Annual Report of the Geosciences Division

1967-1968

Southwest Center for Advanced Studies

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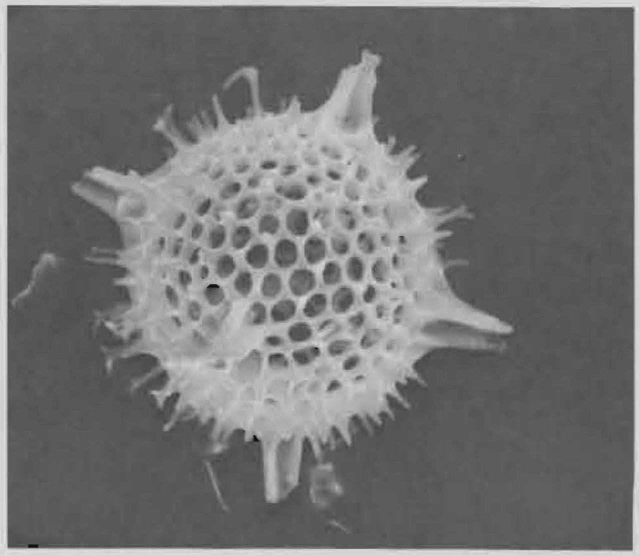
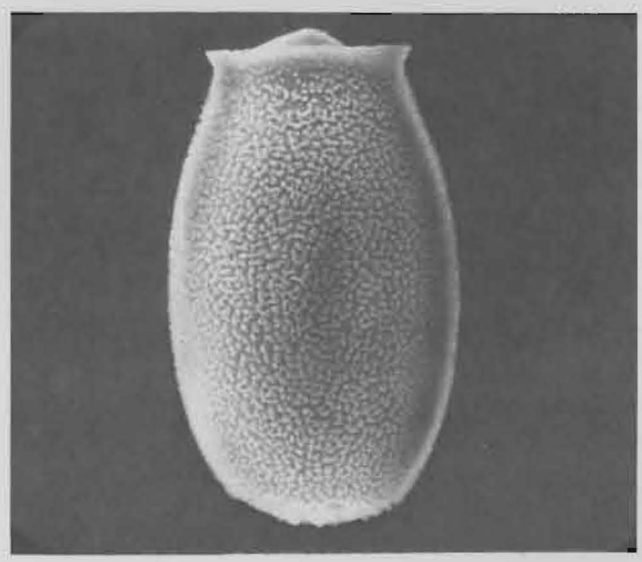


Upper Cretaceous Radiolarian from California Coast Ranges



Desmochitina sp. Solon Member, Cedar Valley Formation, middle Devonian of Iowa

INTRODUCTION

As remarked in our last annual report, there has been much excitement in the earth sciences over the confirmation of the ocean spreading hypothesis of Hess and Dietz from the analysis, initially by Vine and Matthews, and later by others, of the magnetic anomaly patterns near the mid-ocean ridges. It has been demonstrated that the continents have been drifting apart over the past several million years and are probably still separating. The process is one of creation of new crust for the Earth at the ridges, and loss of crust elsewhere, presumably at the continental margins. Thus the hypothesis of continental drift, long an outcast among the hypotheses which were offered to explain the origin of the major features of the Earth's surface, has come into its own.

The demonstration of the creation of new crust at the ridges and the estimation of the rate of spreading were made possible because of careful measurements of the direction of magnetization of accurately dated lava flows of ages up to several million years by Cox, Doell and Dalrymple of the United States Geological Survey. It has been established that during the past few million years the Earth's field has reversed roughly once every million years, and it has been found possible to correlate these dated changes in the direction of the field (the north pole becomes the south pole) with the anomaly pattern in the oceans.

Similar patterns of rapid reversals of the field occur at other periods of Earth history. Dr. Charles Helsley has shown that a similar pattern of reversals can be traced in the rocks of the Moenkopi Formation of Colorado which have an age of 220 million years. There are, however, other periods of time, such as the Permian about 225 to 270 million years ago, in which the field remained throughout of one sign. Dr. Helsley has recently shown that there is a period in which the field was of one sign in the Cretaceous, i.e. a 20 million year period extending from Lower Cretaceous into Middle Upper Cretaceous.

The recent work on ocean spreading has created a consensus in favor of drift, but there are significant questions which are still unanswered. One of these is the configuration of the continents before the breakup. Dr. Martin Halpern has collected samples from southern South America and West Antarctica. The pattern revealed by Dr. Halpern's measurements is consistent with DuToit's reconstruction of the southern continents for late Paleozoic time, approximately 230 to 350 million years ago.

Dr. John Graham, who has recently retired from the staff of the Division as a result of continuing ill-health, showed in 1949 that certain sediments had acquired the direction of magnetization at the time at which they were laid down and that it was possible to determine which sediments had done so.

Dr. Graham recognized that these discoveries made it possible to use the fossil magnetism of rocks for the study of such major problems of earth science as continental drift, and indeed the study of the ancient positions of the continents during the past 19 years stemmed from Dr. Graham's initial study. Paleomagnetic studies offer the most fruitful line of attack on the problem of the determination of the relative positions of the continents, and these studies are the focus of the Division's program in paleomagnetism.

There is still another major problem of drift for which we do not, in my view, have a satisfactory solution. This is the question of the mechanism and, more generally, of the processes which have shaped the Earth. Here I think it important that we should learn more about the properties and composition of the upper mantle and of the processes by which the crust has been derived from the mantle. Mr. William Manton's studies of the isotopic composition of strontium in crustal rocks, Drs. Ian MacGregor and James Carter's geochemical studies of the inclusions in diamond pipes, Dr. Dean Presnall's analysis of partial fusion, and Dr. Glen Riley's studies of the ages of isotopes in pegmatites are all related to the problem of the origin of the crust. The study of the diamond pipe inclusions is, of course, directly related to the problem of mantle composition.

In the mid 1930's Bernal and Jeffreys suggested that the break in the slope of the seismic travel times at 20° arc distance found by Jeffreys and Bullen arose as a result of a phase transition of the silicates in the mantle to a denser crystal structure. For some time it was thought that the transition was spread over a greater depth range than had been proposed by Bernal and Jeffreys. Recent work at a number of laboratories, among which was a Division study by Mr. Rodleigh Green and myself, has shown that there are in fact two relatively sharp transitions at depths of about 350 and 650 km. More important, perhaps from the point of view of a mechanism for drift, has been the demonstration that the low velocity zone in the upper mantle is a zone of high anelasticity, i.e. low viscosity. Since the principal problem in drift is a mechanical one, it is obviously important that more should be known of the properties of the upper mantle and of the variation in its properties between the continents and the ocean basins, between the shield areas and the tectonic areas, and elsewhere. Studies by myself and my colleagues, especially Dr. John Cleary, Mr. Hugh Doyle and Mr. Green, were related to this problem. These studies were based on the travel time of body waves. Surface wave studies are potentially more powerful tools for the study of the upper mantle properties. Here Drs. Mark Landisman and Adam Dziewonski, and Mr. Selwyn Bloch and I have been developing new techniques designed to obtain the maximum amount of information from the surface wave train. These techniques have been applied so far to Africa and Australia.

During the year Dr. John Reitzel left the Center to become Professor of Geophysics at Leeds University, England. Dr. Hartmut Porath is continuing the study of the magnetic variation in the western United States and of its relation to other geophysical phenomena such as heat flow.

The Division's activities were extended during the past year into micropaleontology, palynology and organic geochemistry. The studies in micropaleontology and palynology have been aided by a magnificent new tool, the scanning electron microscope. This instrument has both greater depth of focus and greater resolution than the optical microscope. In time pictures such as those shown in Plates 8B-1 and 8C-1 from Dr. Emile Pessagno's contribution will replace the hand drawn pictures customarily used for the identification of microfossils. The organic geochemistry studies of Dr. Richard Mitterer are concerned with the breakdown of proteins in organic material with time.

The studies of the lunar reflection phenomenon have been discontinued with Dr. Philip Oetking's departure to Corpus Christi to lead the Ocean Science and Engineering Laboratory of the Southwest Research Institute.

The Geosciences Division and the Department of Geological Sciences of Southern Methodist University cooperate in a joint Ph.D. program in geology and geophysics. Three students from this program are currently doing thesis work under Dr. Landisman and one under Dr. Helsley.

Anton L. Hales
Head, Geosciences Division

1. SEISMOLOGY

A. Surface Waves

Mark Landisman
Adam Dziewonski
Brian Mitchell
Robert Massé
Selwyn Bloch

During this past year the seismology group has been able to make some progress in developing new methods for the study of multi-mode seismic signals and in the application of these analytical techniques to the study of the source and the medium of propagation. These efforts complement our continuing study of the physical properties of the Earth's interior by means of the generation, propagation, dispersion, and attenuation of seismic waves.

As in previous years, our efforts have been encouraged by visits from foreign colleagues. Prof. Stephan Mueller and Dr. Claus Prodehl, Geophysical Institute, University of Karlsruhe, Prof. Yasuo Satô, Earthquake Research Institute, The University of Tokyo, and Dr. Flavian Abramovici, University of Tel Aviv, were able to come and work with us for varying periods of time. A reciprocal visit by Prof. Landisman to the University of Karlsruhe permitted a continued exchange of ideas and further progress in the study of the velocity distributions and velocity reversals in the crust and upper mantle for various regions. The Upper Mantle Committee's Fourth International Symposium on Geophysical Theory and Computers in Trieste, Italy, and the 14th General Assembly of the International Union of Geodesy and Geophysics in Zurich, Switzerland, furnished additional opportunities for the exchange of research results, the evaluation of new ideas, and the renewal of international friendships. The biennial graduate seismology course has introduced a number of new graduate students to the field.

Two digital techniques for the analysis of transient multi-mode recordings were intensively developed during this past year. The first is called "moving window" analysis, and is based upon the Fourier analysis of a suitably windowed temporal portion of the recording. The second process, termed the multiple filter technique, uses the fast Fourier algorithm to convert the observed time series into sine and cosine coefficients for a set of harmonic frequencies. Filtration in the frequency domain is followed by inverse transformation into "in-phase" and "quadrature" time series for a range of periods.

In either process, the result is a display of amplitudes in db and/or of phases in circles, evaluated as functions of linear velocity and logarithmic period. An example is shown in Figure 1A-1, the analysis of signals from an event which occurred in southern Malawi, at 02:36:56.8 GMT on 6 May 1966. The recording was made by the long period vertical instrument of the World Wide Standard Seismograph Network (WWSSN) observatory at Pretoria, South Africa, 1288 km from the epicenter. The larger amplitudes are found along ridges, which are interpreted as the observed group velocity curves for each of the modes of elastic wave propagation present in the recording. These and similar multi-mode dispersion data are currently being used in several studies of the crust and upper mantle.

The signals corresponding to the individual propagating modes may be isolated from the observed composite by means of time-variable filters. The characteristics of these filters are based upon the observed dispersion. The most efficient filters appear to be those which operate in the frequency domain, and use the fast Fourier algorithm for the transformation process. The improvement in signal-to-noise ratio associated with time-variable filtration is illustrated in Figure 1A-2.

It appears that more reliable inter-station phase velocities can be calculated from the phase function of the windowed cross-correlogram corresponding to a pair of filtered seismograms. Four events with epicentral locations nearly co-linear to the station pair Charters Towers and Adelaide, Australia, were thus analyzed. Figure 1A-3 shows the Rayleigh mode phase velocity results for the approximately 1800 km path between these stations. The standard deviation is estimated to be 0.016 km/sec for periods less than 80 sec and perhaps four times as great for longer periods where the signal-to-noise ratio is poorer. At short periods, the slowest curve should be the most reliable one. These events, whose USCGS magnitudes ranged from 5.7 to 6.1, appear to have furnished useful phase velocity information over a span of periods ranging from less than 20 to more than 300 sec. Comparable results, shown by the open circles, have previously been measured only for world-circling paths.

Brief highlights from some of the other programs follow. Mr. Massé, a graduate student, has written general purpose

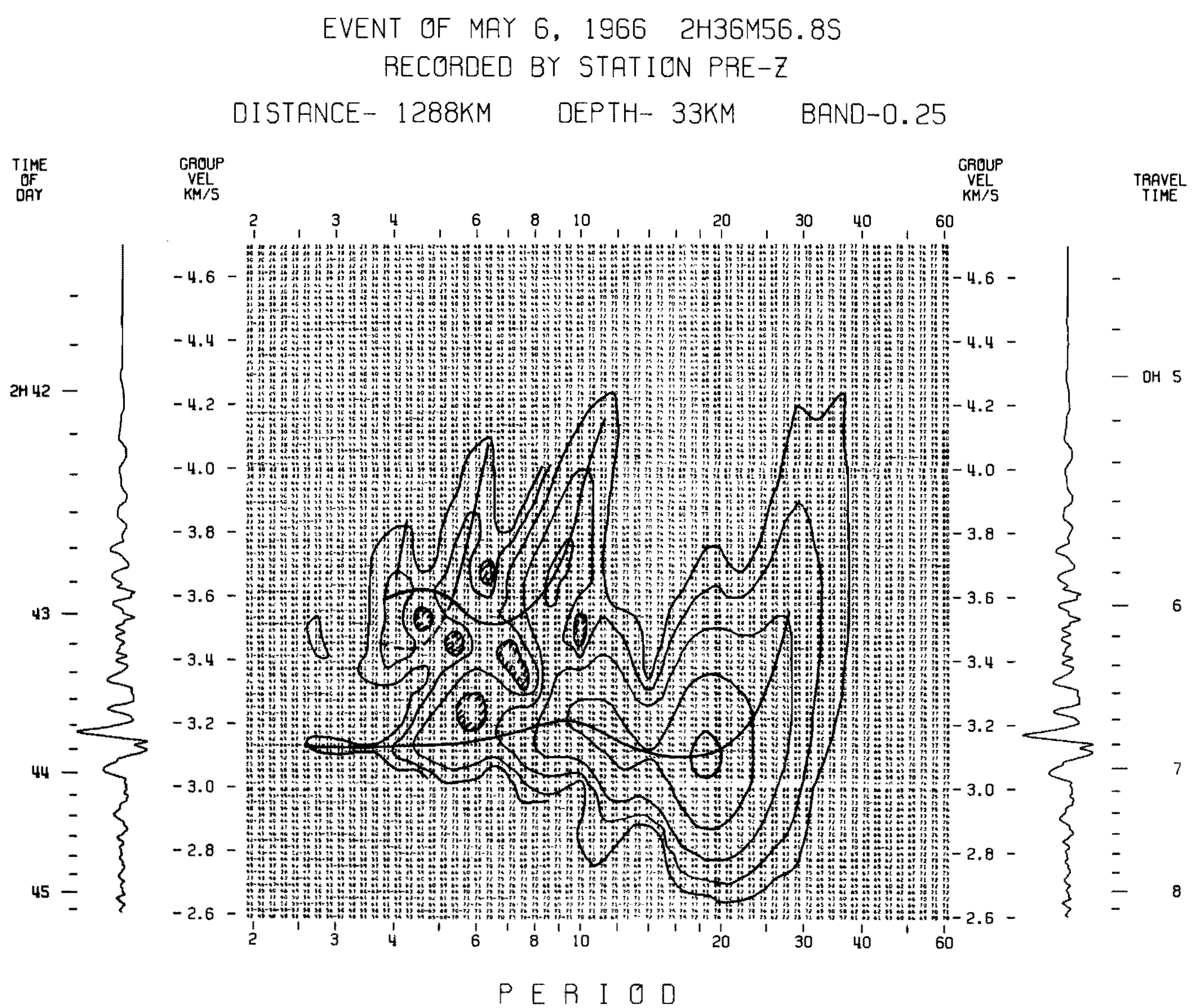


Figure 1A-1. Multiple filter analysis of a multi-mode seismic recording at Pretoria, South Africa, from an event in southern Malawi. Contours of amplitude (5db interval) are shown as functions of group velocity and period. The group velocities of the Rayleigh mode and the first three shear modes are indicated by lines along ridge crests of the contour diagram.

