "The Reaction 4 Enstatite + Spinel $\rightleftarrows$ Forsterite + Pyrope," Ann. Rep. Dir., Geophys. Lab., Carnegie Inst., Wash., Year Book 63, p. 157, 1964.

Oliver, J., and B.L. Isacks, "Some Evidence on the Structure of the Mantle Near an Island Arc," Trans. Am. Geophys. U., 48, p. 219 (abs), 1967.

Plafker, G., "Possible Evidence for Downward-Directed Mantle Convection beneath the Eastern End of the Aleutian Arc," Trans. Am. Geophys. U., 48, p. 218 (abs.), 1967.

C. Study of Ultramafic Nodules from South African Kimberlites

James L. Carter
Ian D. MacGregor

A detailed study of the chemistry and petrology of the mafic and ultramafic nodules from the South African kimberlites continues. Much of the time this year has been spent in sample preparation, and insufficient data are presently available to effect any synthesis of the origin of the nodules. Petrographic studies and studies on the bulk rock chemistry, mineral chemistry and rare earth mineral and rock chemistry are currently in progress.

X-Ray and optical measurements indicate a wide range of composition from $Py_{76}Alm_{18}Gr_6$ to $Py_{35}Alm_{40}Gr_{25}$ for the eclogitic garnets. Garnets from ultramafic nodules vary from $Py_{65}Alm_{28}Gr_7$ to $Py_{50}Alm_{40}Gr_{10}$ and the ultramafic olivines vary in composition from Fo_{87} to Fo_{96}.

D. Mineralogical and Chemical Composition of the Primary Upper Mantle

James L. Carter

The chemical nature of the Earth's upper mantle is assumed by most geologists to be peridotitic in composition. Because this composition is based on indirect evidence and since we must wait to obtain a direct sample of the Earth's upper mantle, other independent methods to determine its composition would be desirable. Therefore, a model for the mineralogical and chemical composition of the primary upper mantle has been developed from a simple partial fusion-fractional crystallization hypothesis for the origin of olivine (ultramafic and mafic) inclusions in basaltic host rocks.

Starting with a solid and upon increasing the temperature above its solidus temperature two things may occur; i.e., total fusion or partial fusion. With partial fusion a residuum product will be formed that is more refractory in nature than the starting material.

This concept may be illustrated by the Fo-Fa equilibrium diagram, Figure 3D-1. Beginning with any solid mixture between the pure end members, the first liquid to form will have a composition more Fe-rich than the starting composition. The starting solid and the liquid become less Fe-rich with increasing temperature, and upon reaching the liquidus, under equilibrium conditions, the solid has the most Mg-rich composition possible and the liquid has the starting solid composition. Crystallization of this liquid under equilibrium conditions will yield the starting solid composition. However, under non-equilibrium conditions i.e., fractional crystallization, the last liquid and solid to form will be more Fe-rich than the starting composition and the liquid may even reach the pure Fe-end member.

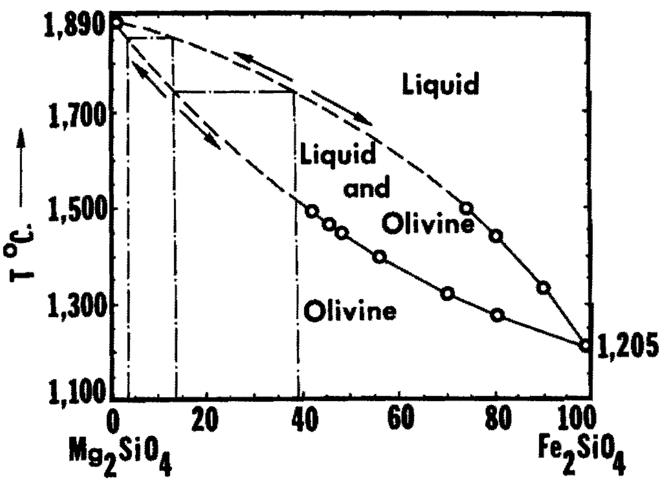


Figure 3D-1. Equilibrium Diagram of the System Mg_2SiO_4-Fe_2SiO_4 (after Bowen and Schairer, 1935)

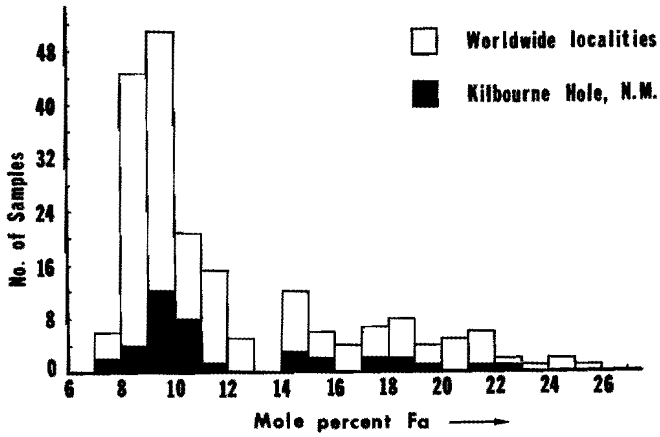


Figure 3D-2. Histogram of Fa from Southwestern U.S.A. Olivine Inclusions

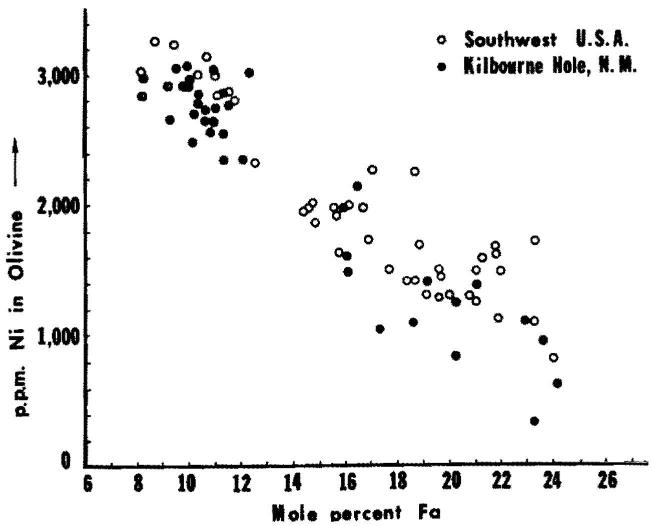


Figure 3D-3. Plot of Ni in Olivine Versus Fa

There are several conclusions which may be drawn from this diagram: (a) with partial fusion there will be a residuum product more Mg-rich than the starting material and a liquid more Fe-rich than the starting material, (b) with fractional crystallization there will be products more Fe-rich than the starting material, and (c) with repeated partial fusion and removal of liquid the starting composition will become more and more Mg-rich; this will result both in a preferred concentration more Mg-rich than the initial material and in a "paucity" of the original initial composition. This results from the fact that all material more Fe-rich than the equilibrium assemblage at a given temperature will be the first to melt. Consequently, one could reconstruct the starting composition if one knew the liquid-solid relationship. A limiting factor would be the absence of a well-defined "gap." A well-defined "gap" would depend on the extent and degree of repeated partial fusion.

Figure 3D-2 is a histogram of Fa, the mole percent fayalite of olivine and of olivine inclusions from southwest U.S.A. localities. Significant points are (a) the strongly preferred composition near Fa8 to 10, (b) the paucity of samples in the Fa12 to 14 range, and (c) similarity of the distribution of the Kilbourne Hole, New Mexico, samples to the other southwest U.S.A. samples. The samples from Kilbourne Hole, New Mexico, are emphasized because they consist of a rather wide range of rock types and because they have been studied extensively (Carter, 1965).

Figure 3D-3 is a plot of nickel in the olivine from the olivine inclusions from the southwest U.S.A. versus Fa. This graph shows a continuous negative correlation of nickel to Fa except for a "gap" between Fa12 and 14. The Kilbourne Hole, New Mexico, samples are distributed similarly.

This plot, other elemental plots and the mode show continuity, except at the "gap" between Fa12 to 14, which indicates crystal-liquid equilibria. Thus, the "gap" between Fa12 and 14 and the elemental and modal correlations may be interpreted as resulting from a partial fusion-fractional crystallization process, as illustrated by the Fo-Fa equilibrium diagram, Figure 3D-1.

Applying the partial fusion-fractional crystallization principles to the preceding data, the "gap" represents the composition of the primary upper mantle (starting material); samples with fayalite content greater than 14 could only be formed by fractional crystallization, whereas residuum of partial fusion could only be samples with fayalite content less than 14 and would represent a depleted or "barren" upper mantle.

Isochemical mineral assemblages for the primary upper mantle under Kilbourne Hole, New Mexico, can be calculated from the plots of mode versus Fa content for low and high pressure conditions and are shown in Figure 3D-1. The ± gives

Upper Mantle Mineral Assemblage	Volume Percent Low Pressure	High Pressure
Olivine $(Mg,Fe)SiO_4$	55 ± 10	59 ± 10
Orthopyroxene $(Mg,Fe)_2SiO_6$	27 ± 5	19 ± 4
Clinopyroxene $Ca(Mg,Fe)Si_2O_6$	15 ± 3	12 ± 2
Spinel $(Mg,Fe)(Al,Cr,Fe)_2O_4$	3 ± 1	0
Garnet $(Mg,Fe)_3(Al,Cr,Fe)_2Si_3O_{12}$	0	9 ± 3

Table 3D-I. Mineral Assemblages for Primary Upper Mantle Under Kilbourne Hole

wt. % Oxide	Pyrolite Model	Partial Fusion Model			Chondrite Model
SiO_2	45.16	44.35	±	0.70	43.25
Al_2O_3	3.54	4.58	±	1.09	3.90
Fe_2O_3	0.46	0.28	±	0.06	
FeO	8.04	9.70	±	0.06	9.25
TiO_2	0.71	0.20	±	0.05	
Cr_2O_3	0.43	0.27	±	0.11	
CaO	3.08	3.01	±	0.70	3.72
MgO	37.47	37.00	±	2.75	38.10
Na_2O	0.57	0.34	±	0.04	1.78
K_2O	0.13	0.02	±	0.01	
MnO	0.14	0.14	±	0.01	
CoO	0.016	0.017	±	0.001	
NiO	0.20	0.21	±	0.03	
CuO	0.0036	0.00108	±	0.00007	
ZnO	0.0073	0.0070	±	0.0006	
Li_2O	0.00098	0.00036	±	0.00006	
Rb_2O	0.00083	0.00087	±	0.00011	

Table 3D-II. Chemical Composition of Primary Upper Mantle Under Kilbourne Hole

the maximum variation, taking the mean values of the mode between Fa 12 to 14.

From the elemental plots and the mineral assemblage, one may compute the chemical composition of the primary upper mantle under Kilbourne Hole, New Mexico, Table 3D-II. The ± gives the maximum variation, taking the mean values for the chemical data between Fa 12 to 14.

It needs to be mentioned that the partial fusion model computations are based on the major phases present; the highly variable minor phases such as phlogophite have been omitted. This results in a lower K_2O content. Also phases may have been present in the starting material that were completely fused and not now present in this residuum.

Table 3D-II gives the composition of the Earth's primary upper mantle by various methods. It is encouraging to note the convergence of a number of different methods towards the same overall composition for the Earth's primary upper mantle.

References

Carter, James L., "The Origin of Olivine Bombs and Related Inclusions in Basalts," Ph.D. Dissertation, Rice University, Houston, Texas, 1965.

Wager, L.R. and R.L. Mitchell, "The Distribution of Trace Elements During Strong Fractionation of Basic Magma—A Further Study of the Skaergaard Intrusion, East Greenland," Geochimica et Cosmochimica Acta, 1, pp. 129-208, 1951.

4. GEOCHRONOLOGY

A. Half-Life Studies of Rb^{87}

Glen H. Riley

The third forbidden non-unique β-transition of Rb^{87}-Sr^{87} is of primary concern in the Rb-Sr absolute age determination scheme. The decay constant of Rb^{87} is imperfectly known at present. This group is investigating the relative merits of specific activity measurements and geologic calibration as a means of determining the half-life accurately.

(1). Rb^{87} Counting Experiments (with C.R. Bowman and R.S. Foote, Texas Instruments).

The parameters of the Rb^{87}-Sr^{87} transition suggest that the β energy distribution is highly unusual. The end point energy is about 272 keV.; the energy spectrum displays no maximum and is seen to increase monotonically at low energies. The main source of errors in previous counting measurements is lack of resolution and sensitivity of the detector in the low energy region.

In the present work, we have attempted to maintain sensitivity and resolve more detail at low β energies and thus to define the shape of the spectrum more adequately.

A lithium-drifted silicon semiconductor particle detector (TMC W802AA) is used with a FET (2N3823) low noise preamplifier. The detector and FET are cooled to 120°K. with liquid nitrogen and operated in a shielded vacuum. Under these conditions, a FWHM resolution of 1.74 keV.

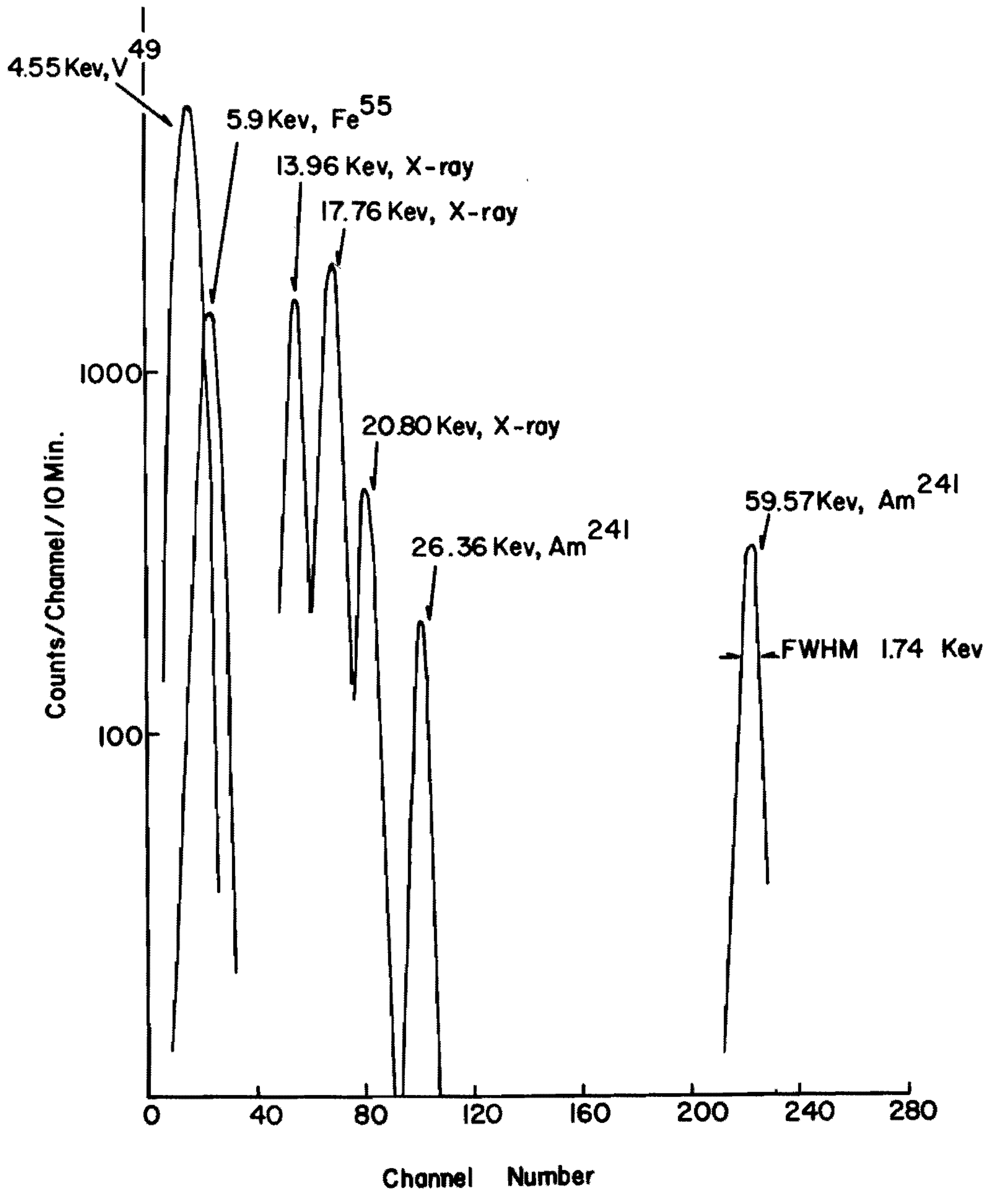


Figure 4A-1. Resolution at Low-Beta Energies

and 0.5 cpm. random noise are achieved. The excellent resolution of the equipment is demonstrated in Figure 4A-1.

A layered source is constructed by evaporating about one milligram of RbC1 on a 4,000 Å thick cellulose substrate, coated with 300-400 Å of aluminum. Energy losses less than 2 keV. may occur at the 500 Å gold layer on the semiconductor surface and the silicon dead layer (about 1/2 micron). The counting experiments so far performed have used a single detector; no energy maximum has been seen down to 4 keV. Future efforts will be made with a dual-detector system approaching 4π geometry to increase efficiency and overcome back-scattering effects.

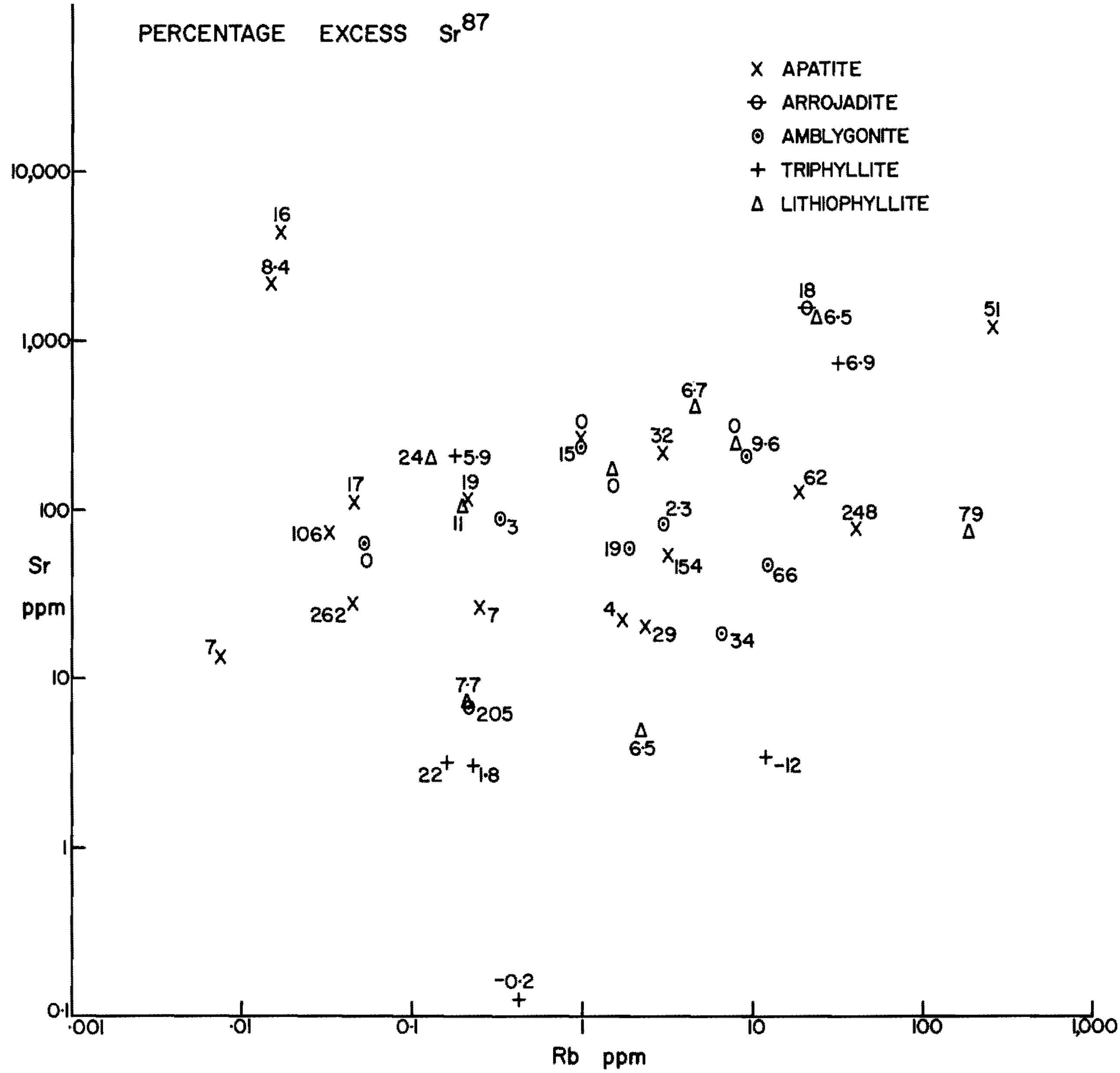


Figure 4A-2. Percentage Excess of Sr^{87} Relative to Rb and Common Sr Concentrations

(2). <u>Geologic Calibration</u>

This technique is based on the postulate that the time of formation of a geologic sample may be determined by two or more independent radioactive decay schemes. We have studied the possibility of using the K^{40}-Ca^{40} scheme as a comparator to the Rb^{87}-Sr^{87} scheme in mineral specimens of ancient lithium-rich pegmatites.