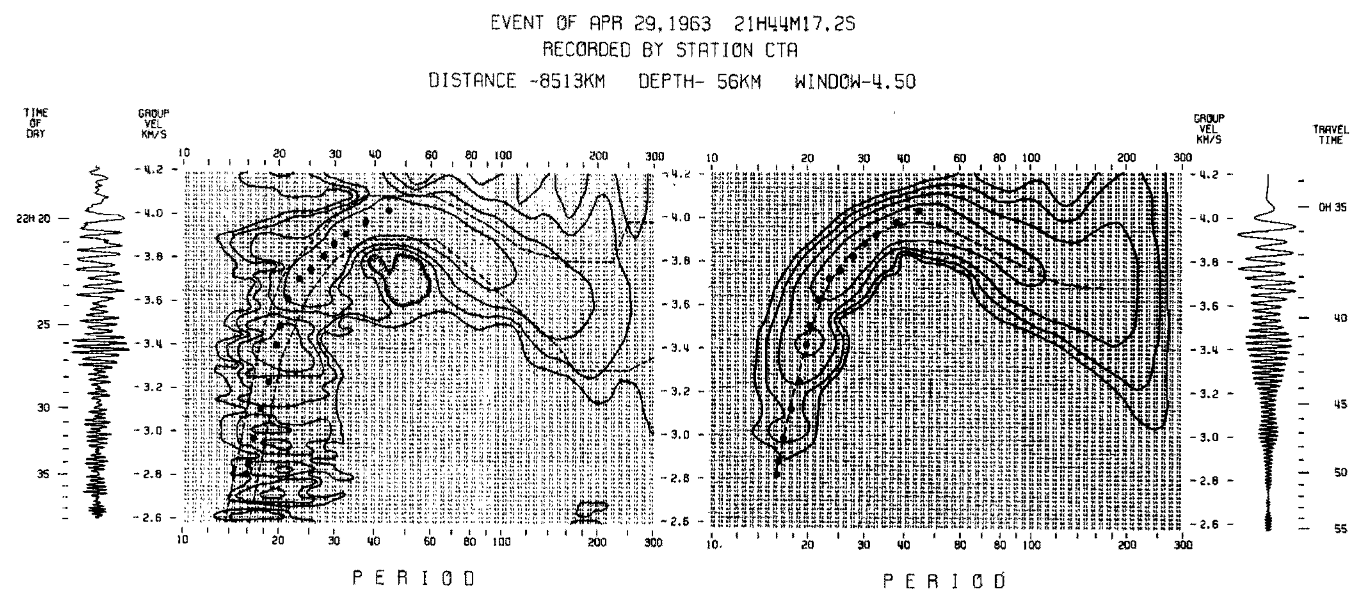


Figure 1A-2. Time variable filtration of oceanic Rayleigh mode recorded at Charters Towers, Australia. The observed seismogram is shown at left. The filter is indicated by the broken lines and the measured dispersion by the dotted curve. The filtered seismogram is shown at the right.

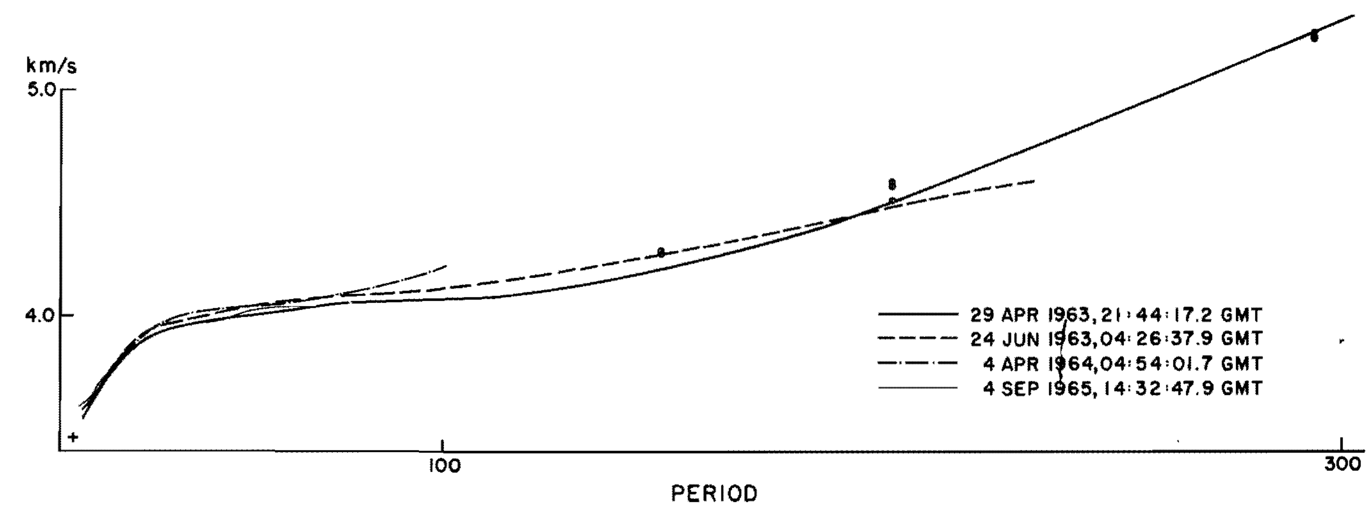


Figure 1A-3. Phase velocities measured for the 1800 km path between Charters Towers and Adelaide, Australia. Seismograms filtered as in Figure 1A-2 were cross-correlated. The phase function of these windowed correlograms was used to calculate the results shown. Comparable data from world-circling paths are shown as circles.

routines for the locked-mode propagation of Love and Rayleigh waves. These routines cover a very broad period range and are characterized by efficient curve-following techniques. Analytic expressions for various derivatives and other parameters related to the dispersion are also being incorporated into the programs. These routines have found great utility in a number of recent dispersion studies.

Dr. Dziewonski is completing dispersion studies for Australia.

Prof. Landisman and Dr. Prodehl are engaged in a study of refraction profiles on the western Atlantic coastal plain.

Several recent studies of theoretical seismograms, in cooperation with Profs. Sato and Usami, have treated the buried torsional source in a realistic medium and a very limited source in a simplified medium. The focusing of short period energy by the Gutenberg low-velocity zone was demonstrated in the former study. The commonly observed tilt of the Rayleigh wave particle motion ellipse was noted in the latter study. It appears to be a near-field phenomenon observable in the simplest of cases; its existence does not imply that the medium has any special properties.

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B. Body Wave Travel Times

Anton L. Hales
Jeanne L. Roberts

A paper summarizing the P travel time studies was presented at the 14th General Assembly of the International Union of Geodesy and Geophysics, Zurich, and has been published in the Journal of Geophysical Research (Hales, et al., 1968). In another paper Drs. Hales and Cleary with Mrs. Roberts (1968) have shown that there is great difference between the character of $dT/d\Delta$ at distances between 0° and 30° and its character beyond 30°. Beyond 30° $dT/d\Delta$ decreases almost linearly with distance as is shown in Figure 1B-1. Between 0° and 30° $dT/d\Delta$ is discontinuous at 20° and 23° to 24° and changes rather slowly between the discontinuities.

Recent studies of $dT/d\Delta$ by Chinnery and Toksöz (1967) and others have shown that there are differences between the values of $dT/d\Delta$ found at LASA for Pacific events and South American events, suggesting that the lower mantle may not be laterally homogeneous.

Considerable attention is now being given to the problem of the inversion of all the seismic data relevant to the determination of the properties of the interior. The weakest link in the inversion chain may well be the S travel times at distances of 80° and 100°. These S travel times are difficult to determine because SKS precedes S beyond 83°, and it is difficult to determine precisely where the second onset begins.

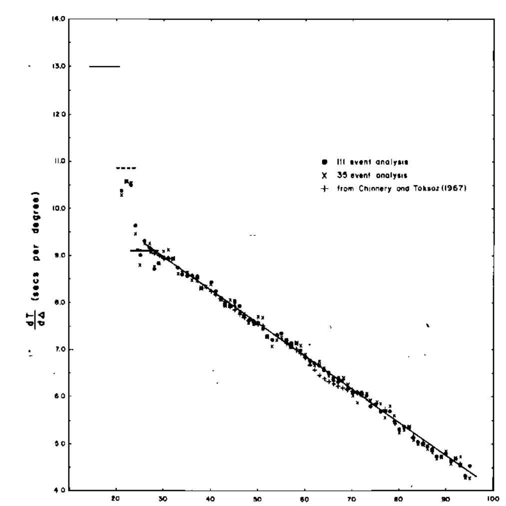

Figure 1B-1. Values of $dT/d\Delta$ calculated over two degree intervals compared with $dT/d\Delta$ as found by Chinnery and Toksöz (1967) from the LASA data. The lines between 15° and 30° are values from Green and Hales (1968).

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C. Surface Wave Studies in Southern Africa

Selwyn Bloch
Anton L. Hales

Surface wave dispersion for a variety of modes has been determined for southern Africa using a number of new techniques developed by Mr. Bloch and Drs. Hales, Landisman and Dziewonski. Rayleigh wave phase velocities have been determined for an array of stations centered around Johannesburg, South Africa, with a radius of approximately 200 km, and for the World Wide Standard Seismograph Network stations at Pretoria, Bulawayo and Windhoek. The WWSSN stations have also been used for determining multi-mode group velocities of both Rayleigh and Love waves from a number of earthquakes located near Kariba Dam, Rhodesia, and one in southern Malawi.

A comparison of the phase velocity dispersion obtained for this area with those for other areas of the world is shown in Figure 1C-1. The shield areas exhibit higher values for both group and phase velocity, indicating probable similarities in crustal structure. The phase velocity curves for Pretoria-Windhoek and Bulawayo-Windhoek have lower velocities than the shield area curves, and are remarkably similar to the phase velocity curves for the central United States and Australia. The higher phase velocities for the array are in good agreement with refraction studies which show an S_n velocity of 4.80 km/sec.

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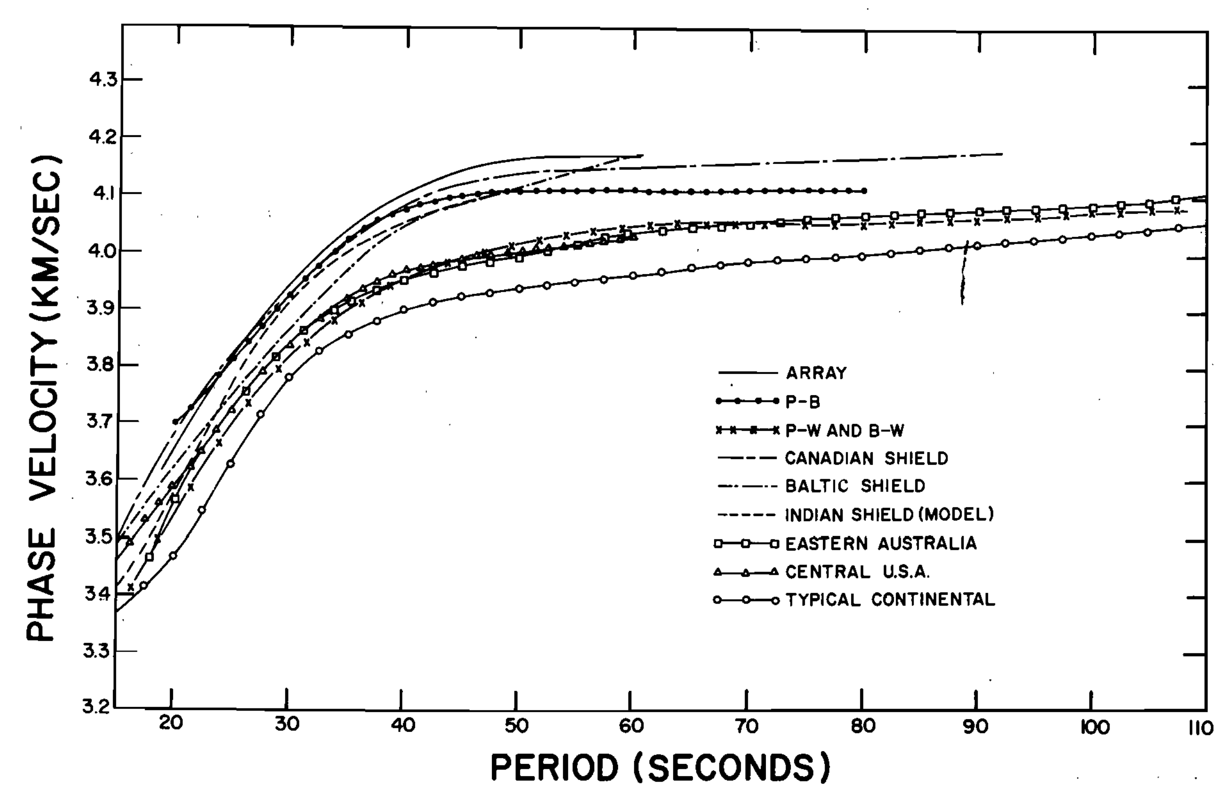

Figure 1C-1. Rayleigh wave phase velocity dispersion for different areas of the world.

2. MARINE GEOPHYSICS

A. East Coast

Anton L. Hales
Joe B. Nation
Charles E. Helsley

A study of the first arrival phases for the East Coast Onshore Offshore Experiment by Mr. J.B. Nation, Dr. A.L. Hales and Dr. C.E. Helsley has led to the conclusions:

(a) that the P velocity for the mantle in North Carolina varies from 7.8 km/sec beneath the Coastal Plain to 8.4 beneath the Piedmont.

(b) that the depth to mantle is 30 km on the Coastal Plain, 36 km in the Piedmont and 41 km in the Cumberland Plateau.

The model derived from the first arrival phases is compatible with the gravity anomaly data along the profile (Woollard and Joesting, 1964) and the two-layer crust beneath the Cumberland Plateau of Tatel and Tuve (1955).

Data from the northern profile across Virginia indicate that the structure is similar except that the evidence for high mantle velocity beneath the Piedmont is inconclusive.

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B. Gulf Coast

Anton L. Hales
Joe B. Nation
Charles E. Helsley

The general conclusions drawn from the Gulf Coast Onshore Offshore Experiment were:

(a) that the low velocity sediments exceed 10 km in thickness in the vicinity of the coast and become thicker offshore.

(b) that the basin appears to be open to the south at least as far as the edge of the shelf.

C. Indian Ocean Program

Anton L. Hales

During the period January through March 1968, a seismic refraction program was carried out in the Indian Ocean off the coast of South Africa in cooperation with the Bernard Price Institute of Geophysical Research, University of the Witwatersrand. The vessel used for the survey was the

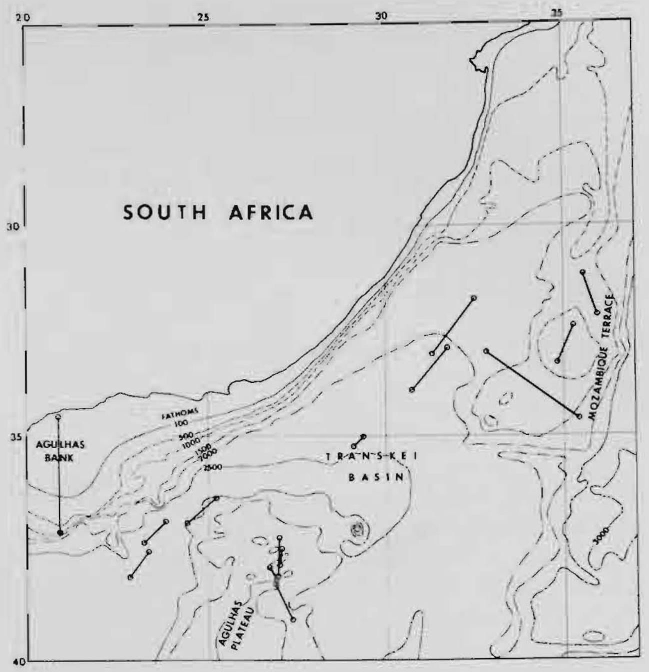

Figure 2C-1. Stations occupied during the Indian Ocean Program.

whaler, Frank Harvey, commanded by Captain Jensen under charter to the Bernard Price Institute.

An Omega navigation system was used throughout the survey. Measurements in port and at fixed locations at sea suggest that the accuracy for long term measurement is of the order of 3 to 4 km with short term accuracies of about half that value.

The positions of the stations are shown in Figure 2C-1. The stations in shallow water on the Agulhas Bank were used for sediment and crustal thickness studies. The intermediate layer phase was very clear as is shown by the record section in Figure 2C-2. Preliminary estimates indicate that the crustal thickness is less than 30 km and that the crust thins toward the edge of the shelf.

The stations on and around the Agulhas Plateau were occupied in an effort to determine whether the Plateau is of volcanic origin or a continental remnant. Stations were located on the Mozambique Terrace for a similar study.

D. Cayman Trough Studies

Charles E. Helsley

The Cayman Trough has long attracted the attention of geologists and geophysicists for it is one of the few places where there are significant structural features on the continent which appear to be the continuation of the submarine fracture zone.