The area exploited most intensively in this project is the Precambrian lithium pegmatites associated with the Harney uplift in the southern Black Hills of South Dakota. Careful Rb-Sr measurements of the sheet silicates and feldspars demonstrate that no unique age record is available from these pegmatites. It appears that these minerals have suffered varying degrees of Sr^{87} loss; no mineral age is as old as the Harney granite. The excess Sr^{87} apparently has been assimilated by the abundant phosphate mineralization common in pegmatites of this type. Consequently, the phosphates are invariably too "old" when dated by Rb-Sr techniques.

This work is the first time that very anomalous enrichments of Sr^{87} have been found in rock systems. The initial postulate that this phenomena is related to localized events affecting the Harney uplift was tested by examining strontium isotope abundances in phosphates originating from lithium pegmatites in other areas. Samples from five different continents spanning almost 3,000 million years of geologic time have been examined and most exhibit some degree of anomalous enrichment in Sr^{87}. The percentage enrichment of Sr^{87} and the rubidium and common strontium concentrations are summarized in Figure 4A-2.

It must be concluded therefore, that it is very unlikely that a lithium pegmatite occurrence will be found that satisfies complete chemical closure. The systematics controlling strontium isotope transport in these bodies has not been studied. Future work will include an attempt to contour Sr^{87} enrichment factors within a single phosphate crystal. Such studies should help to elucidate crystalline growth theories for giant crystals.

B. Precambrian Granites of the Northern Territory, Australia

Glen H. Riley

Previous K-Ar measurements of micas from granites from the Pine Creek and Davenport geosynclines (Walpole and Smith, 1961) indicated that orogenesis occurred at the end stages of Agicondian (1630 myrs.) and Davenportian (1440 myrs.) geosynclinal sedimentation.

We have measured granites from both areas by the Rb-Sr method and the data indicate that all granites, when considered as total rock units, are syntectonic at about 1750 m.y. At the mineral level, granites from the Pine Creek geosyncline are concordant and have retained their initial total rock age. Those from the Davenport geosyncline, and further to the south intruding the Arunta basement, have mineral ages some 10 per cent younger and an isochron indicating anomalous initial strontium. Coarse grained muscovite-biotite pegmatites intruding the basement at Hart's Range are Devonian in age. The Sr isotopic composition of their apatite and plagioclase demonstrate that they were derived by crustal assimilation of basement material.

The Arunta gneiss has muscovite and biotite ages of 1150 and 1000 myrs. respectively. Thus, the Devonian event that generated the Hart's range pegmatites has caused a partial loss of Sr^{87} in the basement micas; no profound redistribution was suffered by the Jinka granite intruding the basement at Grant's Bluff.

The Agicondian and Davenportian Series both consist of folded geosynclinal sediments intruded by granites of a single epoch, viz, 1750 m.y. Furthermore, a prominent unconformity separating Davenportian and Agicondian is visible in some areas. As the unconformity and folding predate the intrusive granites, sedimentation probably began prior to 2000 m.y. The crystalline basement rocks are high grade metamorphics separated from succeeding Precambrian rocks by a very strong structural and metamorphic unconformity. Based on the age of the Agicondian Series, the Northern Territory basement may, in fact, be comparable in age with the Archean rocks of the Western Australian Shield. The apparently younger mineral ages measured on micas from the Arunta block are probably related to partial redistribution of radiogenic strontium during the Paleozoic metamorphism affecting the Ngalia Trough.

Reference

Walpole, B.P. and Smith, K.G., Bull. Geol. Soc. Am., 72, pp. 663-668, 1961.

C. Alkali Ionization

Glen H. Riley

The precision with which relative isotopic abundances may be determined by mass spectrometry using thermal ionization, can be severely limited by minor fluctuations in the ion beam intensity. A triple filament ion source has been used to study the temperature dependence of alkali ion emission.

Neutral particles, volatilized by radiation from the hot (rhenium) center filament, are ionized by impact with the hot metal surface. Under these conditions, the ion beam intensity i is related to the filament current I by a simple law of the form

$$i \propto I^n$$

The exponent, n, has been determined for various alkalis and for different anions. A summary of the results is shown in Table 4C-I.

It is obvious that the stability requirement of the filament current is n times the maximum tolerable intensity fluctuation of the ion beam. Thus if a beam stable to 1 in 5,000 is desired from an alkali compound with an emission ex-

	Cl^-	NO_3^-	$SO_4^=$	$CO_3^=$	$C_2O_4^=$	$Cr_2O_7^=$	$MnO_4^=$
Li	25						
Na	30						
K	37	48	54	65	66	50	44
Rb	56	52	48	72			
Cs	61						

Table 4C-I. Alkali Emission Exponents

ponent of, say, 50, the filament current stability must be 4 ppm. or better.

A simple, economical current regulator whose stability to load variations is better than 2 ppm., has been constructed. Its use in geochronologic studies requiring high precision in isotope ratio determinations, has proved to be very valuable.

D. Initial Sr^{87}-Sr^{86} Ratios of Continental Basic Rocks

William I. Manton

(1). Bushveld Igneous Complex

Two anorthosites, one from Rustenburg in the western portion of the B.I.C., the other from Dwarsrivier in the eastern portion yielded initial ratios of 0.7066 and 0.7068, respectively (Table 4D-I). These values are surprisingly high for basic rocks with an age of 2 b.y. Work is currently in progress to determine the initial ratio of the Bushveld granite.

(2). Western United States

Two types of basalt have been sampled: tholeiitic basalts from the Yellowstone Park, Wyoming and from the Snake River Valley, Idaho and alkali olivine basalts from New Mexico and Arizona. Rb and Sr concentrations and Sr^{87}-Sr^{86} ratios are listed in Table 4D-II. The data fall into two groups: the alkali olivine basalts with Sr contents of 500-1000 ppm. and low Sr^{87}-Sr^{86} ratios similar to those of oceanic basalts; and the tholeiites with Sr contents generally less than 400 ppm. and variable Sr^{87}-Sr^{86} ratios ranging from 0.705 to 0.710. The pattern shown by the tholeiites is similar to that obtained from the Lebombo-Nuanetsi igneous province (Manton, 1968), where the writer argued that the variation in Sr^{87}-Sr^{86} ratios was due to contamination by radiogenic Sr^{87} in the upper levels of the crust.

(3). Contaminated Karroo Dolerites (with J.J. Frankel, University of New South Wales).

Kent and Frankel (1948) described a suite of contaminated Karroo dolerites from the Effingham district, Natal. At Frankel's request the writer analyzed five of these (Table 4D-III, Nos. 1-5) and three normal Karroo dolerites (Nos. 6-8).

The data support the contamination which Kent and Frankel proposed on the basis of the chemical composition of the rocks. The high initial ratio of sample No. 6, however, also implies some contamination by crustal Sr^{87}, even though this is not apparent in the major element composition of the rock.

E. Origin of the Lebombo Rhyolites

William I. Manton

To continue the study of the Lebombo rhyolites, samples were collected from the newly constructed railway cutting along the gorge of the Mbuluzi River in Swaziland and Mozambique. A near continuous section is exposed from near the base of the rhyolites to their contact with the upper basalts. The samples collected have been analyzed for Rb and Sr by atomic absorption spectrophotometry. The Rb-Sr ratios are close to unity and show some tendency to increase towards the top of the succession. Complete data are available on samples taken from the middle of the rhyolite succession and the initial ratio seems identical to that obtained from the lowermost flows.

References

Kent, L.E., and J.J. Frankel, Trans. Geol. Soc. S. Africa, 51, 179 (1948).

Manton, W.I., J. Petrology, in press, 1968.

	Rb	Sr	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}	(Sr^{87}/Sr^{86})*
Anorthosite, Dwarsrivier	4.9	412	0.03	0.7076	0.7068
Anorthosite, Rustenburg	0.55	337	0.005	0.7066	0.7066

*Assuming an age of 2 by.

Table 4D-I. Bushveld Anorthosite Ratios

	Rb p.p.m.	Sr p.p.m.	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
YB1	6.9	383	0.05	0.7056
YB2	29	299	0.27	0.7071
YB6	107	963	0.31	0.7052
SBR2	12	284	0.11	0.7055
SBR3	15	321	0.13	0.7060
SBR4	42	319	0.36	0.7098
SBR5	50	296	0.48	0.7101
SBR6	16	351	0.13	0.7070
Capulin, New Mexico	28	598	0.13	0.7044
Peridot, Arizona	24	978	0.07	0.7038
Williams, Arizona	12	900	0.04	0.7038
Kilbourne's Hole, New Mexico	30	565	0.15	0.7040
Potrillo, New Mexico	23	592	0.11	0.7031
San Rafael, New Mexico	19	270	0.20	0.7062

YB - Yellowstone basalt

SBR - Snake River basalt, Recent.

Rb and Sr concentrations by isotope dilution

Table 4D-II. Rubidium and Strontium Measurements from Tertiary and Recent Basalts from Western United States

	Rb	Sr	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
1. Black Dolerite Glass	50	680	0.2	0.7229
2. Purple Dolerite Glass	110	237	1.3	0.7199
3. Dolerite, Effingham	100	140	2.4	0.7228
4. Dolerite	80	200	1.1	0.7153
5. Dolerite Chaka's Rock Beach	60	160	1.0	0.7206
6. Karroo Dolerite	30	320	0.3	0.7124
7. Karroo Dolerite	15	230	0.2	0.7075
8. Karroo Dolerite	20	240	0.2	0.7071

Rb and Sr concentrations by atomic absorption spectrophotometry.

Table 4D-III. Contaminated and Normal Karroo Dolerites from Natal, South Africa

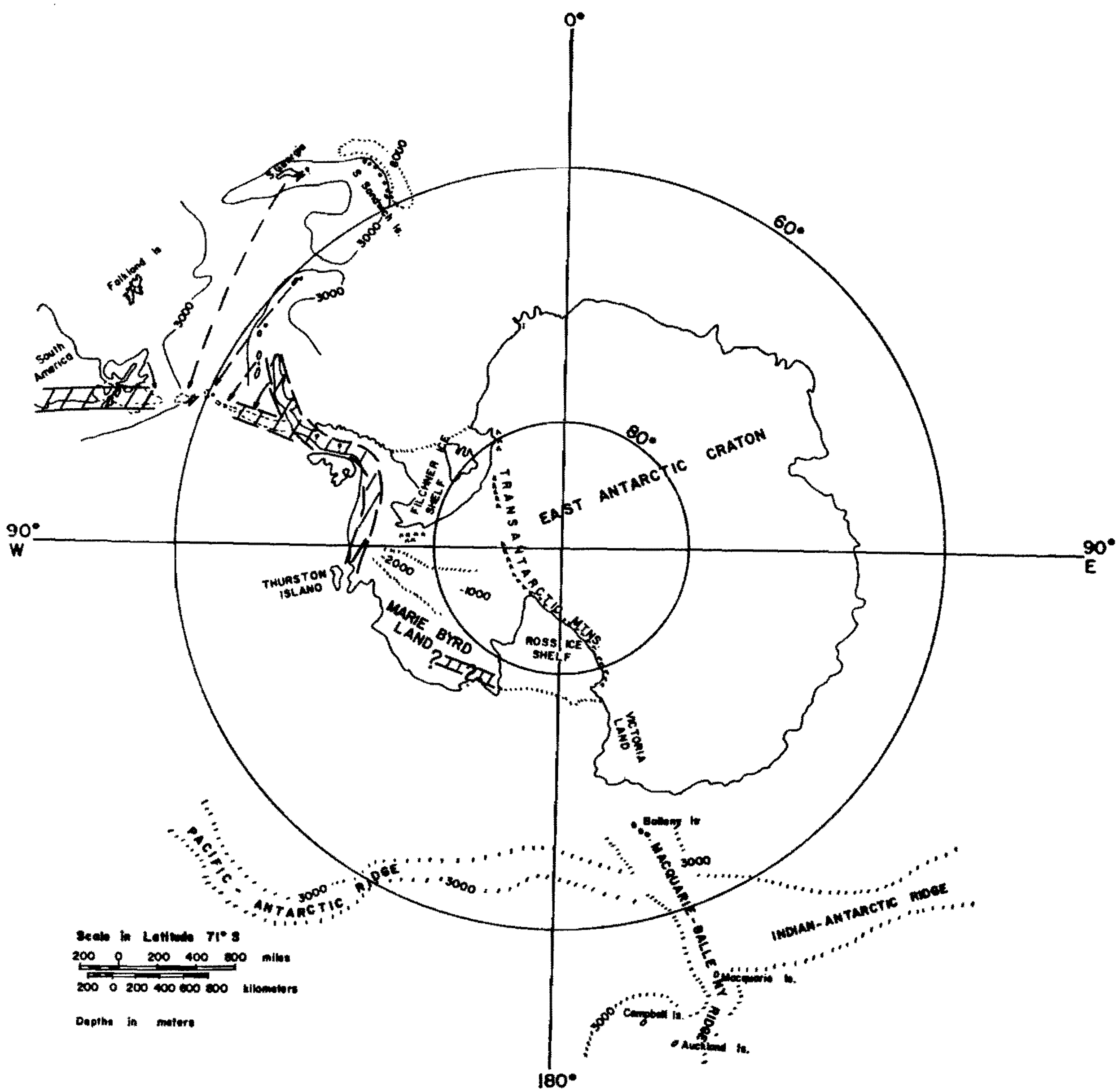


Figure 4F-1. Trend of late Mesozoic plutonic activity in Southern South America and West Antarctica

F. Geologic Significance of Isotopic Age Measurements of Rocks from South America and West Antarctica

Martin Halpern

Radiometric age dating of southern Chile and West Antarctic rocks has been completed.

Rb-Sr isochron dates from duplicate analyses of whole rock and biotite concentrates of eight samples from the Beagle Canal and Straits of Magellan regions of southern Chile give the following ages: (1) 12 m.y. for the Cerro Paine quartz monzonite laccolith which intrudes Upper Cretaceous sedimentary rocks; (2) 57 to 71 m.y. for granitic samples from morainal material at the tongue of Ventisquero Alemania which flows southerly out of Cordillera Darwin; (3) 77 to 82 m.y. for granitic samples of the Andean intrusive suite which intrudes the Lower Cretaceous Yahgan Formation; and (4) 267 m.y. for granodiorite gneiss from the basement of the Magellan basin near the eastern end of the Straits of Magellan. K-Ar dating of three samples gives the following ages: (1) 92 m.y. for hornblende from andesitic volcanic rock at Isla Bertrand; (2) 64 m.y. for porphyroblastic muscovite from paraschist at Bahia Yendegaia; and (3) 38 m.y. for hornblende from amphibolite at Ventisquero Italia (Halpern, 1967a).

West Antarctic (eastern Ellsworth Land) plutonic igneous rocks intrusive into folded Jurassic sedimentary rock have been dated at 102 to 109 m.y. At Tisné Point on the northwest coast of the Antarctic Peninsula, granodiorite is dated at 96 m.y. (Halpern, 1967b).

Field relationships, geochronology and geochemistry indicate that Cretaceous plutonism of southern South America and of the Antarctic Peninsula extended at least as far south as Ellsworth Land, and probably continued into the Ford Ranges near the Ross Sea. Disruption of a continental strip once joining South America and Antarctica probably occurred in post Cretaceous time (Figure 4F-1).

Presently planned major programs involving Rb-Sr geochronology are the following:

(1). Analyses of metamorphic and intrusive igneous rocks from the Ford Ranges to understand the relationships of this region to the geologic provinces of East and West Antarctica.

(2). Analyses of basement rocks from southern Argentina and Chile to provide a chronologic framework for comparison with other southern hemisphere land masses.

References

Halpern, Martin, "Geologic Significance of Isotopic Age Measurements of Rocks from Tierra del Fuego, Chile," UNESCO Symposium on Continental Drift, Montevideo, Uruguay, Oct. 1967(a).

Halpern, Martin, "Rb-Sr Isotopic Age Measurements of Plutonic Igneous Rocks in Eastern Ellsworth Land and Northern Antarctic Peninsula, Antarctica," J. Geophys. Res. 72(20), pp. 5133-5142, 1967(b).

5. PALEOMAGNETISM

A. Analytical Technique for Paleomagnetic Data

John W. Graham

Directions in space are frequently of considerable importance in Geosciences. The data from rock magnetism have engendered a number of ways of carrying out statistical analyses so that objectively one can gauge the average directions and the reliability of the average. These mathematical treatments of the data, however, depend on

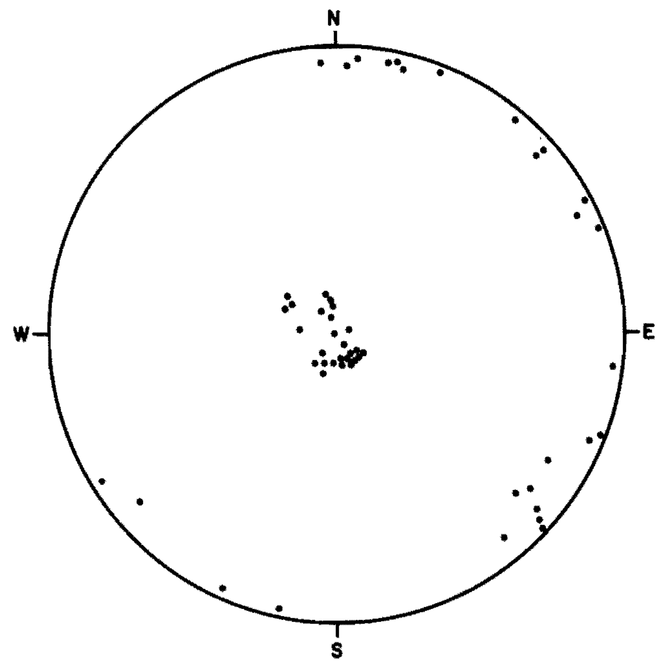


Figure 5A-1. Conventional plot on an equal area projection of principal axes of magnetic susceptibility observed in undeformed Permian redbeds at Carrizo Creek, Arizona; least susceptibility axes are at the center of the plot, and maxima lie dispersed in the plane of the bedding.

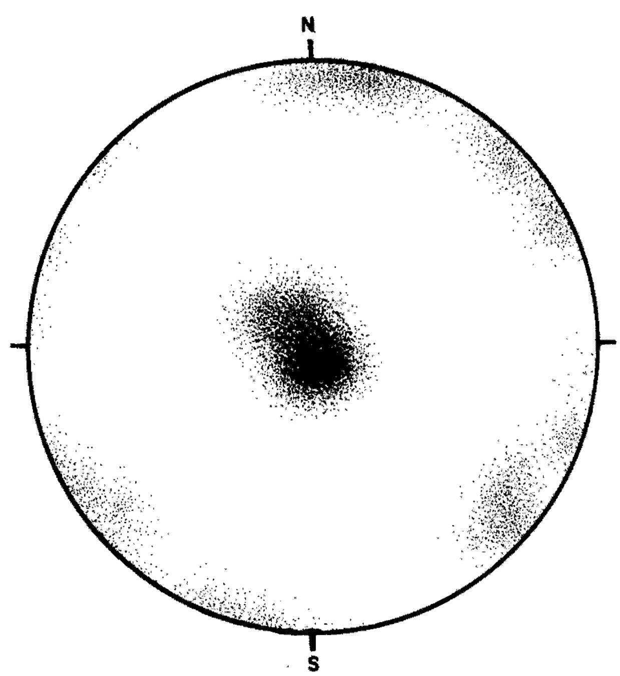


Figure 5A-2. Here each data point of Figure 5A-1 has been replaced by a swarm of tiny dots, the size of the swarm at the 1σ diameter being 1% of the area of the projection circle. By adjusting the size of the swarm it is possible to control the amount of smoothing of the original data.

some initial assumption about the pattern of distribution of directions in the population being considered; if, for some reason the model does not fit the distribution, then the resulting statistics may be misleading.