During March of this year a series of heat flow and seismic reflection observations were made in this region with the cooperation of personnel from the U.S. Naval Oceano-

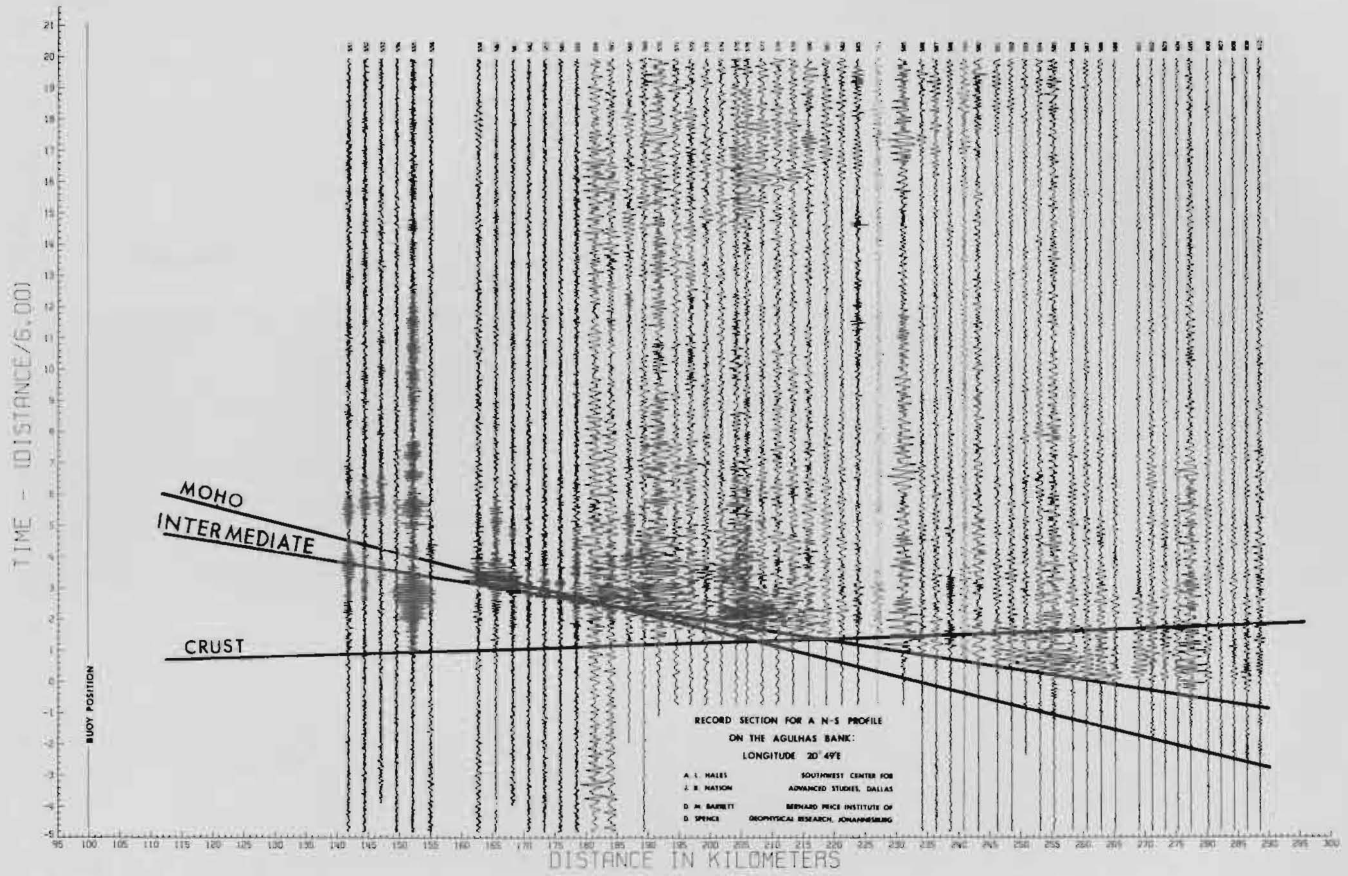

Figure 2C-2. Record section for a crustal profile on the Agulhas Bank.

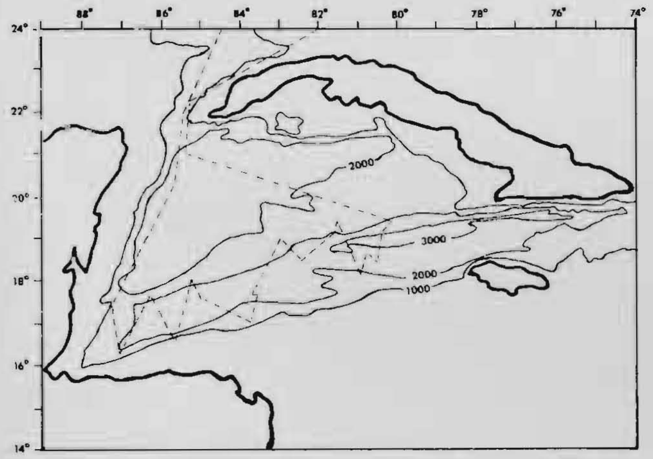

Figure 2D-1. Ship track of USNS Gillis.

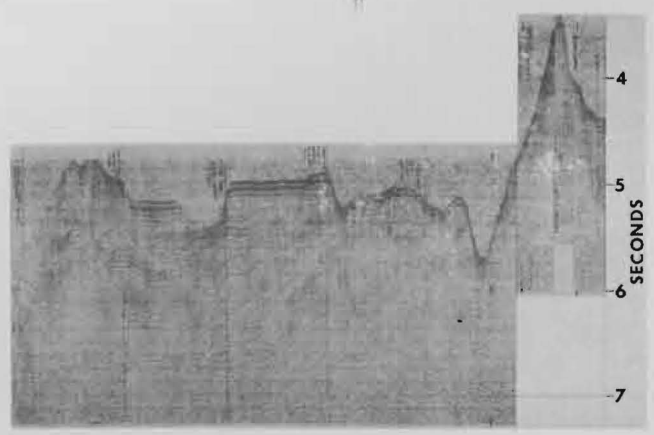

Figure 2D-2. Air gun profile at western end of Cayman Trough.

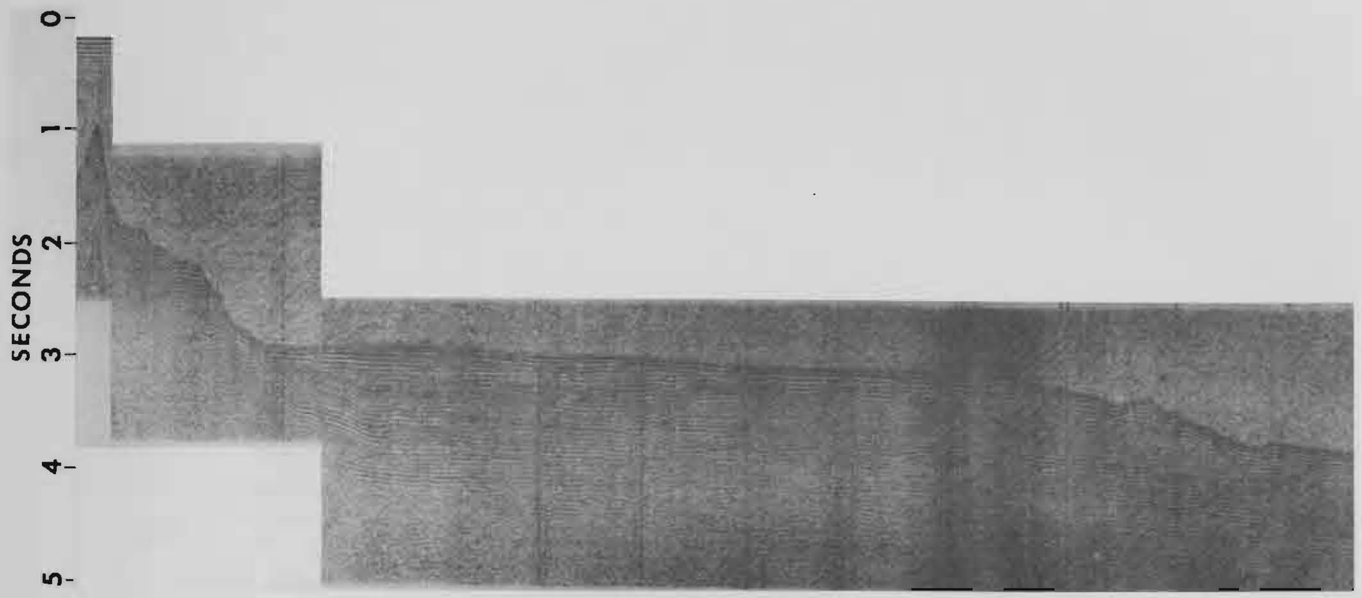

Figure 2D-3. Air gun profile northwest of Cuba showing prominent erosional unconformity.

graphic Office aboard the USNS Gillis. The heat flow measurements were carried out by A.L. Ericson of the Massachusetts Institute of Technology. These observations were primarily in the western part of the Cayman Trough (Figure 2D-1) and were designed to elucidate the relations between the boundaries of the Cayman Trough and the structures mapped on land. Figure 2D-2 shows the western most crossing of the trough where numerous faults, unconformities, and erosional features can be seen in the sub-bottom sediments.

To the east these faults continue to be present. However, the sediments are much thinner and the trough seems to break up into a series of troughs that have little or no interconnection.

A remarkable erosional unconformity was found north of Cuba on our return to port. Figure 2D-3 shows the air gun profile in this region where more than 500 meters of sediment have been removed to expose an older sedimentary sequence more than 1000 meters thick.

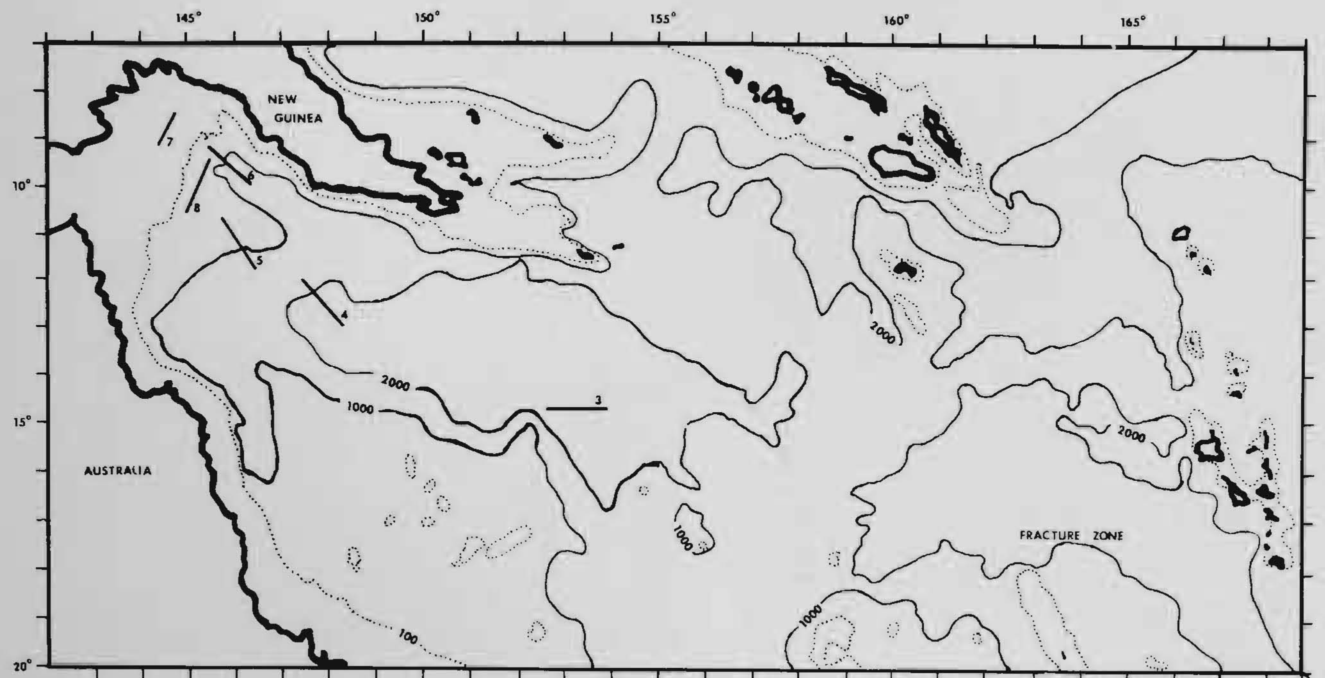

Figure 2E-1. Location of seismic profiles observed in the Coral Sea region.

E. Coral Sea Observations

Charles E. Helsley

During July and August 1967, a program of seismic refraction and reflection observations was carried out in cooperation with the Scripps Institution of Oceanography in the Coral Sea. The profiles observed are shown in Figure 2E-1. Wide angle reflection profiling was carried out at most of the stations and a portion of a wide angle reflection section compiled from buoy records of the air gun is shown in Figure 2E-2. The sharp increase in amplitude associated with critical reflection from the interfaces at a distance near 8 km should provide a sensitive means of determining the velocity in the near surface sediments. These amplitude variations as well as the refracted arrival that begins near 11 km allow better determination of the velocity in the sediment package than could have been done with explosives alone.

The preliminary analysis of the records has shown one interesting feature, namely that in profile 4 the greatest velocity observed was 6.8 km/sec, although the profile extended to a distance of 80 km. This suggests either a thick crust overlying a normal mantle or a very thin crust overlying an abnormally low velocity mantle. Preliminary results from profile 7 on the shelf in the Gulf of Papua indicate sediments in excess of 8,000 meters overlying a basement with a velocity of 5.6 km/sec, which is very reminiscent of some of the observations made along the Gulf Coast of Texas.

During the cruise several interesting structures were outlined. An example is the fracture zone that was found along 17.5°S. This fracture zone terminates against the New Hebrides Trench on the east, and apparently coincides with the southern margin of the Coral Sea Basin in the west. This feature was traced in detail for 800 km and probably continues at least 800 km further west. With the combined use of air gun reflections and bathymetry, the structural analysis of this feature was much easier for the subbottom reflections often allowed distinction between the several parallel basins that make up the fracture zone. An example of the quality of the air gun records, made at a speed of 11.5 knots during this cruise, is shown in Figure 2E-3.

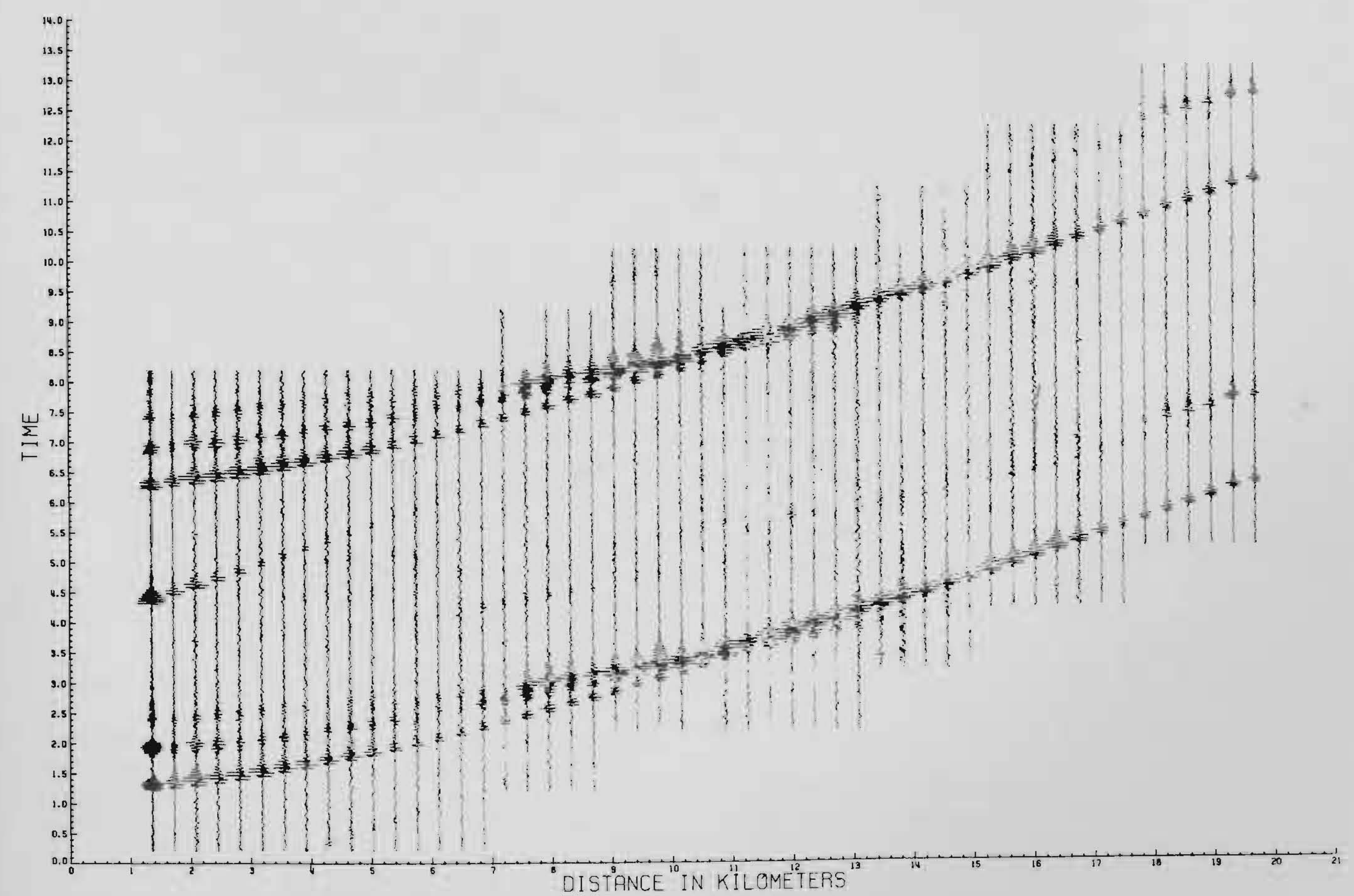

Figure 2E-2. Wide angle reflection profile observed in the Coral Sea.