In many cases it is preferable to utilize graphical procedures for representing directions in space, as is commonly practiced in structural geology studies. Conventionally, directions are represented by points on some type of spherical projection, and then, by any one of several rather arbitrary procedures, the point densities on the projection are contoured. Given such a plot, one generally is able to make a reasonable judgment of whether the directions represent several mixed populations or a single simple one.

But the contouring procedures are subject to several criticisms: they do not lead to identical appearance of the final plot, they may ignore distortion of the projection and they are time consuming.

By way of circumventing these objections, I have devised a procedure using photographic techniques in which each data point on the original equal area projection becomes represented on a new plot by a swarm of tiny dots that are dispersed in a circular normal distribution; the size of the swarm can be chosen to suit the character of the data. The argument is that where there are many data points near one another, the comingling of swarms causes darkening of the plot which then can be evaluated easily and quickly by eye. Distortion of the projection is accounted for by using various dot swarms that have been appropriately distorted. Figure 5A-2 shows the result of applying this technique to the data points shown in Figure 5A-1.

It is expected that this technique will provide useful guidance in the selection of the most appropriate manner for the statistical analysis of directional data.

B. Studies of Textures and Structures of Rocks

John W. Graham

In earlier studies (Graham, 1966), it was demonstrated that the patterns of magnetic susceptibility anisotropy in sedimentary rocks are clearly related to the deposition and deformation of the specimens. This fact was interpreted as indicating that the spatial arrangement of irregular elongated ferromagnetic grains can be used for purposes of structural geology.

Not all rocks, however, contain sufficient numbers of magnetic particles that magnetic anisotropy can be measured and alternative procedures for determining the fabric of the component grains are highly desirable. Some vague reports in the literature have indicated that dielectric anisotropy may be useful, and accordingly a study has been started to compare the results of magnetic and dielectric anisotropy on a suite of samples about which a great deal is already known.

Dielectric anisotropy, conventionally, is determined by noting how the electric capacity of an air condenser is modified as the sample, of regular shape, is turned within it to various orientations. What is called for, then, is a system which is exceedingly sensitive to small changes of capacity.

It has been found that by relatively simple modification of the instrument used previously (Graham, 1967) for magnetic measurements, it is possible to achieve the necessary sensitivity ($\sim 10^{-16}$ F) for making dielectric measurements. Furthermore, this modified instrument has the capability, as well, of detecting anisotropy of electrical conductivity. Studies with this instrument have brought out the fact that in the conventional scheme of dielectric anisotropy measurement, the conductivity anisotropy of the sample couples in electrically with the effect produced by dielectric anisotropy. In other words, the conventional measurement should more properly be referred to as determination of electrical anisotropy. It has been established in the case of several representative rock samples, however, that the orientation of the conductivity anisotropy is congruent with the dielectric anisotropy and it appears electrically in the conventional measurement as an augmentation of the dielectric anisotropy. Thus, it seems unlikely that electrical and dielectric anisotropies will oppose one another, and accordingly, measurements by the conventional scheme should give geologically useful results bearing on the fabrics of rocks. This is a matter of great practical value for it means that it is possible to get anisotropy information in three dimensions by measurements on a cubic sample and there is no necessity for the cylindrical samples which are required for the conductivity anisotropy measurements.

Some reconnaissance measurements have been made of the thermal conductivity anisotropy of samples known to have a pronounced magnetic susceptibility anisotropy. The limited experience indicates that the available measurement techniques are of marginal utility, and at this time the magnetic and electrical anisotropies appear more promising as means for deducing the gross fabrics of rock samples.

References

Graham, John W., "Significance of Magnetic Anisotropy in Appalachian Sedimentary Rocks," The Earth Beneath the Continents, Geophysical Monograph No. 10, John S. Steinhart and T. Jefferson Smith (Editors), American Geophysical Union, Washington, D.C., 1966.

Graham, John W., "Preliminary Account of a Refined Technique for Magnetic Susceptibility Anisotropy Measurement of Rocks," Developments in Solid Earth Geophysics 3, Methods in Palaeomagnetism, D.W. Collinson, K.M. Creer and S.K. Runcorn (Editors), Elsevier Publishing Company, Amsterdam, 1967.

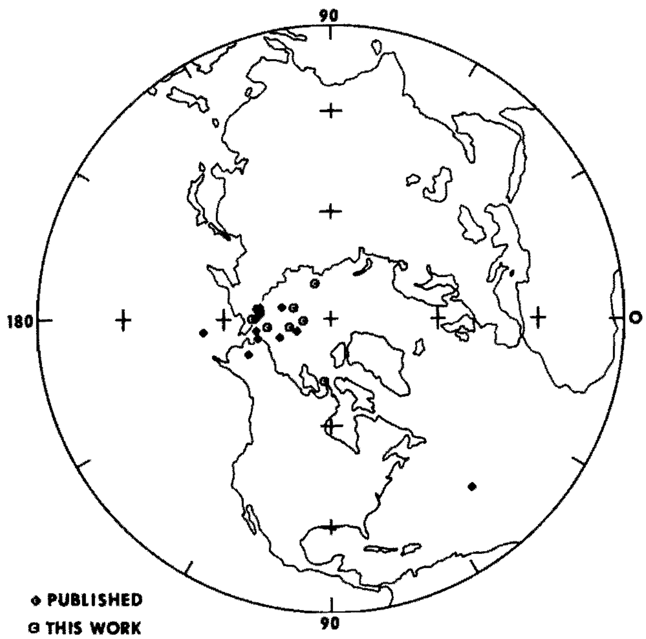


Figure 5C-1. North American Cretaceous Paleomagnetic Poles

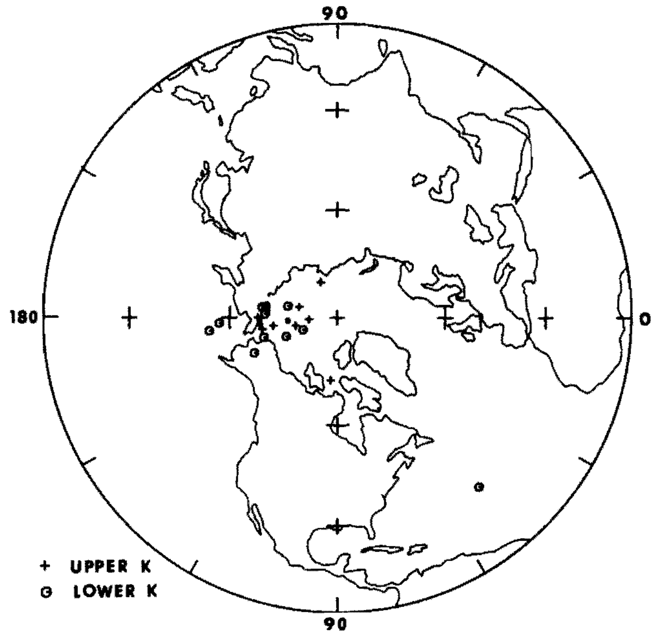


Figure 5C-2. Suggested Polar Movement in Cretaceous Time

C. Paleomagnetism of Cretaceous Rock From North America

Charles E. Helsley

Paleomagnetic studies made on rocks from eleven widely separated localities have provided additional evidence for locating the position of the North American Cretaceous paleomagnetic pole. These data, when combined with the published data from other localities in North America, give a virtual pole position in the Arctic Ocean at 72° N. 178°W with an α_{95} of 6° (Figure 5C-1). Since these samples came from widely separated parts of the North American continent, the observation that all of the data from structurally uncomplicated areas gives the same pole position strongly supports the assumption of a dipolar field during most, if not all, of Cretaceous time. The polarity of all samples used in this study, as well as those reported from previous studies on Cretaceous, rocks are normal except for those whose age is given as Cretaceous-Jurassic or Cretaceous-Paleocene. This suggests that the Cretaceous period may have been dominated by a field of normal polarity much as the Permian was dominated by a field of reversed polarity.

It is also interesting to note that an analysis of all available Cretaceous data from North America in terms of Upper Cretaceous and Lower Cretaceous (Figure 5C-2), using the best available age criteria, provides two pole positions seven degrees apart each having a α_{95} of 6°. Although this difference may not be significant it suggests that the pole did move during Cretaceous time. The movement of the pole is from south to north along approximately 180°W and its direction and rate of movement extrapolates to be consistent with the results for Early, Middle and Late Tertiary rocks from North America. Thus, if the polar wandering is interpreted as the result of continental drift, the results of this study suggest that the drift of North America has maintained a constant direction and has been more or less continuous since early in the Cretaceous.

D. Petrology and Magnetic Properties

Henry R. Spall

There is a growing literature concerning the petrologic differences between normal and reversely magnetized basalt lavas (e.g., Wilson and Haggerty, 1966). Attention has focused primarily on the oxidation states of titanomagnetite grains, although separate ilmenite and olivine can also be oxidation indicators.

An attempt is being made to extend this petrologic work into intrusive rocks, and to relate the Fe-Ti oxide mineralogy with the magnetic properties of Precambrian granitic rocks, described in the annual report for 1966.

The mineralogy of the granites has been found to be relatively straightforward. In general two main phases are observed:

(a). Separate ilmenite

(b). Titanomagnetite in varying amounts of oxidation to hematite.

The magnetic properties of the granites are often spurious, so that a quantitative analysis of the petrology must be made. Data so far suggest that two factors contribute to magnetic behaviour:

(1). Grain Size.

The most unreliable behaviour is associated with an abundance of massive titanomagnetic grains (600-700 microns width). It is thus probable that each grain acts effectively as a number of self-cancelling multidomains, so that the magnetization present is simply of soft, isothermal type.

(2). Extent of oxidation to hematite.

Oxidation of titanomagnetite to hematite is the commonest form of alteration in the opaque oxides. Two patterns of oxidation occur: (a). as lamellae along octahedral planes in titanomagnetite, and (b). in irregular form along grain margins.