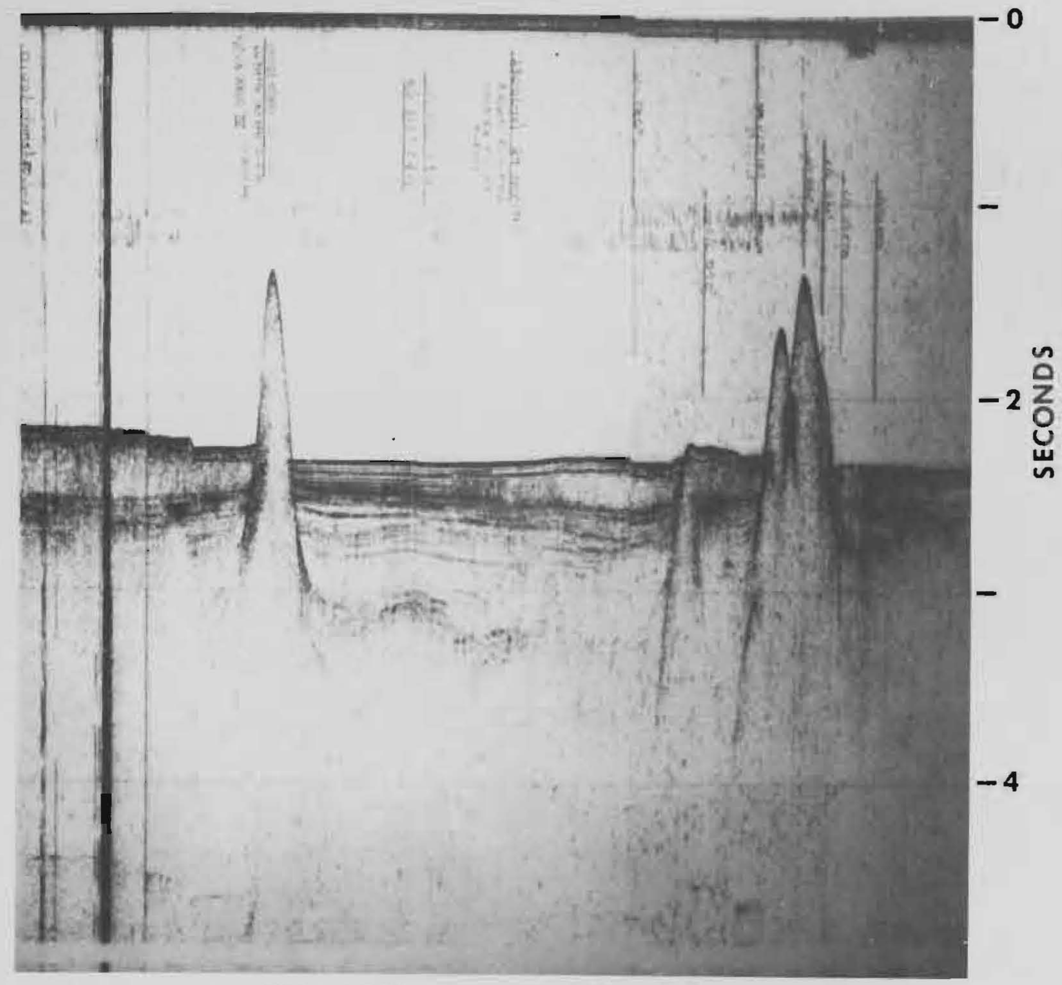

Figure 2E-3. Typical air gun record from the Coral Sea.

3. EXPERIMENTAL PETROLOGY

A. The System MgO-SiO_2-TiO_2 and its Bearing on the Distribution of TiO_2 in Basalts

Ian D. MacGregor

Experimental determination of the liquidus and solidus relationships in the Mg_2SiO_4-$MgSiO_3$-TiO_2-$MgTi_2O_5$ portion of the system MgO-SiO_2-TiO_2, with a solid media, piston cylinder device, indicates that the following univariant reactions occur between 1 atmosphere and 40 kilobars:

$$En + M = Fo + 2Rt \quad (1)$$
$$L_2 = Fo + En + M \quad (2)$$
$$L_3 + Fo = M + En \quad (3)$$
$$L_4 = M + En + Rt \quad (4)$$
$$L_5 + M = Fo + Rt \quad (5)$$
$$L_6 = Fo + En + Rt \quad (6)$$
$$L_7 = M + Fo + Rt \quad (7)$$

(where $En = MgSiO_3$, $M = MgTi_2O_5$, $Fo = Mg_2SiO_4$, $Rt = TiO_2$, L_n = liquid). The compositions of the liquids 2 through 7 become progressively more TiO_2-rich and MgO- and SiO_2-poor with increasing pressure (Figure 3A-1). Reactions (1), (3), (4), (5) and (6) intersect at an invariant point at 1489°C and 15.2 kilobars (Figure 3A-2).

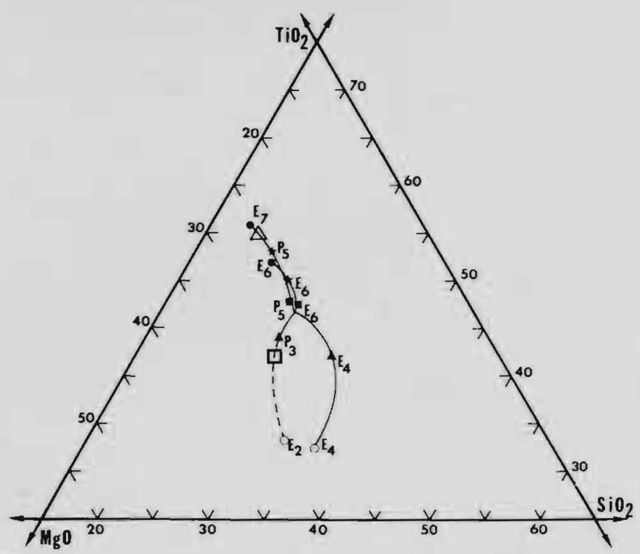

Figure 3A-1. Summary of the change of composition of ternary peritectics (P_3 and P_5) and ternary eutectics (E_2, E_4, E_6 and E_7) with pressure in the system MgO-SiO_2-TiO_2. (Open circles – 1 atmosphere, solid triangle – 10 kilobars, solid square – 15.5 kilobars, solid star – 20 kilobars, solid circle – 40 kilobars, open square – interpolated point at 4.6 kilobars, open triangle – interpolated point at 35.6 kilobars.)

The results of discriminant function analysis (Chayes and Velde, 1965) suggest that TiO_2 is by far the best oxide for distinguishing between Cenozoic basalts from oceanic island and circumoceanic localities. However, model ultramafic compositions in the system MgO-SiO_2-TiO_2 give rise to successively TiO_2-rich partial fusion products with increasing pressure, suggesting a qualitative analogy that basaltic magmas are progressively enriched in TiO_2 the greater their depth of origin. Comparison of the experimental compositions with those of Cenozoic basalts suggests that the successful geographic division into oceanic island and circumoceanic environments is related more to the tectonic setting than regional geochemical variations.

Reference

Chayes, F. and D. Velde, "On Distinguishing Basaltic Lavas of Circumoceanic and Oceanic Island Type by Means of Discriminant Functions," Am. Jour. Sci., 263, pp. 206-222, 1965.

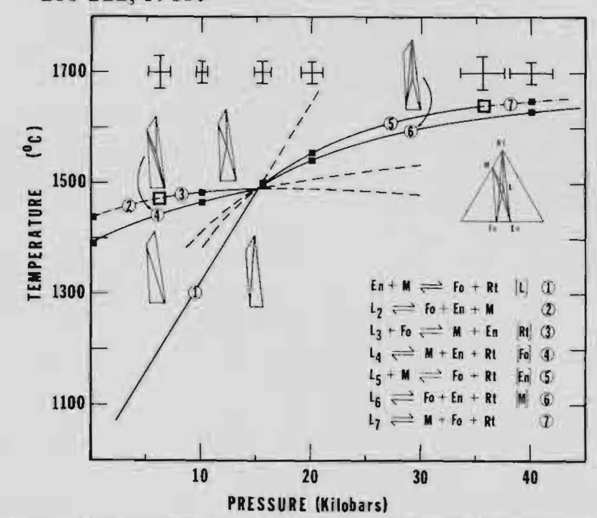

Figure 3A-2. Temperature-pressure section showing univariant equilibria for reactions (1) through (7). (Solid curves give the stable portions of univariant reactions that intersect at the invariant point; dashed curves give metastable extensions; dash-dot curves are for reactions (2) and (7) which do not intersect at invariant point; solid squares give data points; open squares give interpolated data points; error bars at 1700°C give estimated errors for each pressure where data available.)

B. The Quantitative Treatment of the Fusion of Rocks

Dean C. Presnall

Current hypotheses point to the origin of the now differentiated earth from an initially homogeneous cold earth by fusion and separation into its three major units: crust, mantle, and core (Birch, 1965; Ringwood, 1960). Subsequent fusion of the crust and mantle in more recent geologic time is thought to play a vital role in controlling the compositions of most of the igneous rocks now seen on the Earth's surface. Theories have been proposed suggesting that the compositions of granites (Winkler, 1967), andesites (Green and Ringwood, 1968), and various types of basalt (Kuno, 1959; Kushiro, 1968) are controlled primarily by fusion processes. Even if one subscribes to the concept of Bowen that fractional crystallization of basalt is responsible for the production of other igneous rock types, the composition of the basaltic parent must ultimately be controlled in large measure by fusion processes. Clearly, it is important to be able to analyze the fusion of rocks in a quantitative way.

In a series of excellent papers Bowen (1914, 1915, 1933, 1935, 1941) explained and demonstrated the geometrical methods for deriving paths of crystallization on a phase diagram. He (Bowen, 1928, pp. 27, 31, 33, 43-44, 48) discussed fusion briefly and showed that it does not always yield the same sequence of liquids as are produced by crystallization; but despite this demonstration, one frequently encounters the statement that fusion is simply the reverse of crystallization. In view of the importance of melting phenomena to petrogenetic theory and in view of the confusion that sometimes surrounds this subject, it seems useful to present the geometrical methods by which the quantitative aspects of fusion may be understood on a phase diagram. These methods are exactly analogous to those used by Schreinemakers (1905) and Bowen in their discussions of crystallization.

Bowen (1941) distinguished two types of crystallization, *equilibrium crystallization* and *fractional crystallization.* In the former, crystals formed on removal of heat continually react and re-equilibrate with the liquid. In the latter, the crystals are immediately isolated from the system as soon as they are formed and prevented from further reaction with the liquid. A precisely analogous distinction will be made here with respect to fusion. *Equilibrium fusion* will refer to the situation in which the liquid produced on heating continually reacts and re-equilibrates with the crystalline residue. *Fractional fusion* will refer to the situation in which the liquid is immediately isolated from the system as soon as it is formed and is thereby prevented from further reaction with the crystalline residue.

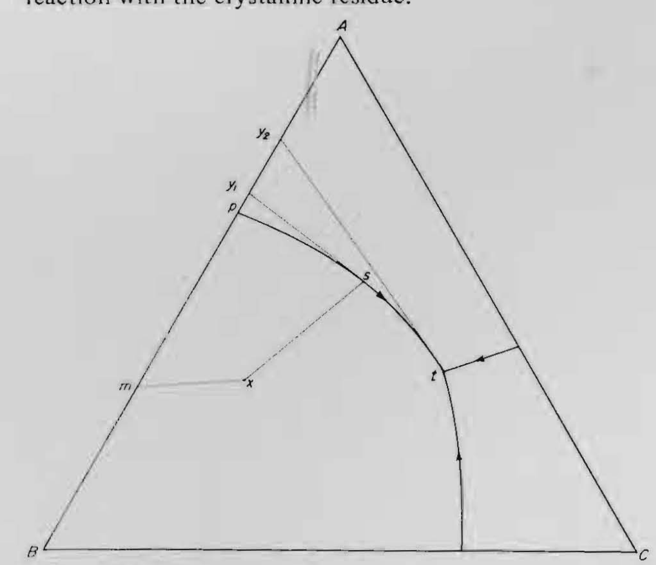

Figure 3B-1. Diagram to illustrate liquid and crystal paths. Heavy lines are liquidus boundary curves with arrows indicating directions of falling temperature.

In nature, all gradations may exist between fractional and equilibrium fusion, but it is convenient to start by examining the two end-member situations. Consider first a phase diagram with a ternary eutectic and with complete immiscibility of the solid phases (Figure 3B-1). During equilibrium crystallization of composition x, the composition of the liquid will change along path x-s-t, here called the ***liquid path.*** Simultaneously, the aggregate composition of the precipitating crystals will change along the path B-m-x, called the ***crystal path.*** During fractional crystallization, the liquid path in this special case is the same as for equilibrium crystallization, but the crystal path is discontinuous and consists of the point B, the line y_1-y_2 and the point t. The lines y_1-s and y_2-t are tangents to the boundary curve p-t at the points s and t respectively. The discontinuous nature of the crystal path is characteristic of layered intrusions formed by fractional crystallization (for example, see Wager, 1960, Figures 3 and 4).

Equilibrium fusion of composition x results in precisely the reverse sequence of events as equilibrium crystallization. The liquid changes composition along the liquid path t-s-x and the aggregate composition of the crystals simultaneously changes along the crystal path x-m-B.

Fractional fusion of composition x produces quite a different result. As with equilibrium fusion, the first liquid produced is at the eutectic t. Removal of this liquid as it is formed drives the aggregate composition of the residual crystals directly away from t along the line x-m. Throughout this stage of melting, the temperature remains constant at t. When the crystal path reaches point m, no further fusion takes place until the temperature rises to that of the binary eutectic p. Further addition of heat results in no increase in temperature while liquid p is produced, and the aggregate composition of the residual crystals is driven from m to B. After the crystal path reaches B, there is a temperature interval between the eutectic temperature p and the melting point of pure B when no fusion takes place. Upon reaching the melting temperature of pure B, a final liquid is produced of this composition. The liquid path, then, is discontinuous and consists of three points t, p and B, 35 per cent of the original starting mixture being produced as liquid t, 31 per cent as liquid p, and 34 per cent as liquid B. In contrast, the crystal path x-m-B has no compositional breaks.

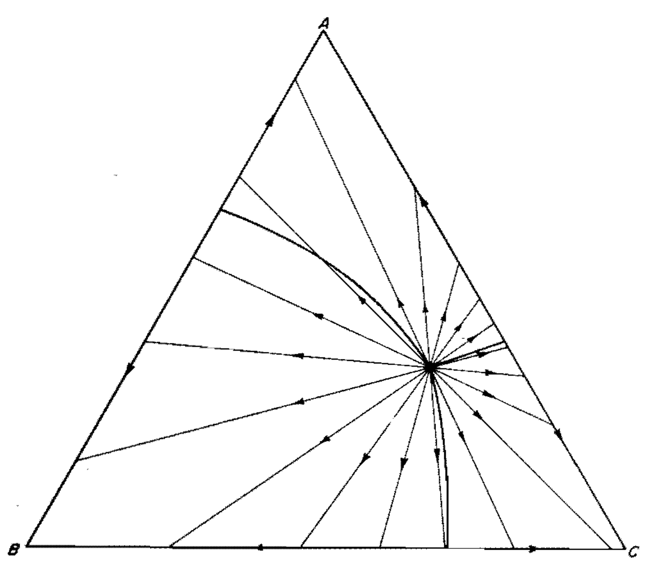

Figure 3B-2. Solidus fractionation lines for the system illustrated in Figure 3B-1. Arrows indicate directions of change in the aggregate composition of the residual crystals during fractional fusion.

In Figure 3B-1 any starting composition (except the one corresponding to the eutectic t) will have a similar fractional fusion history. The crystal path will always move directly away from t until it reaches a side of the triangle, and then will move directly toward either A, B, or C. Figure 3B-2 shows the family of lines that describe this behavior; these lines will be called *solidus fractionation lines.*

To summarize, equilibrium fusion produces precisely the same sequence of events as equilibrium crystallization, except in reverse order. On the other hand, fractional fusion and fractional crystallization yield distinctly different results. During fractional fusion the liquid path is compositionally discontinuous and the production of each liquid is separated by a temperature interval during which no fusion occurs; the crystal path is compositionally continuous. During fractional crystallization the liquid path is compositionally continuous and shows only one point of overlap *(t)* with the liquid path produced by fractional fusion; the crystal path is compositionally discontinuous and contains one point of overlap *(B)* with the crystal path produced by fractional fusion.

Now consider a ternary system with one component *(A)* showing complete solid immiscibility with the other two components, and with these other two components *(B, C)* showing complete solid solution with each other. Assume further that the solidus and liquidus curves of the system B-C show a continuous decrease in temperature toward B. Such a system is diopside-albite-anorthite (Bowen, 1915). Figure 3B-3 is drawn nearly identically to the system diopside-albite-anorthite except the liquidus boundary line m-n has been drawn perfectly straight rather than curved, as it actually exists.

Crystallization behavior in a system of this type has already been treated (Bowen, 1915) and need not be repeated. In deriving paths of fusion, it is first necessary to picture the shape of the solidus surface. In the previous example (Figures 3B-1 and 3B-2), this was a trivial matter since the solidus surface consisted merely of an isothermal plane. Where solid solution exists, as in Figure 3B-3, the solidus surface is a sloping, generally curved, surface. In Figure 3B-3 the solidus surface slopes to the left, and isotherms on this surface consist of a family of straight lines, all passing through the apex A and intersecting the base B-C. For example, all mixtures on the solidus isotherm A-p will start melting at the same temperature, and the composition of the first liquid to form will be s. For any starting composition on the line A-p, say x, subtraction of an infinitesimal amount of liquid s during fractional fusion will drive the aggregate composition of the residual crystals

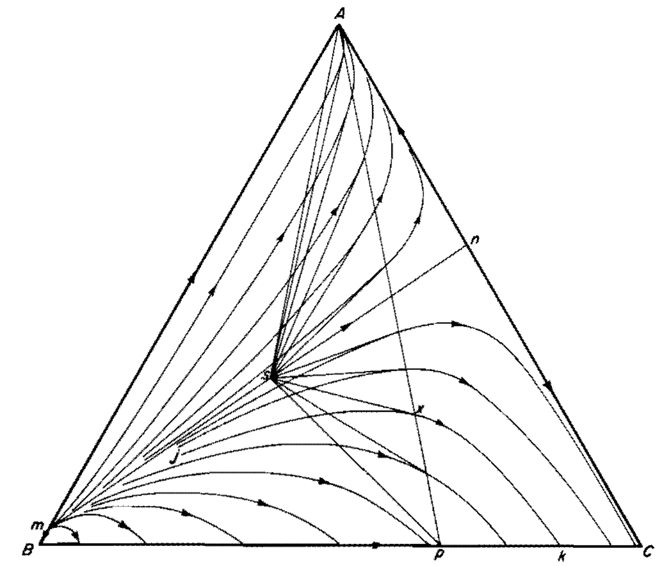

Figure 3B-3. Solidus fractionation lines (lines with arrows) for a system showing complete solid solution between B and C. The line m-n is also a liquidus boundary line that decreases in temperature toward m. Arrows are used as in Figure 3B-2.

directly away from s; the direction of the crystal path at x is thus given by the line s-x. Repetition of this construction over the entire diagram yields a family of solidus fractionation lines, one of which is j-x-k. These lines are drawn so as to be always tangent to lines such as s-x at x. Given the solidus fractionation line through any aggregate crystalline composition *(x)*, the composition *(s)* of the liquid in equilibrium with that aggregate crystalline composition is defined by the intersection of the tangent to the solidus fractionation line at x and the appropriate liquidus boundary line *(m-n)*. A solidus fractionation line, then, describes the crystal path followed during perfect fractional fusion. The lines called fractionation curves by Bowen (1941) will be referred to here as *liquidus fractionation lines;* they describe the liquid path followed during perfect fractional crystallization.

In deriving crystal and liquid paths during equilibrium fusion, one may use familiar methods for determining the equilibrium crystallization history and recall that equilibrium fusion yields precisely the reverse sequence of events as equilibrium crystallization. On the other hand, it is more convenient and instructive to derive certain parts of the equilibrium fusion history directly from the solidus fractionation lines. Figure 3B-4 illustrates the method. From the starting composition x lying on the solidus fractionation line s_1, tangents to the fractionation lines s_2, s_3, and s_4 are drawn at p_2, p_3, and p_4. The crystal path, x-p_2-p_3-p_4, is the locus of all such points of tangency. At each stage of fusion, the starting composition must lie on the join between the composition of the liquid and the aggregate composition of the crystals. Thus, as the crystal path moves from x through p_2 and p_3 to p_4, the liquid path moves from a_1 through a_2 and a_3 to a_4.

The solidus fractionation lines define only the aggregate composition of crystals in equilibrium with liquids on the boundary curve m-n. In order to complete the melting of composition x at temperatures above p_4, the liquid path leaves the boundary line m-n and travels along a curved line (not shown) to x as the crystal path moves a short distance toward C from p_4. Therefore, this part of the equilibrium fusion history cannot be deduced from the solidus fractionation lines; it is necessary to use the liquidus fractionation lines (see Bowen, 1941, for a discussion on the use of liquidus fractionation lines).

On the other hand, an understanding of the complete course of fractional fusion of composition x does not require the liquidus fractionation lines, for the only liquids produced lie either on the boundary line m-n or the base of the triangle B-C. That is, the liquid path is discontinuous and consists of the lines a_1-d and f-C; a_1-x and d-e are tangents at x and e to the solidus fractionation line s_1. The point f marks the composition of the first liquid produced on melting the crystalline solid solution e and is determined from a knowledge of the binary system B-C; it cannot be determined from either the solidus or liquidus fractionation lines. The crystal path during fractional fusion of x is the continuous path x-e-C.

Again, as in the case of the previous example of a system with a ternary eutectic, the crystal path during fractional fusion is compositionally continuous and the liquid path is discontinuous with a temperature gap at the discontinuity during which no fusion occurs.

The methods of deducing crystal and liquid paths on more complex diagrams are analogous to those just described. One complication arises from the fact that boundary lines are generally not straight as shown in Figures 3B-3 and 3B-4, but space does not permit discussion of this complication here.

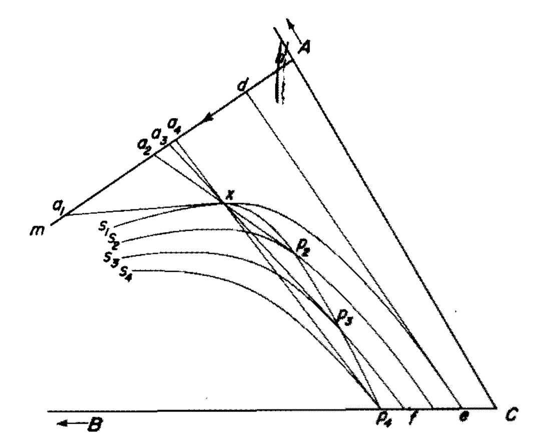

Figure 3B-4. A portion of the system shown in Figure 3B-3 to illustrate derivation of liquid and crystal paths during equilibrium fusion. The arrow on the liquidus boundary line m-n indicates the direction of decreasing temperature.

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C. Mineralogical and Chemical Composition of the Earth's Upper Mantle by a Partial Fusion-Partial Crystallization Model

James L. Carter

Work is continuing on the study of the chemical nature of the Earth's upper mantle. The thesis proposed in last year's annual report for ascertaining the chemical nature of the upper mantle under an ultramafic and mafic nodule locality (Kilbourne Hole, New Mexico) has been extended to data from Dreiser Weiher, Germany; Potrillo, New Mexico; and Hawaii. The mineralogy of the unaltered upper mantle under these localities was determined by the partial fusion-partial crystallization hypothesis and is listed in Table 3C-I. In Table 3C-II the chemistry of the unaltered upper mantle, established by this hypothesis, is compared to estimates of the unaltered upper mantle composition derived by other methods.

Volume Percent	Dreiser Weiher, Germany	Hawaii	Kilbourne Hole, New Mexico	Potrillo, New Mexico	Average of Columns 1 to 4
Olivine $(Mg,Fe)_2SiO_4$	44	52	50 ± 5	50	49 ± 5
Orthopyroxene $(Mg,Fe)SiO_3$	34 ± 2	25	22 ± 2	28	27 ± 7
Clinopyroxene $Ca(Mg,Fe)Si_2O_6$	19 ± 1	19	25 ± 3	20	21 ± 4
Spinel $(Mg,Fe)(Al,Cr,Fe)_2O_4$	3 ± 2	4	3 ± 1	2	3 ± 2

Table 3C-1. Unaltered upper mantle major phase mineral assemblages at intermediate pressure.

Wt. %	Kilbourne Hole	Dreiser Weiher	Hawaii	Average of Columns 1 - 3	Pyrolite*	Nicholls[+]	Average of Ultramafic Rock
SiO_2	43.48 ± 0.17	45.08 ± 1.48	43.98	44.17 ± 0.91	45.16	45.1	44.42
TiO_2	0.33 ± 0.08	0.15 ± 0.01	0.23	0.23 ± 0.08	0.71	0.5	0.09
Al_2O_3	6.18 ± 0.68	6.26 ± 1.53	5.76	6.07 ± 0.31	3.54	4.1	2.60
Cr_2O_3	0.20 ± 0.03	0.44 ± 0.23	0.25	0.30 ± 0.14	0.43	0.3	0.35
Fe_2O_3	0.54 ± 0.12	1.39 ± 0.03	0.03	0.65 ± 0.74	0.46	2.0	1.25
FeO	9.14 ± 0.31	7.00 ± 0.11	9.73	8.62 ± 1.62	8.04	7.9	6.95
MnO	0.14 ± 0.01	0.09 ± 0.01	0.16	0.13 ± 0.04	0.14	0.2	0.13
NiO	0.20 ± 0.03	0.22 ± 0.01	0.25	0.22 ± 0.03	0.20	0.2	0.30
MgO	34.56 ± 1.79	34.91 ± 0.12	35.50	34.99 ± 0.51	37.47	36.7	41.41
CaO	4.45 ± 0.42	3.97 ± 0.21	3.64	4.02 ± 0.43	3.08	2.3	2.30
Na_2O	0.76 ± 0.15	0.44 ± 0.02	0.47	0.57 ± 0.13	0.57	0.6	0.25
K_2O	0.02 ± 0.01	0.06 ± 0.01	-----	0.04 ± 0.02	0.13	0.02	0.02
CoO	0.016 ± 0.001	0.015 ± 0.003	-----	0.015 ± 0.01	-----	-----	-----
Total Fe	7.48 ± 0.32	6.41 ± 0.11	7.58	7.15 ± 0.74	6.57	7.54	6.28

Table 3C-II. Unaltered upper mantle chemical compositions from partial fusion-partial crystallization models compared to ultramafic rock plus basalt models (Ringwood, 1966, and Nicholls, 1967) and an ultramafic rock model.*

A comparison of the compositions obtained by the different methods reveals similarities (see Table 3C-II). Differences occur mainly for the easily fusible elements TiO_2, Na_2O and K_2O. The thesis is advanced that these elements are concentrated in magma by the partial fusion of minor phases such as amphibole and phlogophite. Since the residuum from partial fusion of the unaltered upper mantle is more refractory than the unaltered upper mantle composition, the upper mantle beneath the continents, and to a lesser extent under islands and island arcs, is probably composed mainly of residuum material.

The more refractory region of the Earth's upper mantle is lighter than the upper mantle immediately below it. The extent and degree of this heterogeneity is unknown. Extension of the scheme for ascertaining the chemical nature of the upper mantle under an ultramafic and mafic nodule locality to additional world-wide nodule localities should help to define the degree and extent of this upper mantle heterogeneity.

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D. Petrology and Chemistry of Ultramafic Nodules from South Africa

Ju-chin Chen

Two-hundred and seventy ultramafic nodules collected from the kimberlites in South Africa are being studied petrologically and chemically. Rock types include eclogite, harzburgite, spinel-harzburgite, garnet-harzburgite, lherzolite, spinel-lherzolite, garnet-lherzolite, wehrlite, clinopyroxene-phlogopite, glimmerite, garnet-websterite, serpentinite and dunite. Major components of these ultramafic rocks are olivine, orthopyroxene, clinopyroxene and garnet; minor minerals include spinel, phlogopite, opaque minerals, rutile, kyanite, amphibole, chlorite, serpentine and carbonate. Comparison of histograms of olivine and orthopyroxene for various harzburgites and lherzolites discloses similarity in chief ingredients (olivine = 50-60 volume per cent, orthopyroxene = 25-35 volume per cent) and differences in peakedness and skewness. The clinopyroxene and garnet contents are generally less than 4 per cent of the total rock (harzburgites and lherzolites) by volume. Most of the ultramafic rocks fall close to the olivine-orthopyroxene side in the ternary plot of Ol-Opx-Cpx (Figure 3D-1).

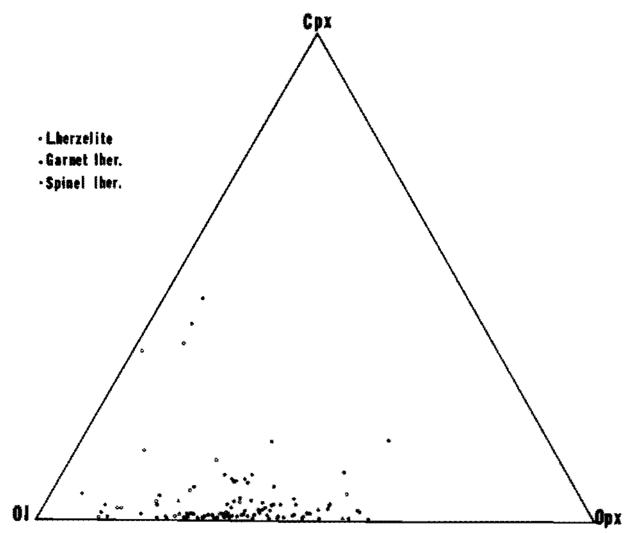

Figure 3D-1. Ternary plot of various lherzolite nodules from South Africa.

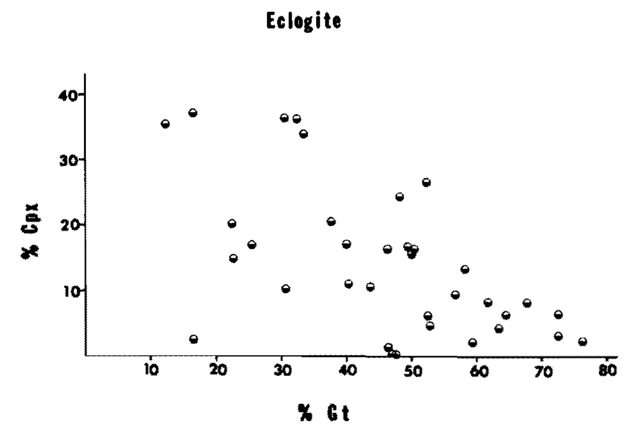

Figure 3D-2. Modal clinopyroxene versus garnet for Roberts Victor Mine eclogites.

The lack of a straight line relationship in the plotting of clinopyroxene (Cpx) versus garnet (Gt) in eclogites (Figure 3D-2) indicates the general alteration character of these rocks.

Chemical analyses of these ultramafic rocks are under way. Both major (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, Cr, Ni) and trace (Sr, Rb, Li, Zn, Pb, Cs, Cu, Cd, Ba, V) elements will be studied by atomic absorption. By means of the studies mentioned above it is hoped to shed some light on the chemistry of the upper mantle.

E. Chemistry of Clinopyroxene and Garnets of Nodules from the Roberts Victor Mine, South Africa

Ian D. MacGregor
James L. Carter

Coexisting clinopyroxenes and garnets from eclogites and lherzolites have been analyzed. Both minerals show a wide range of chemistry (Table 3E-I). There is a sympathetic variation of chemistry between the coexisting phases, but little correspondence of chemical variation to a differentiation index, such as the Fe:Fe+Mg ratio. The chemical data suggest that the nodules have a complex history involving an origin, either by fractional crystallization from a cooling magma, or as residua from partial fusion. Subsequent subsolidus and liquid-crystal reactions have helped to cloud the original history of the samples. Work is continuing on the chemistry of the coexisting phases, by use of the electron microprobe for variations in major and minor elements, and by use of the atomic absorption spectrophotometer for trace elements, to help in the elucidation of the complex history of the nodules.

	GARNET (weight percent)	CLINOPYROXENE (weight percent)
Al_2O_3	19.5 – 22.5	1.2 – 15.3
TiO_2	0.02 – 0.48	0.08 – 0.6
Cr_2O_3	0.02 – 4.29	0.04 – 3.42
FeO*	6.52 – 21.3	1.8 – 7.7
MgO	5.36 – 21.0	7.3 – 17.0
CaO	3.61 – 26.63	8.6 – 22.4
MnO	0.14 – 1.22	0.03 – 0.29
Na_2O	0.06 – 0.35	1.5 – 7.8
K_2O	0.0002 – 0.056	0.02 – 0.34

*Total Fe as FeO

Table 3E-I. Range of chemistry of garnets and clinopyroxenes of nodules from the Roberts Victor Mine, South Africa.

4. GEOCHRONOLOGY

A. Pegmatite Studies

Glen H. Riley

The decay constant of Rb^{87} is an important parameter in geologic studies involving radioactive dating. Two very careful determinations, based on laboratory time and using completely different techniques, are in good agreement (1.47×10^{-11} sec^{-1}, Flynn and Glendenin, 1960, and McMullen, Fritze and Tomlinson, 1966). Aldrich *et al.* (1956) reported a value of 1.39×10^{-11} sec^{-1} using a technique based on geologic time. The discrepancy is significantly outside the limits of experimental error.