Preliminary work suggests a relationship between amount of oxidation and magnetic reliability. Oxidation may thus have broken down the multidomains so that their dimensions become closer to magnetically hard, single domains.

It is hoped that future work will resolve two problems:

(a). It is not known whether the oxidation is either deuteric or hydrothermal. Goethite is present in many specimens, implying a low temperature alteration.

(b). It is not known at what time oxidation took place, for when large amounts of hematite have been formed, it is possible that these will acquire a magnetization in the direction of the ambient geomagnetic field.

6. OTHER STUDIES

A. Plankton and Hurricanes

John W. Graham

A digression was taken from usual pursuits to consider the possibility that important relationships exist between the growth of plankton at sea and the development of hurricanes. The reasoning that led me to associate the two phenomena is as follows.

Various planktonic organisms release to sea water a number of substances which are capable of forming thin films on the sea surface. Characteristically, thin films suppress evaporation and thus cause an enhanced retention of heat in the water, and a depletion of the supply of moisture to the atmosphere. The issue to examine is whether or not these surface films can, in practice, assume importance in influencing the thermal balance between the atmosphere and ocean in the tropical areas where hurricanes are spawned. What needs to be looked for is the possibility that changing conditions–either a greatly increased production of film-forming material by a plankton "bloom," or a slacking of average surface winds so that effective films could form more readily–would set up a gross energy imbalance in the atmosphere-ocean system, and thus lead to the development of a hurricane.

A reconnaissance was made of the oceanographic and meteorological data that are available for examining this question, and it was concluded that as of now, they are just marginal. However, it can be expected that rather soon, with improved coverage by weather satellites, oceanographic monitoring buoys and meteorological soundings in the important areas concerned, the possibility of associating plankton with hurricanes can be considered carefully.

B. Magnetic Deep Sounding

John S. Reitzel

Remarkable differences have been observed in many places between geomagnetic variations at stations only a few tens of miles apart. These differences are due to lateral changes in the earth's electrical conductivity at depth; many of these changes in turn are best ascribed to lateral temperature changes in the upper mantle. The systematic exploration and study of magnetic variations over a region is likely to be a powerful method of mapping differences of deep temperature.

Our program in this field began two years ago with the development by Drs. Gough and Reitzel of a three-component variometer that could be made cheaply enough to let us deploy a large array of instruments at reasonable cost. The good resolution and stability attained by the prototype instrument were reported in last year's Annual Report. During the summer of 1966, the first eight of a projected set of twenty variometers were completed, and these were taken to Colorado last October to be given a field trial on a profile across the eastern front of the southern Rocky Mountains.

A variety of studies has indicated that the Great Plains, the Southern Rockies with the Colorado Plateau, and the Basin-and-Range Province form three distinct geophysical provinces with sharp boundaries, marked by successive decreases in crustal thickness and mantle seismic velocities, and by increases in heat flow, going from east to west. In Southern New Mexico and West Texas, speaking very broadly, the Plains and the Basin-and-Range Province close up together around the Southern Rockies. In this region, Schmucker (1964), observed magnetic variations along an east-west profile in 32° N. Lat. He found consistently low

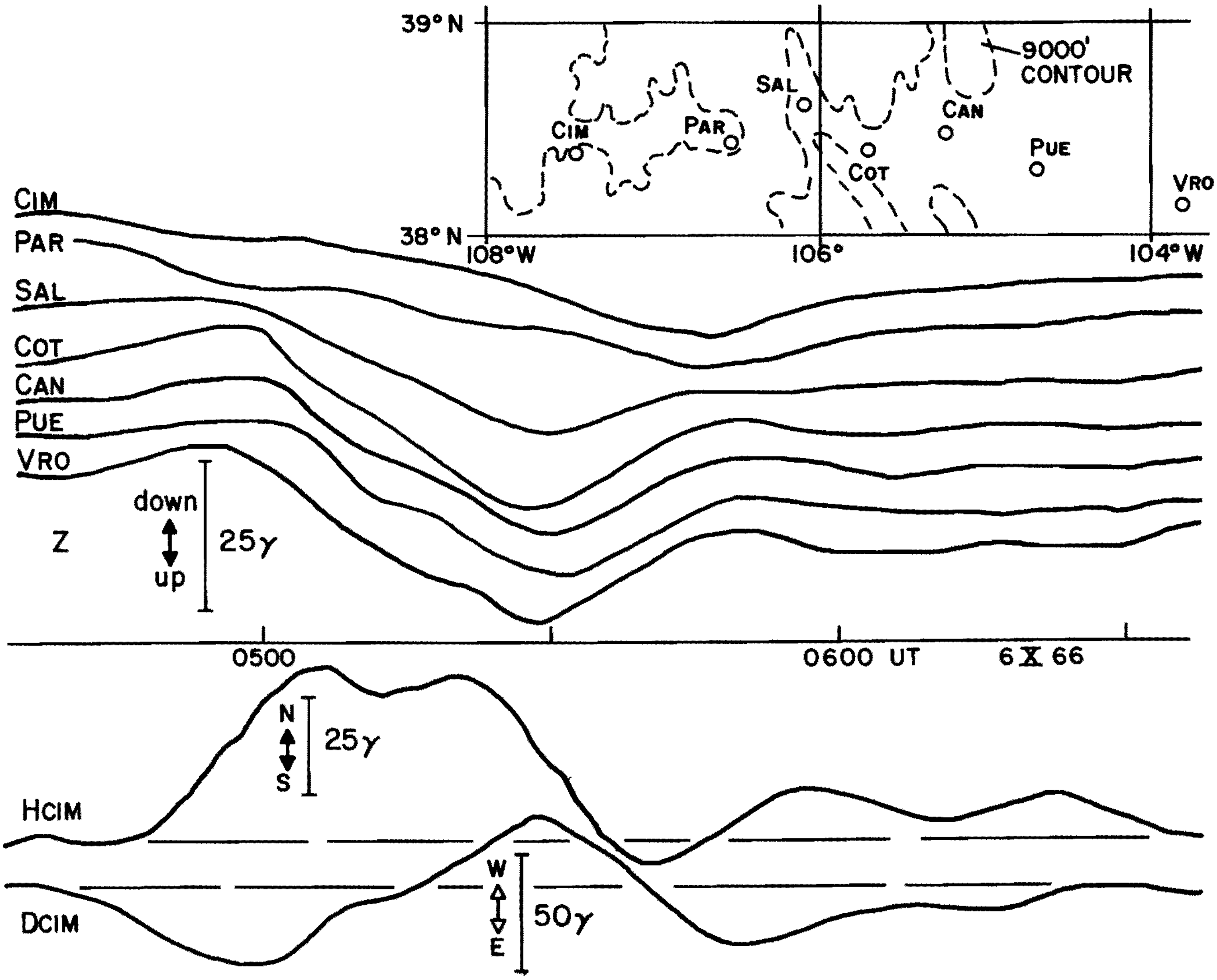


Figure 6B-1. First Profile from Colorado Plateau Across Eastern Ranges of Rocky Mountains.

amplitudes of vertical variation (Z) west of 106° W. Longitude and consistently higher Z-amplitudes east of 106°, with highest amplitudes near the transition and a good correlation between upward Z-variations and westward horizontal variations. All these results he interpreted as due to an abrupt rise of mantle conductivity west of 106°.

Our own first profile ran from about 103° to 107½° W. Longitude, in about 38½° N. Latitude, from the high plains onto the Colorado Plateau across the eastern ranges of the Rockies. The observations of one bay disturbance on this profile are shown in Figure 6B-1. As on Schmucker's profile, Z amplitudes rise markedly east of 106° W. for variations with periods of a few thousand seconds. For anomalous Z-variations, referred to the westernmost station, the upward variation fields are coherent with horizontal variations in the direction N56W, indicating that the trend of a steplike conductivity change here would be somewhere near N34E.

Isolated profiles with six or eight instruments cannot be extrapolated too far to the sides. Our intention in building twenty variometers is to survey variations over a two dimensional net of stations. At present, the twenty variometers are complete, and twenty more have been built by Dr. Gough at the University of Alberta. The whole set of forty is now being put out by SCAS and the University of Alberta in an array covering the area from 102° to 117° W. Longitude and from 35° to 42° N. Latitude. This region extends over the full width of the Southern Rockies and Colorado Plateau, and this season's work may help to make clear the separate effects at the east and west boundaries of this province.

While the last variometers were being built, seven of the original eight were placed through the winter of 1966-67 about the Large Aperture Seismic Array in eastern Montana, for a joint investigation with Massachusetts Institute of Technology of possible relations between variation anomalies and seismic anomalies observed within the array. The most striking qualitative result of this work is the large amplitude of Z at Baker, Montana (about 104° W.) compared with those at several stations west of 105° W., and the correlation of upward Z with northeasterly, rather than westerly, horizontal variations.

This correlation, suggesting a region of high conductivity under the plains northeast of Baker, reminds us that the distribution of conductivity beneath western North America is probably sown with more or less local complications, of deep or shallow origin; the value of a large set of variometers becomes more and more clear as work continues.

References

Gough, D.I., and J.S. Reitzel, "A Portable Three-Component Magnetic Variometer," J. Geomag. and Geoelec. 19(3), pp. 203-215, 1967.

Gough, D.I., and J.S. Reitzel, "Magnetic Deep Sounding and Local Conductivity Anomalies," NATO Adv. Studies Inst., Newcastle Symposium Volume, in press.

Schmucker, Ulrich, "Anomalies of Geomagnetic Variations in the Southwestern United States," J. of Geomag. and Geoelec. XV, pp. 193-221, 1964.

C. Lunar Studies

Philip Oetking

The search to determine the cause for the peak in brightness of the light reflected from terrestrial samples near zero phase angle (when the direction of the incident beam and the direction of observation are nearly coincident) has continued. The study stemmed from an investigation which attempted to locate a terrestrial material which would duplicate the lunar photometric data, namely, the increased brightness at full Moon. This study has shown that this characteristic of the Moon is not unique as had been thought. Most terrestrial dielectric materials reflect light in a similar manner when examined under like conditions. A pronounced rise in reflectivity begins at about 8 to 10° before a position of zero phase angle and reaches a maximum at zero phase angle.

Several hundred samples and variations of each have been examined at different wavelengths of light in an attempt to determine which property or properties control the angular breadth and percentage rise of the backscattering effect or "opposition peak." It is assumed that the major cause of the light intensity variation is a shadowing effect of the surface configuration and internal properties of the reflecting media. The more nearly the direction of the incident beam coincides with the direction of the line of observation the less the shadowing, hence the stronger the light intensity.

A large number of controlled experiments have been performed on a variety of models for an examination of this assumption. For example, glass plates ground with different depths of roughness, were tested. The results clearly showed that the "opposition peak" increased proportionally with the increased roughness of the surface. Similar results were obtained from a series of runs on very fine grained basalt slabs polished to various degrees of smoothness. So as to avoid interference of the specular reflection and the opposition effect on the smoother surfaces, all the target surfaces were angled appreciably away from the perpendicular to the detector. This separates the two light intensity peaks. The finer the polish on the sample the sharper and more intense the specular reflection; the reverse is true for the opposition reflection. A highly polished surface i.e., glass plate, mirror, shiny metal, or the like, shows very little or no "opposition peak." Liquids, even when sonically vibrated, lack the opposition rise.

Smoke blackened sewing needles equally spaced and adjustable so as to establish progressively different interval spacings, were placed at the front side of a standard surface. As expected, the closer the spacing of the needles, the stronger and more abrupt was the "opposition peak." This series of tests supported the assumption that large scaled surface obstructions cast broader shadows at larger phase angles and gave rise to an overall increase in light intensity at small phase angles where the shadowing diminishes. The narrowing of the spacing between the needles effectively deepened the surface irregularities, broadened the shadows at larger angles, and as a consequence increased the contrast in the intensity of the reflected light at small angles. Although this demonstrates that gross shadowing can develop the "opposition peak", it does not appear that shadowing is a wholly satisfactory explanation of the peak developed on very fine grained materials.

Additional model studies, selected to investigate the shadowing influence of an irregular surface, involved a series of furrows and cross furrows of various widths and depths. The surfaces were smoked with magnesium oxide (a standard diffusing material). The gross features did not alter the reflectivity pattern normally obtained from the undisturbed magnesium oxide surface. The conclusion from this series of tests suggests that control of the peak may be sub-wavelength in dimension.

The cause of the "opposition peak" remains uncertain.

D. Geological Highway Map

Philip Oetking

Map No. 2 of the United States Geological Highway Map series, sponsored by the American Association of Petroleum Geologists, was released at the annual convention, April, 1967. The Southern Rocky Mountain Region map includes the states of Arizona, Colorado, New Mexico and Utah. Like the Mid-Continent Region (Map No. 1), the map was prepared by a national committee under the chairmanship of Dr. Oetking. Dr. Dan E. Feray, Texas Technological College, and Dr. H.B. Renfro, Dallas geologist, are the other members of the committee. Technical and material assistance for the map series is being furnished by the U.S. Geological Survey, state bureaus and geological surveys, regional and local geological societies, educational institutions, oil companies, and individuals.

The eleven maps form a public education program sponsored by A.A.P.G. with support from funds raised by the association from principal oil companies.

The publication, a convenient 28 by 36-inch size (4 3/4 in. x 9 3/8 in. folded), presents the geology of the four state region in a series of color coordinated illustrations. On the principal map (scale 1 inch = 30 miles), printed in 40 vivid colors, the surface geology is superimposed on a cultural grid showing the highways, cities, distances and major points of interest. In addition, there are supplemental illustrations, a chart of time and rock units, a tectonic map, a physiographic map, several cross sections, and a series of diagrams which depict the geologic history of the region. Each of the illustrations are designed to join the adjacent regional maps; i.e., upon completion of the series the cross sections will be continuous from coast to coast and border to border.

The third map in the series, the Pacific Southwest Region, covering California and Nevada, will be completed early in 1968.

FACULTY AND STAFF 1966-1967
Geosciences Division

Faculty

GRAHAM, John W. (Professor)
HALES, Anton L. (Professor and Division Head)
LANDISMAN, Mark (Professor)

HELSLEY, Charles E. (Associate Professor)
MacGREGOR, Ian D. (Associate Professor)

HALPERN, Martin (Assistant Professor)
MANTON, William I. (Assistant Professor)
PRESNALL, Dean C. (Assistant Professor)
REITZEL, John S. (Assistant Professor)
RILEY, Glen H. (Assistant Professor)

Postdoctoral

BURCHART, Jan (Research Associate)
CARTER, James L. (Research Associate)
CHEN, Ju Chin (Research Scientist)
DOWLING, John J. (Research Associate)
DZIEWONSKI, Adam (Research Associate)

Scientific

BLOCH, Selwyn (Research Scientist)
DOYLE, Hugh A. (Research Associate)
GREEN, Rodleigh W. E. (Research Scientist)

Visiting Scientists

JEFFREYS, Sir Harold (Visiting Professor)

Engineering

BACON, D. Lee (Associate Engineer)
KEILLER, John A. (Instrument Engineer)

Research Assistants

BELFLOWER, M. Doyce (Research Assistant)
BUTTERMORE, Jack L. (Research Assistant)
COUCH, Yvonne V. (Research Analyst)
NATION, Joseph B. (Research Assistant)
ROBERTS, Jeanne L. (Programmer)

Predoctoral Students

Ph. D. Candidates at Southern Methodist University

FELDHAUSEN, Peter H.
GOSE, Wulf A.
MASSÉ, Robert P.
MITCHELL, Brian J.
SPALL, Henry R.

Technical

BELL, Eugene J. (Technician)
BERNHARDT, Brian M. (Machinist II)
BIANCHI, Romee A. (Machine Shop Supervisor)
BONE, Valerie J. (Laboratory Technician)
CLARK, Brenda A. (Laboratory Technician)
COMBS, Bobby J. (Laboratory Technician)
DUCOTE, Priscilla (Laboratory Technician-Trainee)
EDMONDSON, David B. (Electronics Technician)
HAAS, Herbert (Engineering Technician)
HANSON, Dale F. (Laboratory Technician)

HIGGINBOTHAM, Wayne (Laboratory Technician)
HUCKABY, Antoinette (Laboratory Technician)
JONES, Theodore (Apprentice Machinist)
MARTIN, David J. (Technician)
MATHIS, Patricia J. (Laboratory Technician)
MICHAEL, Fouad Y. (Laboratory Technician)
MIROWITZ, Lee E. (Laboratory Assistant)
REYNOLDS, Catherine L. (Student Laboratory Assistant)
THIGPEN, Roger D. (Laboratory Technician)
TONEY, James B. (Electronics Technician)
TUCKER, James (Machinist)
TURELLA, Robert (Laboratory Technician)
YORK, Doug (Technician)

Administrative

CALTON, Suzanne (Secretary)
GOERTZEN, Sandra (Secretary)
FISHER, Patricia (Secretary)
McCLELLAN, Sherry (Secretary)
MURRAY, Kenneth A. (Executive Officer)

New Arrivals to Faculty and Staff (after July 1, 1967)

BRUECKNER, Hannes K. (Research Associate) – Petrology
BUREK, Peter J. (Research Associate) – Paleomagnetism
MITTERER, Richard M. (Assistant Professor) – Organic Geochemistry
PESSAGNO, Emile A. (Assistant Professor) – Micropaleontology
PORATH, Hartmut (Research Associate) – Geomagnetism
URBAN, James B. (Research Scientist) – Palynology

PUBLICATIONS OF THE GEOSCIENCES DIVISION

Ables, J.G. and G.H. Riley, "A Filament Current Regulator for Solid Source Mass Spectrometers," *Rev. Sci. Instrum.*, in press. (Contribution No. 53)

Bloch, S. and A.L. Hales, "New Techniques for the Determination of Surface Wave Phase Velocities," *Bull. Seism. Soc. Am.*, in press. (No. 59)

Chen, J., "Hydrothermally Altered Rocks from Puerto Rico," submitted to *American Journal of Science.* (No. 62)

Cleary, J. and A.L. Hales, "Analysis of the Travel Times of P Waves to North American Stations, in the Distance Range 32° to 100°," *Bull. Seism. Soc. Am. 56*, pp. 467-489, 1966. (No. 17)

Cleary, J. and A.L. Hales, "Azimuthal Variation of U.S. Station Residuals," *Nature 210*, pp. 619-620, 1966. (No. 30)

Dowling, J.J., "The East Coast Onshore Offshore Experiment: II. Seismic Refraction Measurements on the Continental Shelf between Cape Hatteras and Cape Fear," *Bull. Seism. Soc. Am.* in press. (No. 56)

Doyle, H.A. and A.L. Hales, "An Analysis of the Travel Times of S Waves to North American Stations, in the Distance Range 28° to 82°," *Bull. Seism. Soc. Am. 57*, 761-771, 1967. (No. 42)

Faul, H., "Tektites are Terrestrial," *Science 152*, pp. 1341-1345, 1966.(No. 29)

Fuchs, K. and M. Landisman, "Results of a Re-interpretation of the N-S-Refraction Line Adelebsen-Hilders-South in West Germany," *Zeitschrift für Geophysik 32*, 1966. (No. 27)

Fuchs, K. and M. Landisman, "Detailed Crustal Investigation along a North-South Section through the Central Part of Western Germany," in *The Earth Beneath the Continents*, Geophysical Monograph 10, J. Steinhart and T. Smith, editors, American Geophysical Union, Washington, D.C., pp. 433-452, 1966. (No. 41)

Gough, D.I., "A Spinner Magnetometer at Salisbury," in *Methods in Palaeomagnetism*, D. Collinson, K. Creer and S. Runcorn, editors, Elsevier Publishing Co., Amsterdam, pp. 119-130, 1967. (No. 8)

Gough, D.I., "Notes on Rock Sampling for Palaeomagnetic Research," in *Methods in Palaeomagnetism*, D. Collinson, K. Creer and S. Runcorn, editors Elsevier Publishing Co., Amsterdam, pp. 3-7, 1967. (No. 9)

Gough, D.I., "Magnetic Anomalies and Crustal Structure in the Eastern Gulf of Mexico," *Amer. Assoc. Petrol. Geologists Bull. 51*, pp. 200-211, 1967. (No. 38)

Gough, D.I. and J.S. Reitzel, "A Portable Three-Component Magnetic Variometer," *J. Geomag. Geoelec. 19*, pp. 203-215, 1967. (No. 43)