A geologic calibration requires the assumption that a given rock unit becomes an isolated, closed system for all the decay schemes it contains at the same point in time. Aldrich *et al.* chose to compare Rb-Sr ages with U-Pb ages in minerals from zoned lithium-rich pegmatites. If the geologic decay constant is in fact uniformly 6 per cent lower, it implies that the lepidolite lattice effectively closes with respect to the Rb-Sr system substantially later in the pegmatite's history than the monazite and uraninite which define U-Pb closure. If the time difference is sufficiently long for significant growth of Sr^{87}, then this isotope may be used as a natural tracer to investigate the development of pegmatites in their early stages of crystallization.

BLACK HILLS, APPARENT AGE SEQUENCE

GRANITE
PEGMATITIC MICROCLINE
" MUSCOVITE
" BIOTITE — 60 my.
" LEPIDOLITE
" POLLUCITE
REPLACEMENT ZONES — 70 my.

EXCESS Sr^{87} IN PHOSPHATES
ALBITE
SPODUMENE

Table 4A-I. Rb-Sr age summary and location of excess Sr^{87} in zoned pegmatites from the Black Hills, South Dakota.

The area chosen for this study was the Black Hills Uplift, South Dakota, where large complex pegmatites intrude Precambrian schists around the periphery of the Harney Granite. Detailed Rb-Sr isotopic measurements have been made on samples of the granite and three pegmatites. One of these pegmatites (Bob Ingersoll) was used by Aldrich *et al.* in their half-life determination. The data indicate that an apparent age difference exists between pegmatitic minerals and the related Harney Granite, and that age differences are present within the mineral assemblage of each pegmatite. A large excess of the isotope Sr^{87} is observable in a number of Rb-poor phases. The apparent age sequence and location of anomalous strontium is summarized briefly in Table 4A-1.

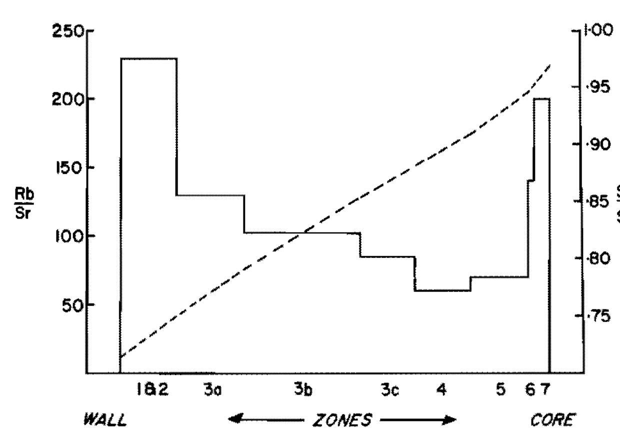

Figure 4A-1. Slow cooling hypothesis for the development of zoned pegmatites. The Rb/Sr ratio inferred from the bulk composition of each zone implies that successive zones crystallize with increasingly higher ratios of initial Sr^{87}/Sr^{86} (dotted line). Thus the initial Sr^{87}/Sr^{86} value of core zone (and replacement unit) magma approached unity for a 60 million year time delay after isolation of the pegmatitic fluid.

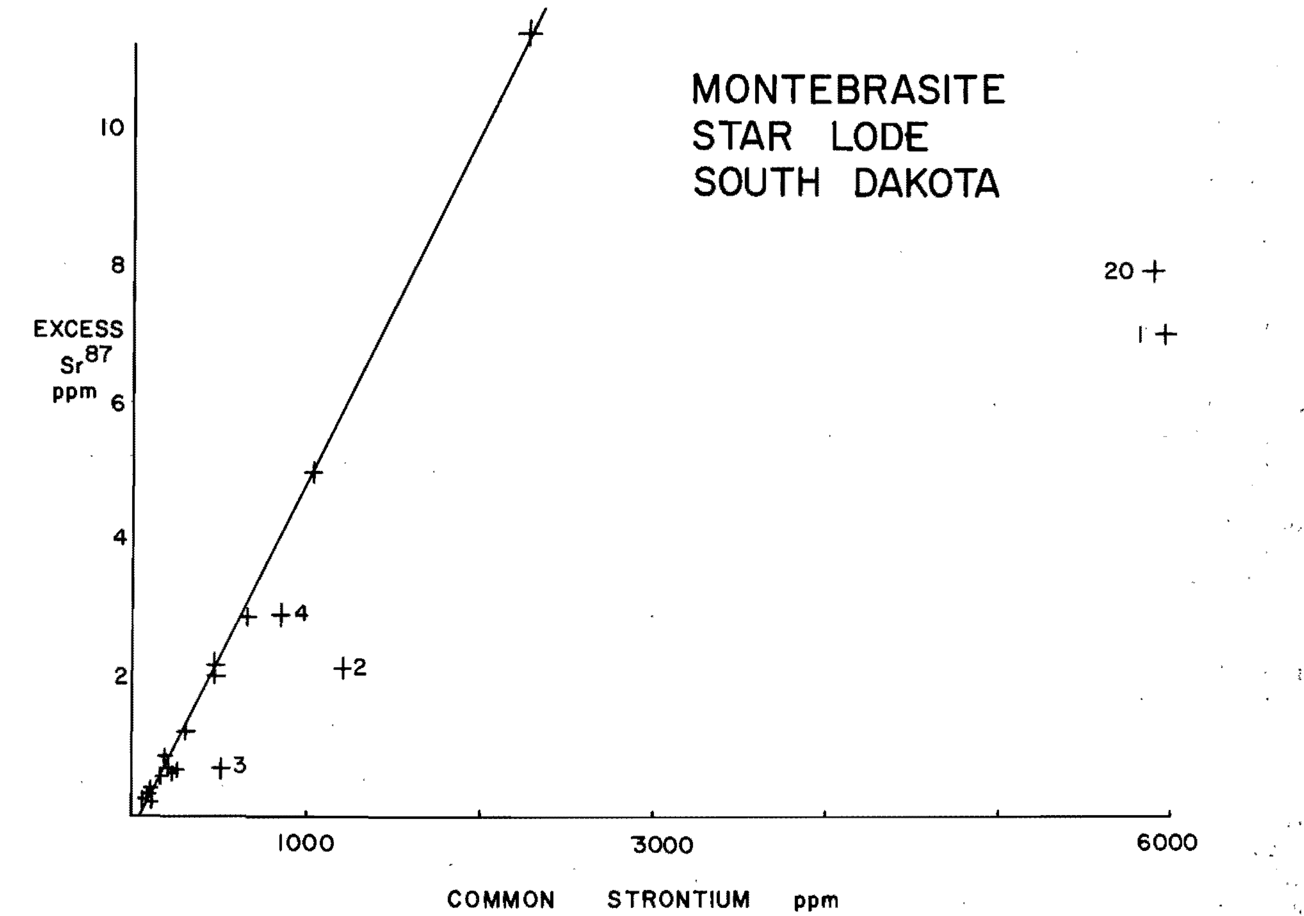

Figure 4A-2. Concentration of excess Sr^{87} as a function of total (common) Sr concentration in a montebrasite nodule from the Star Lode, South Dakota. Non-linear points (20, 1, 2, 3, 4) are thought to be related to subsequent weathering phenomena.

A survey of the isotopic abundance of Sr^{87} in phosphates from complex pegmatites from world-wide localities has shown that an excess of this isotope is the rule rather than the exception (Riley, 1967). Thus, it is to be expected that all such pegmatites will exhibit age discordance of at least a few percent. Under these conditions, a geologic half-life calibration of Rb^{87}, where decay scheme comparators are extracted from different minerals in the pegmatite system, will lead to an erroneous value.

A possible mechanism explaining both the apparent age sequence and excess Sr^{87} in the phosphate minerals is shown schematically in Figure 4A-1. Here the assumption is made that each zone in the pegmatite crystallizes slowly over a lengthy period of time (arbitrarily chosen as 10 million years). The tonnage and mineralogical composition of each zone (Norton, Page and Brobst, 1962) have been used to compute the zonal Rb-Sr ratio (full lines); the consequent Sr^{87}/Sr^{86} ratio in the remaining magma as each zone develops is shown as a dotted line. The strontium isotopic composition in the core zone, while substantially enriched in Sr^{87}, is inadequate to explain even higher values observed in some apatite crystals.

The distribution of excess Sr^{87} in four individual phosphate megacrysts (apatite, griphite and montebrasite) has been studied. It is found that the rubidium, common strontium and the Sr^{87}/Sr^{86} ratio are very inhomogeneously distributed throughout the crystals. Nevertheless, there is a systematic correlation between excess Sr^{87} and common strontium (Figure 4A-2) suggesting that almost isotopically pure Sr^{87} was incorporated into the phosphate crystal, the deposition sites being controlled by the abundance of strontium of normal isotopic composition. Departures from the linear relationship are all margin samples for which other studies (Mossbauer spectra, natural γ-ray spectra) show various weathering phenomena. Their significance is not germane to this brief report.

It is clearly seen that zoned pegmatites are complex systems, both chemically and isotopically. A fine structure of isotopic and age data exists, and will be important in elucidating their early cooling history. The comparison of ages derived from two independent decay schemes co-existing in particular mineral phases will be a critical test of the slow cooling hypothesis; this work is presently in progress.

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Riley, G.H., "Anomalous Strontium Isotope Ratios in Lithium Pegmatites," Trans. Am. Geophys. U., 48, p. 245, 1967.

B. Rb-Sr Investigations of Igneous Suites from the Norwegian Caledonides

Hannes K. Brueckner

Salic, mafic, and ultramafic rocks in the Norwegian Caledonides are being studied utilizing Rb-Sr isotope techniques. The aim of the study, in addition to determining ages, is to ascertain the extent and mechanisms of material exchange between the upper mantle and the crust in an orogenic zone. The results obtained to date may be summarized as follows:

(1) A Rb-Sr whole rock isochron of a granite intrusion (the Herefoss Granite) within the Precambrian Shield adjacent to the Norwegian Caledonides yields an age of 1.00 x 10^9 years and an initial Sr^{87}/Sr^{86} ratio of 0.704. Isochrons from granitic basement gneisses within the Caledonian orogenic system (the Basal Gneiss Region) yield similar ages and initial ratios. The basement gneisses are interpreted as large scale granitic intrusions that were subsequently recrystallized during Caledonian deformation (see also Brueckner, Wheeler and Armstrong, 1968). The low initial Sr^{87}/Sr^{86} ratios (0.704 to 0.706) of the 1.00 x 10^9 year old igneous complexes suggest a mantle origin.

(2) Rb-Sr results from Caledonian geosynclinal metasediments do not define isochrons and have not proved useful in age determinations.

(3) Present day Sr^{87}/Sr^{86} ratios of gabbros and related monzanites and syenites from Vesterålen and near Øksfjord range from 0.703 to 0.709. It is hoped that precise ages may be determined for these rocks. During the coming year, the study will be extended to associated suites of salic and ultramafic rocks.

Reference

Brueckner, H.K., R.L. Wheeler and R.L. Armstrong, "Rb-Sr Isochron for Older Gneisses of the Tafjord Area, Basal Gneiss Region, Southwestern Norway," Norsk Geologisk Tidsskrift, in press, 1968.

C. Origin of the Lebombo Rhyolites

William I. Manton

To supplement the data that have already been published (Manton, 1968) analyses have been completed of 25 additional samples from the Mbuluzi Gorge which traverses the rhyolite succession in Swaziland at the southern end of the Lebombo monocline. All the data obtained from the Lebombo to date are plotted in Figure 4C-1. The salient features are: (1) the inhomogeneity of the basaltic magmas; (2) the difference between the Sr^{87}/Sr^{86} ratio of the rhyolite magmas at the two ends of the monocline; and (3) the homogeneity of the rhyolite magmas in each area.

Interpretation is difficult. If it is assumed that the continental upper mantle is like the oceanic and has much the same values of Sr^{87}/Sr^{86} over large areas, it would seem that the homogeneity of the rhyolite magmas argues more in favor of their derivation from the mantle than from the crust. The lack of isotopic homogeneity in the basaltic magmas may imply they were selectively contaminated during their passage through the crust. On the other hand, this lack of homogeneity may be used to argue that the continental upper mantle, unlike the oceanic, is inhomogeneous. If this were to prove to be the case, it would be difficult to find the homogeneous source of the Lebombo rhyolites.

The origin of the Lebombo Rhyolites will be pursued through two new research projects. The first will be to carry out lead isotopic analyses on the samples already analyzed for strontium. The second, which is under way and is described in Section 4D, is to investigate the isotopic homogeneity of the continental upper mantle by means of the eclogitic and ultramafic inclusions of the kimberlite pipes.

Reference

Manton, W.I., "The Origin of Associated Basic and Acid Rocks in the Lebombo-Nuanetsi Igneous Province, Southern Africa, as Implied by Strontium Isotopes," Jour. Petrol., 9, pp. 23-39, 1968.

D. Isotopic Composition of Lead and Strontium in Eclogites and Related Rocks (with Dr. M. Tatsumoto, U.S. Geological Survey, Denver, Colorado)

William I. Manton

Five eclogites from the Roberts Victor Mine, South Africa, have been analyzed and found to have U^{238}/Pb^{204} ratios ranging from 1.56 to 11.0 and Pb^{206}/Pb^{204} ratios ranging from 15.36 to 18.88. When U^{238}/Pb^{204} is plotted against Pb^{206}/Pb^{204} a straight line is obtained, the slope of which corresponds to an age of 2.3 x 10^9 years (Figure 4D-1). It is inferred that the eclogites are of this age. The date for the

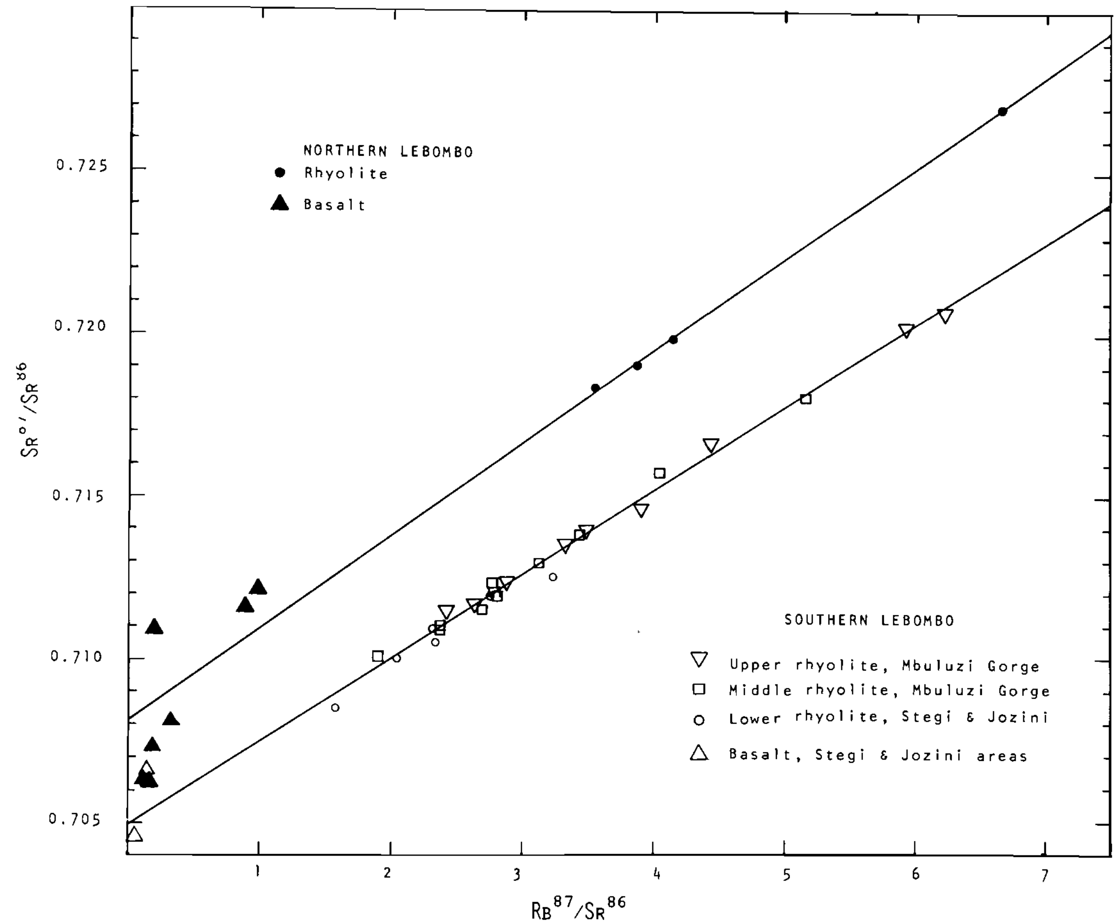

Figure 4C-1. Rb-Sr isochron plot of data from the Lebombo volcanics.

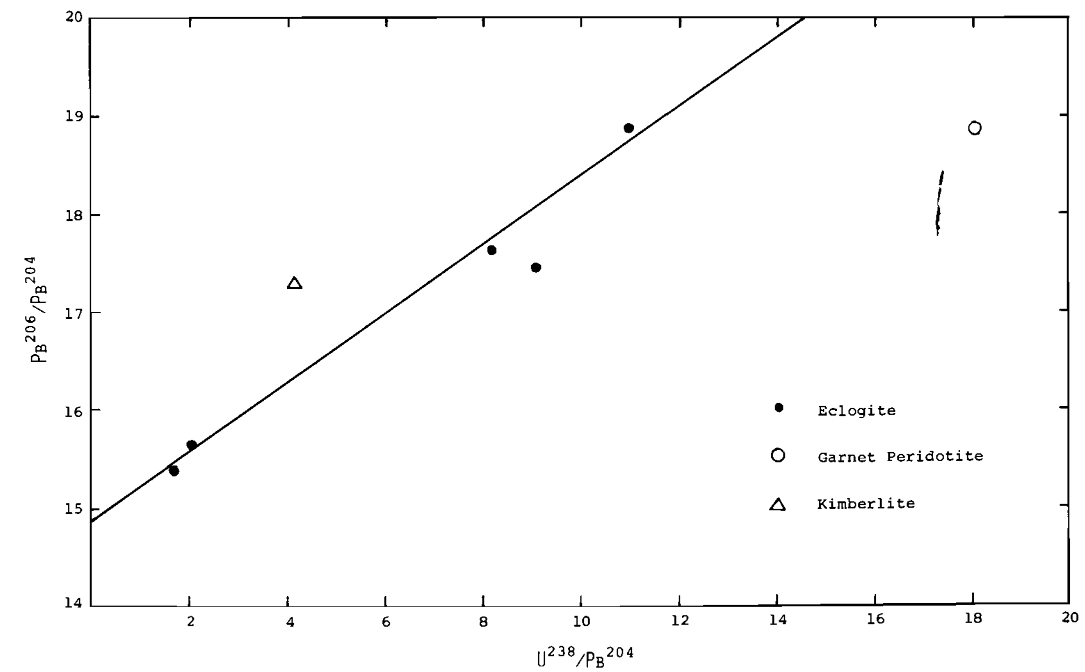

Figure 4D-1. U-Pb isochron plot of data from kimberlite, eclogite and peridotite of the Roberts Victor Mine.

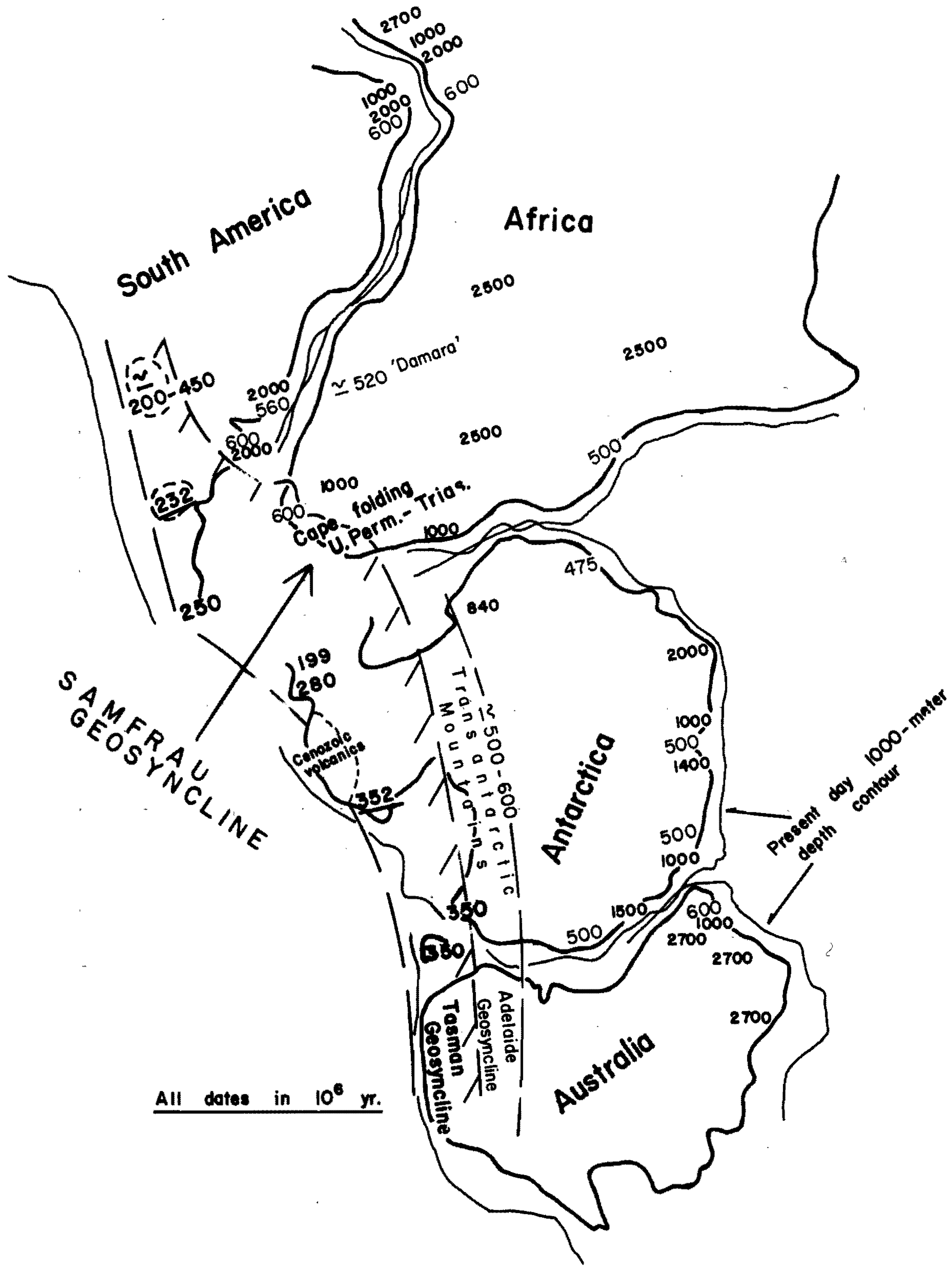

Figure 4E-1. Geochronoligic Reassembly of Gondwana "Samfrau" Geosyncline (orogen) of the Late Paleozoic.

kimberlite (1 sample) and the garnet peridotite (1 sample) fall off the line defined by the eclogites. The garnet peridotite appears to be much younger.

To date only the isotopic composition of strontium in the eclogites has been measured. It ranges from 0.704 to 0.710.

Although the data are still incomplete, the following conclusions may be drawn:
(1) The eclogites in the Roberts Victor Mine are of great age and were accidentally incorporated in the kimberlite magma.
(2) The garnet peridotites are not related to the eclogites.
(3) The upper mantle beneath the Roberts Victor Mine has remained a closed system since the early Precambrian.
(4) Melting of old eclogite may have produced the basalts with high Sr^{87}/Sr^{86} ratios reported from the Lebombo.

E. Ages of Southern Hemisphere Rocks Bearing on Continental Drift

Martin Halpern

During this past year an examination of continental drift, based on published age data and Rb-Sr dating of rocks from key areas in Antarctica and Argentina, led to the reconstruction illustrated in Figure 4E-1. Results to date reaffirm the existence of DuToit's "Samfrau" Geosyncline linking South America, Africa, Antarctica and Australia during the late Paleozoic (Halpern, 1968).

Programs planned for the coming year or presently underway will examine the geology and ages of rocks at other locations along this Paleozoic orogenic belt.

A cooperative program between a Uruguay scientist and Dr. Halpern to examine the ages of rocks from the crystalline basement of Uruguay for their bearing on the paleogeographic fit of South America and Africa is in the planning stage.

Reference

Halpern, M., "Ages of Antarctic and Argentine Rocks Bearing on Continental Drift," Earth and Planetary Science Letters, 5, pp. 159-167, 1968.

5. PALEOMAGNETISM

A. Paleomagnetic Studies of Continuous Stratigraphic Sequences

Charles E. Helsley

During the past ten years paleomagnetic studies have established generalized polar wander paths for most of the continents. The divergent, yet consistent, nature of these observations, along with the magnetic anomaly patterns observed on the flanks of mid-ocean ridges, has provided world wide evidence in support of the hypothesis of continental drift. The problem is no longer to establish that drift has taken place, but to establish the motions of the continents during their drifting episodes and to continue to study the polarity reversal history of the magnetic field.

(1) Cretaceous Studies

Paleomagnetic studies of Cretaceous rocks from more than 35 widely separated sites in North America have provided additional evidence for the position of the Cretaceous paleomagnetic pole. All of the data from structurally uncomplicated areas are highly consistent and thus provide strong support for the dipolar character of the Cretaceous magnetic field. Moreover, the polarity at all but two of the sites is consistently normal, suggesting that the Cretaceous period may be characterized by a magnetic field dominantly of one polarity. The published literature concerning Cretaceous rocks substantiates this hypothesis and indicates that reversals are present primarily in the Lower Cretaceous and the upper portion of the Upper Cretaceous period. The longest period of constant normal polarity consistent with the data presently available is about 25 million years and is present in rocks from upper Albian to middle Santonian age. This period of constant normal polarity is about half as long as the consistently reversed Kaiman interval of the Pennsylvanian and Permian. Magnetic anomaly patterns at sea show a smooth interval older than anomaly 32 (80 million years in age) which may correspond to this long period of normal polarity observed in Cretaceous rocks from North America.

(2) Triassic Studies

Oriented cores, taken at stratigraphic intervals of 9-12 inches, have been collected from the basal 450 feet of the Moenkopi Formation along the Dolores River in western Colorado. The NRM of these samples (Figure 5A-1) indicates a long period of reversed polarity, followed by a long normal interval. These periods are followed by three thinner reversed intervals separated by very thin (20-30 feet) normal units. Three normal and two reversed intervals are known from reconnaissance measurements in the overlying 150-foot section. The upper 150 feet of the formation have not been sampled. Additional reversals are known from the overlying Chinle Formation. Samples with clustered NRM results remain tightly grouped upon demagnetization. Samples that were initially scattered, however, generally remain scattered even after thermal or AC demagnetization. Several sequences of samples collected at 6- to 12-inch intervals show pronounced systematic changes in declination and inclination similar to those observed in archeomagnetic work and are thus interpreted as evidence of secular variation of the Triassic field. Systematic changes of declination and inclination in the transition zones between reversals have not been observed. These results, plus those of Picard (1964), suggest that periodic sequences of normal and reversed polarity zones (more than 15) are characteristic of the Triassic red beds of the western United States.

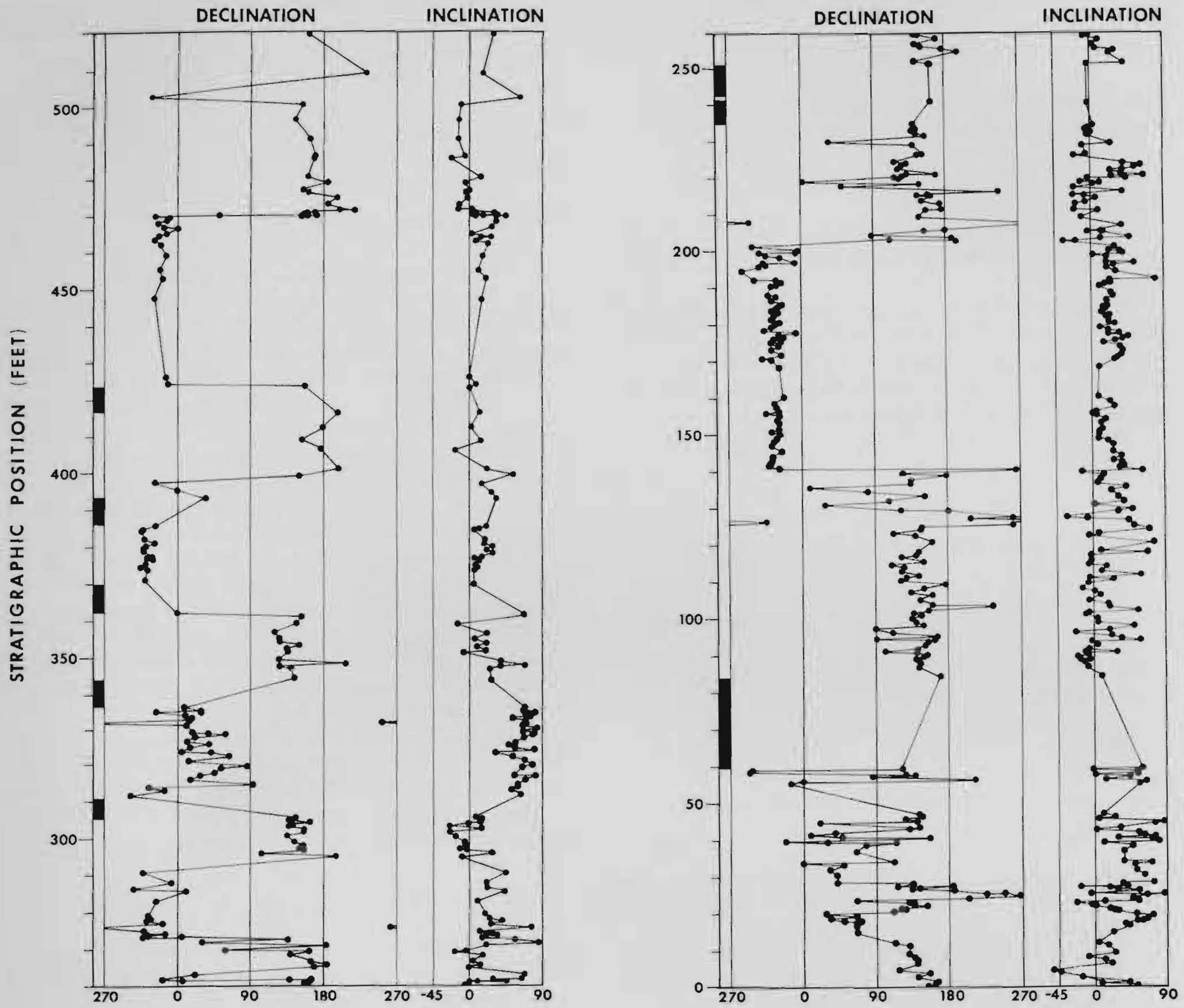

Figure 5A-1. Reversal sequences observed in Lower Triassic Moenkopi Formation.

Reference

Picard, M.D., "Paleomagnetic Correlation of Units Within Chugwater (Triassic) Formation, West-Central Wyoming," Bull. Amer. Assoc. Petrol. Geol., 48, pp. 269-291, 1964.

B. Reversals as a Stratigraphic Auxiliary Tool

Peter J. Burek

The directions of the remanent magnetization of rock samples from the Middle and Upper Buntsandstein (Lower Triassic) in southwest Germany fall into two groups with normal and reversed polarities. Nine reversely magnetized zones have been observed, five of which could be correlated over a distance of approximately 350 km. Polarity reversals are not related to differences in the lithology, suggesting that they are caused by polarity reversals of the geomagnetic field. A stratigraphy based upon polarity reversals agrees with the correlation of sedimentation cycles obtained by stratigraphic studies using vertical facies changes and fossil soils which were carried out simultaneously with the paleomagnetic work (Figure 5B-1). This suggests that reversals can be used effectively as markers in certain fossil-poor sedimentary sequences. Comparison of these results with the equivalent North American Triassic paleomagnetic data indicates that on a world-wide basis the older Mesozoic (Triassic) is characterized by numerous field reversals (more than 12), quite in contrast to the long reversed Kiaman Interval of the Upper Paleozoic (Permian).

C. Structural Effects of Sea-floor Spreading in the Gulf of Aden and the Red Sea on the Arabian Shield

Peter J. Burek

A review of recent oceanographic research shows that the Gulf of Aden and Red Sea can no longer be considered as simple graben structures, but are rift troughs in an early stage of development. A comparison between both troughs demonstrates that the Aden rift trough is the more mature. Intrusion and extrusion of basic igneous material, which is interpreted as the emplacement of a quasi-oceanic crust, resulted in an expansion of the rift troughs, i.e. ocean-floor spreading, thus separating the Arabian block from Africa.

Volcanism, epirogenic and orogenic events, as well as movement along pronounced fault systems on the Arabian Shield, are closely associated with the events in the rift troughs. Four major regional features are related in age and trend to the Gulf of Aden and Red Sea:

(1) Two volcanic episodes which differ in age and geographic location can be separated into: (a) the "Trap Series" (Figure 5C-1) which occurs only in the Gulf of Aden area and ranges in age from Late Cretaceous into Early Miocene (the most intense volcanism occurred, however, during Eocene to Oligocene time); and (b) the "Aden Volcanics" Belt (Figure 5C-2), which extends from the Afar Depression over the western Arabian Shield to southeast Turkey. The age of these volcanics spans Miocene to Recent time with eruption peaks during the Plio-Pleistocene.