Graham, K.W.T., C.E. Helsley and A.L. Hales, "Determination of the Relative Positions of Continents from Paleomagnetic Data," *J. Geophys. Res. 69* pp. 3894-3900, 1964. (No. 2)

Graham, K.W.T. and A.L. Hales, "Surface-Ship Gravity Measurements in the Agulhas Bank Area, South of South Africa," *J. Geophys. Res. 70*, pp. 4005-4011, 1965. (No. 5)

Graham, J.W., "Preliminary Evaluation of a New Resonance Magnetometer," in *Methods in Palaeomagnetism*, D. Collinson, K. Creer and S. Runcorn, editors, Elsevier Publishing Co., Amsterdam, pp. 96-99, 1967. (No. 10)

Graham, J.W., "Preliminary Account of a Refined Technique for Magnetic Susceptibility Anisotropy Measurements of Rocks," in *Methods in Palaeomagnetism*, D. Collinson, K. Creer and S. Runcorn, editors, Elsevier Publishing Co., Amsterdam, pp. 409-424, 1967. (No. 11)

Graham, J.W., "The Significance of Magnetic Anisotropy in Appalachian Sedimentary Rocks," in *The Earth Beneath the Continents*, Geophysical Monograph 10, J. Steinhart and T. Smith, editors, American Geophysical Union, Washington, D.C., pp. 627-648, 1966. (No. 26)

Green, R.W.E. and A.L. Hales, "Seismic Refraction Measurements in the Southwestern Indian Ocean," *J. Geophys. Res. 71*, pp. 1637-1647 1966. (No. 20)

Green, R.W.E. and A.L. Hales, "The Travel Times of P Waves to 30° in the Central United States and Upper Mantle Structure," *Bull. Seism. Soc. Am.*, in press. (No. 55)

Hales, A.L., "A Look at the Mantle," *Geotimes*, July-August, 1964. (No. 1)

Hales, A.L., "East Coast Onshore Offshore Experiment," *VESIAC*, Special Bulletin, University of Michigan, June 10, 1965. (No. 4)

Hales, A.L., "The Core and Mantle," in *The Earth in Space*, H. Odishaw, editor, Basic Books, Inc., New York, pp. 59-67, 1967. (No. 33)

Hales, A.L., J.R. Cleary, H.A. Doyle, R.W. Green and J.L. Roberts, "P-Wave Station Anomalies and the Structure of the Upper Mantle," *J. Geophys. Res.*, in press. (No. 58)

Hales, A.L. and H.A. Doyle, "P and S Travel Time Anomalies and their Interpretation," *Geophys. J. Roy. Astron. Soc. 13*, pp. 403-415, 1967. (No. 47)

Hales, A.L., C.E. Helsley, J.J. Dowling, J.B. Nation, "Some Logistics of the East Coast Onshore Offshore Experiment," *Earthquake Notes XXXVII*, pp. 25-32, 1966, (No. 32)

Hales, A.L., C.E. Helsley, J.J. Dowling and J.B. Nation, "The East Coast Onshore Offshore Experiment, I. The First Arrival Phases," *Bull. Seism. Soc. Am.*, in press. (No. 50)

Hales, A.L., J.B. Nation and C.E. Helsley, "The Gulf Coast Onshore Offshore Experiment: Some Preliminary Results," *Trans. Am. Geophys. U. 48*, pp. 753-756, 1967. (No. 45)

Hales, A.L. and J.B. Nation, "Reflections at the M Discontinuity and the Origin of Microseisms," in *The Earth Beneath the Continents*, Geophysical Monograph 10, J. Steinhart and T. Smith, editors, American Geophysical Union, Washington, D.C., pp. 529-537, 1966. (No. 31)

Hales, A.L. and T. Asada, "Crustal Structure in Coastal Alaska," in *The Earth Beneath the Continents*, Geophysical Monograph 10, J. Steinhart and T. Smith, editors, American Geophysical Union, Washington, D.C., pp. 420-432, 1966. (No. 34)

Halpern, M., "Geochronologic Investigation in Eastern Ellsworth Land," *Antarctic Jour. of U.S.*, July-August, 1966. (No. 36)

Halpern, M., "Rubidium-Strontium Date from Mt. Byerly, West Antarctica," *Earth Planet. Sci. Letters 1*, pp. 455-457, 1966. (No. 40)

Halpern, M., "Rubidium-Strontium Isotopic Age Measurements of Plutonic Igneous Rocks in Eastern Ellsworth Land and Northern Antarctic Peninsula, Antarctica," *J. Geophys. Res. 72*, pp. 5133-5142, 1967. (No. 44)

Halpern, M., "Geologic Significance of Isotopic Age Measurements of Rocks from Tierra del Fuego, Chile," in *Proceedings of the UNESCO Symposium on Continental Drift, Montevideo, Uruguay, October 16-19, 1967*, in press. (No. 52)

Helsley, C.E., "Paleomagnetic Results from the Lower Permian Dunkard Series of West Virginia," *J. Geophys. Res. 70*, pp. 413-424, 1965. (No. 3)

Helsley, C.E., "Polar Wandering and Continental Drift," in *1966 McGraw-Hill Yearbook of Science and Technology*, McGraw-Hill Co., New York, 1966. (No. 19)

Helsley, C.E. and H.R. Spall, "A Compilation of Paleomagnetic Investigations of Rocks from North America," *Trans. Am. Geophys. U. 47*, pp. 291-302, 1966. (No. 28)

Helsley, C.E., "Design of Spinner Magnetometers," in *Methods in Palaeomagnetism*, D. Collinson, K. Creer and S. Runcorn, editors, Elsevier Publishing Co., Amsterdam, pp. 115-118, 1967. (No. 12)

Helsley, C.E., "Advantages of Field-Drilling Samples for Palaeomagnetic Studies," in *Methods in Palaeomagnetism*, D. Collinson, K. Creer and S. Runcorn, editors, Elsevier Publishing Co., Amsterdam, pp. 26-30, 1967. (No. 13)

Helsley, C.E., "Design of a Transistorized Portable Air Turbine Spinner Magnetometer," in *Methods in Palaeomagnetism*, D. Collinson, K. Creer and S. Runcorn, editors, Elsevier Publishing Co., Amsterdam, pp. 142-148, 1967. (No. 14)

Landisman, M. and S. Mueller, "Seismic Studies of the Earth's Crust in Continents, Part II: Analysis of Wave Propagation in Continents and Adjacent Shelf Areas," *Geophys. J. Roy. Astron. Soc. 10*, pp. 539-548, 1966. (No. 16)

Landisman, M., Y. Satô and T. Usami, "Propagation of Disturbances in a Gutenberg-Bullen A' Spherical Earth Model: Travel Times and Amplitudes of S Waves," in *The Earth Beneath the Continents*, Geophysical Monograph 10, J. Steinhart and T. Smith, editors, American Geophysical Union, Washington, D.C., pp. 482-494, 1966. (No. 39)

MacGregor, I.D., "Mineralogy of Model Mantle Compositions," in *Ultramafic and Related Rocks*, P. Wyllie, editor, John Wiley & Sons, Inc., New York, pp. 382-392, 1967. (No. 21)

MacGregor, I.D., "Mafic and Ultramafic Inclusions as Indicators of the Depth of Origin of Basaltic Magmas," *J. Geophys. Res.*, in press. (No. 54)

Manton, W.I., "The Origin of Associated Basic and Acid Rocks in the Lebombo-Nuanetsi Igneous Province, Southern Africa, as Implied by Strontium Isotopes," *J. Petrology*, in press. (No. 46)

Mueller, S. and M. Landisman, "Seismic Studies of the Earth's Crust in Continents, Part I: Evidence for a Low-Velocity Zone in the Upper Part of the Lithosphere," *Geophys. J. Roy. Astron. Soc. 10*, pp. 525-538, 1966. (No. 15)

Oetking, P., "Photometric Studies of Diffusely Reflecting Surfaces with Applications to the Brightness of the Moon," *J. Geophys. Res. 71*, pp. 2505-2513, 1966, (No. 18)

Reitzel, J., "Use of Boundary Sources in Problems of Heat Conduction," *J. Appl. Phys. 38*, pp. 3808-3810, 1967. (No. 35)

Riley, G.H. and D.L. Bacon, "A Flexible Digital Data System for Sector Field Instruments," in *Proceedings of the Fourteenth Annual Conference on Mass Spectrometry and Allied Topics, May 22-27, 1966, Dallas, Texas*, American Society for Testing and Materials, pp. 305-311, 1966, (No. 37)

Riley, G.H., "Rhenium Concentration in Australian Molybdenites by Stable Isotope Dilution," *Geochim. Cosmochim. Acta 31*, pp. 1489-1497, 1967. (No. 48)

Riley, G.H., "Isotopic Analysis of Rhenium from a Thermal Ionization Source," *J. Sci. Instrum. 44*, pp. 769-774, 1967. (No. 49)

Spall, H., "The Paleomagnetism of Basement Granites from Southern Oklahoma, and its Geologic Implication: Progress Report," submitted to the *Bulletin of the Oklahoma Geological Society*. (No. 60)

Spall, H., "Anomalous Paleomagnetic Poles from Late Mesozoic Dolerites from Spitsbergen," submitted to *Earth and Planetary Science Letters*. (No. 61)

Satô, Y., T. Usami and M. Landisman, "Theoretical Seismograms of Spheroidal Type on the Surface of a Gravitating Elastic Sphere: II. Case of Gutenberg-Bullen A' Earth Model," *Bull. Earthq. Res. Inst., Univ. Tokyo*, in press. (No. 57)

Satô, Y., T. Usami and M. Landisman, "Theoretical Seismograms of Torsional Disturbances Excited at a Focus within a Heterogeneous Spherical Earth," *Bull. Seism. Soc. Am.*, in press. (No. 63)

Usami, T., Y. Satô and M. Landisman, "Preliminary Study of the Propagation of Spheroidal Disturbances on the Surface of a Heterogeneous Spherical Earth," *Geophys. J. Roy. Astron. Soc. 11*, pp. 243-251, 1966. (No. 22)

Usami, T., Y. Satô and M. Landisman, "Theoretical Seismograms of Spheroidal Type on the Surface of a Heterogeneous Spherical Earth," *Bull. Earthq. Res. Inst., Univ. Tokyo, 43*, pp. 641-660, 1965. (No. 25)