(2) Two different sets of epirogenic warps which are essentially parallel and adjacent to the rift troughs can be recognized: (a) structures related to the Gulf of Aden (Figure 5C-1) appeared during the Lower Cretaceous. They reached their present configuration during the Late Eocene and Oligocene. (b) epirogenic structures (Figure 5C-2) that parallel the Red Sea are younger and occur only on the northern Arabian Shield where the structures associated with the Gulf of Aden die out. The first indications of their appearance are found during the Late Cretaceous, but their present morphology was developed during Plio-Pleistocene times.

(3) Orogenic structures (the Toros-Zagros Mountains and its S-shaped foreland belt) surround the Arabian Shield to the north and east (Figure 5C-2). Orogenic phases are apparently correlative with epirogenic movements observed on the Shield.

(4) Pronounced fault systems such as the initial Red

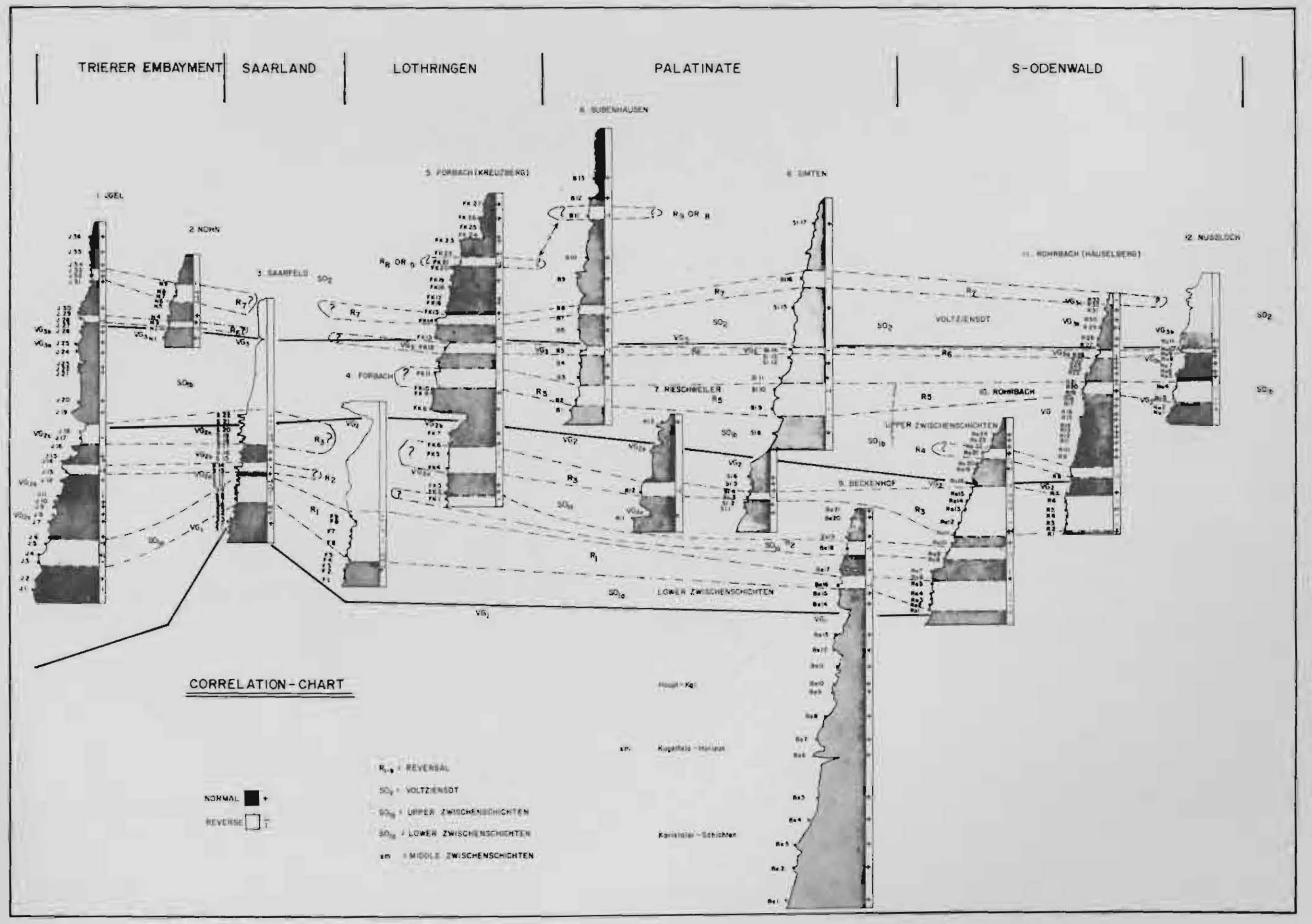

Figure 5B-1. Correlation chart of Lower Triassic reversals in Germany.

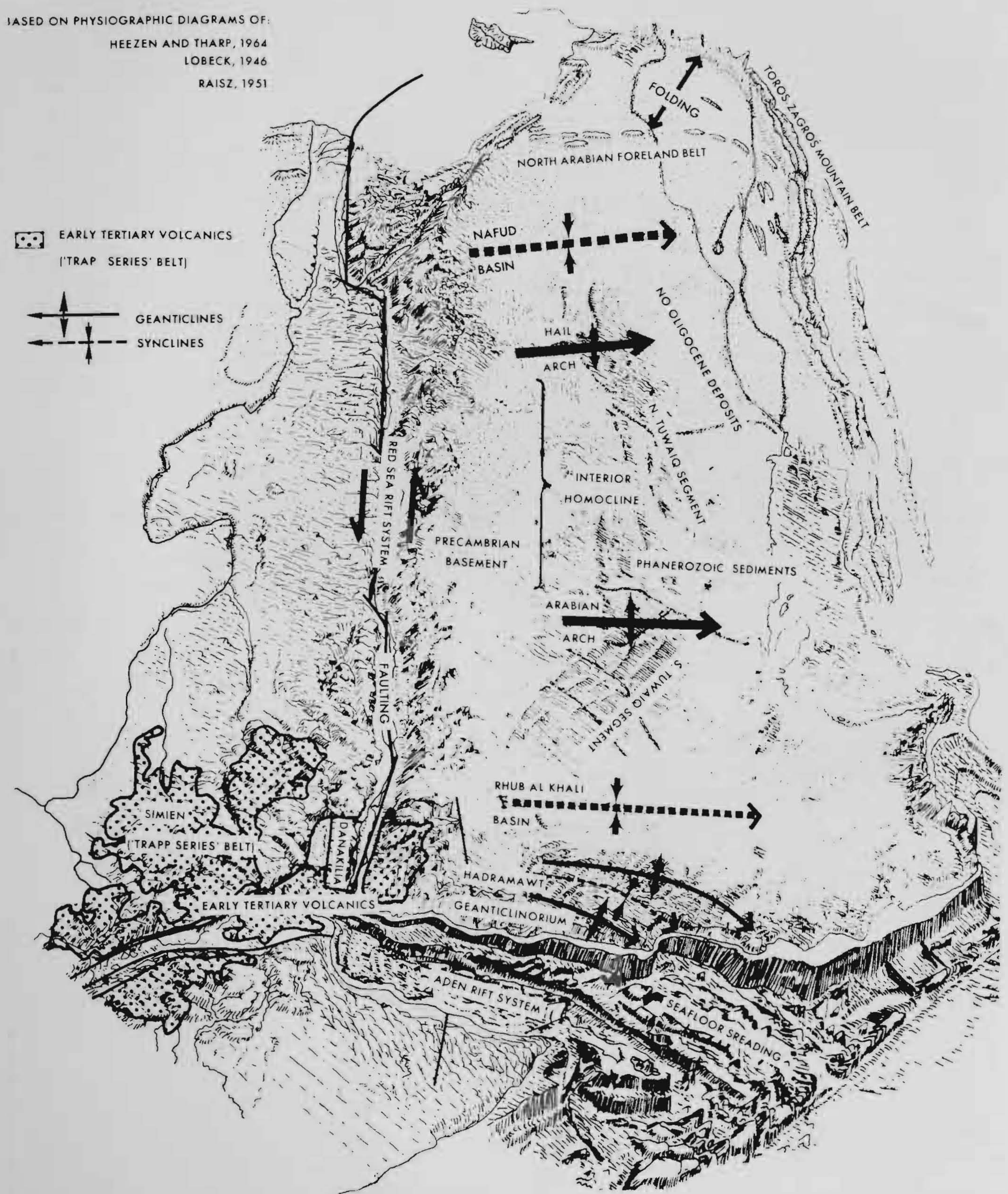

Figure 5C-1. Schematic physiographic sketch. Upper Eocene to Oligocene. Phase I.

Figure 5C-2. Schematic physiographic sketch, Miocene to Recent. Phase II.

Sea fault system and the Levant fault zone are associated with the different movements of the Shield.

The time sequence of the structural evolution of Arabia can be separated in two phases:

Phase I. The Gulf of Aden extension of the Carlsberg Ridge first became active during the early Cretaceous and continued to develop in several phases that culminated in Late Eocene time. The spreading in the Gulf of Aden resulted in a north-northwest movement of the Arabian Shield (Figure 5C-1). Left-lateral movement along the initial Red Sea-Suez fault system allowed the separation of Arabia from the Nubian Shield. The shield area itself underwent repeated compressional stresses resulting in epirogenic warping (Figure 5C-1). Several phases of orogenic folding and thrusting in the unstable shield margin are associated with the northward drift of Arabia. Volcanism around the western Aden trough is confined to the marginal fault systems.

Phase II. The evolution of the Red Sea Basin is younger (Figure 5C-2) than the Gulf of Aden. Although paleogeographic evidence indicates Late Cretaceous movements, the major tectonic activity peaks date from Miocene to Recent. Since the estimated extension of the Suez Graben cannot account for the whole amount of separation in the Red Sea, it seems reasonable to suggest that the northeast movement of Arabia, associated with the spreading in the Red Sea, occurred along the Levant (Aqaba-Orontes) fault zone. The subsequent volcanic, epirogenic and orogenic development is very similar to that for the spreading in the Gulf of Aden.

The separation of the Arabian Shield from the African continents is our most recent example of continental drift and thus most suitable for the study of the tectonic effects of ocean floor spreading. The structural evolution of the Arabian Shield implies that the tectonic forces that caused epirogenic and orogenic movements and volcanism originated in the rift troughs, i.e. they are related to sea-floor spreading.

D. Chemical Demagnetization Experiments on Red Sandstones

Peter J. Burek

Paleozoic red sandstones from Derik, southeast Turkey (Lower Cambrian) and from Wadi Ram, Jordan (Upper Cambrian-Lower Ordovician), exhibit NRM directions parallel to the present geomagnetic field. Thermal and alternating field demagnetization do not yield very clear trends of NRM directions. On pressing 3n HCl through the samples (see Figure 5D-1) the red staining is removed and the directions of NRM move considerably. This implies that the secondary component is of chemical origin due to recent groundwater circulation. The Cambro-Ordovician magnetic pole positions for the Arabian Shield can now be determined and are found to lie west of North Africa in the Atlantic Ocean.

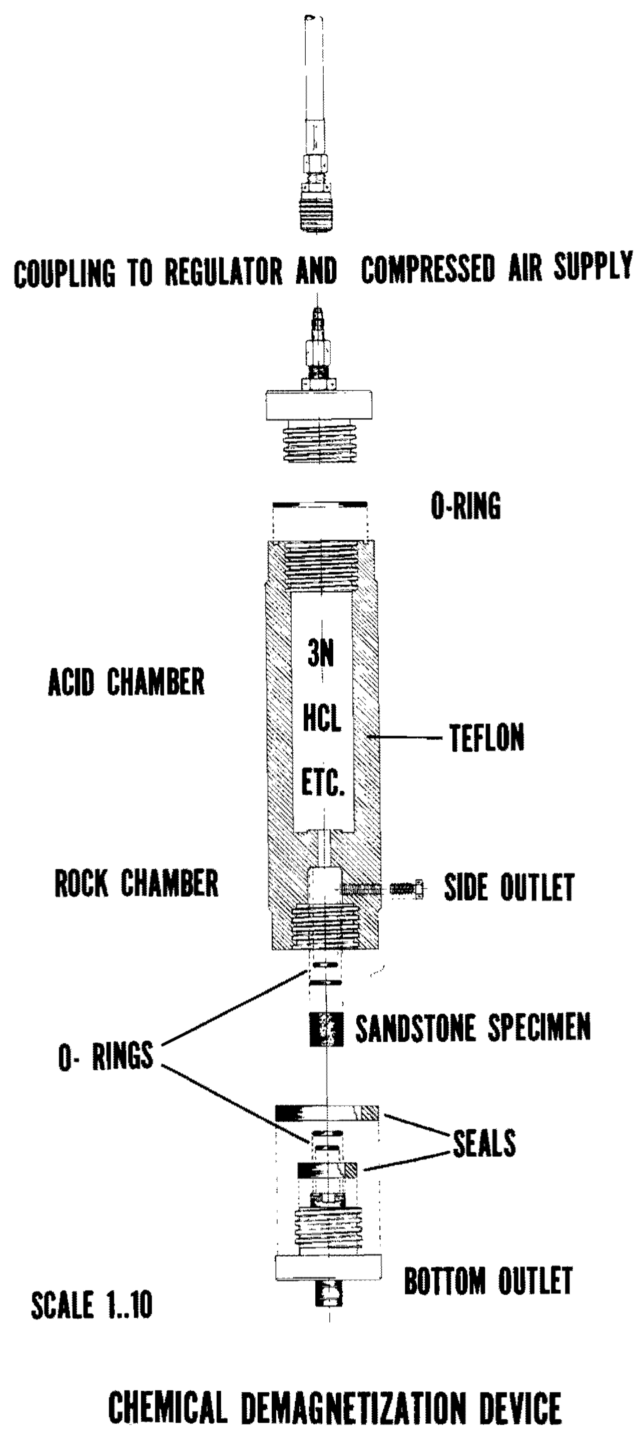

Figure 5D-1. Chemical demagnetization device.

Since red sediments often do not react to standard demagnetization techniques (AC or thermal demagnetization), chemical demagnetization of clastic sediments seems to be a most promising tool.

E. Mössbauer Spectroscopy – A New Tool in Geology

Wulf A. Gose

During recent years the Mössbauer effect has proven to be a most useful tool in solid state physics. The techniques involved and the parameters determining the shape of the spectrum are now well enough understood that it is possible to exploit Mössbauer spectroscopy as an analytical tool.

The Mössbauer effect involves nuclear resonance phenomena as follows: a gamma-ray of appropriate energy is emitted by a solid radioactive source; as this radiation passes through a solid absorber some of it is absorbed resonantly by suitable nuclei. The nuclear levels in the absorber may be split by hyperfine interaction (coupling of the nuclear magnetic dipole moment with the magnetic electrons or coupling of nuclear electric mono- or quadrupole moments with the crystalline field gradient). Then there will be a number of different energies at which absorption takes place. If now the source is moved relative to the absorber with a velocity of a few mm/sec, a very small amount of energy is added to or subtracted from the emitted gamma-ray. The counting rate at the detector will drop whenever this Doppler velocity brings the emitted gamma-ray into coincidence with an absorption energy in the absorber. The spectra shown are obtained by this technique (Figures 5E-1 and 2).

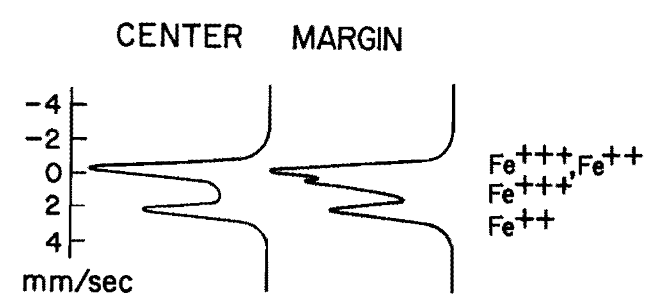

Figure 5E-1. Mössbauer spectra of a griphite crystal.

With a given radioactive source one looks at one particular nucleus. An apparatus has been built using a Co^{57} source which emits a gamma radiation appropriate for interaction with Fe^{57}. Iron is the most suitable Mössbauer element. It is of broad interest in geology and of particular importance in paleomagnetism. A Mössbauer spectrum yields information on the oxidation state of iron, the ratio Fe^{2+}/Fe^{3+}, crystal structure, magnetic state, and order-disorder relations.

As an example, a griphite crystal (five feet across), on which Dr. Glen Riley has done isotopic analyses, was studied. The spectrum of the sample from the center of the crystal exhibits only Fe^{2+}, whereas the one from the margin shows both Fe^{2+} and Fe^{3+} (Figure 5E-1) indicating that the crystal has been partially weathered. This may explain the rather striking changes in the strontium concentration found by Dr. Riley.

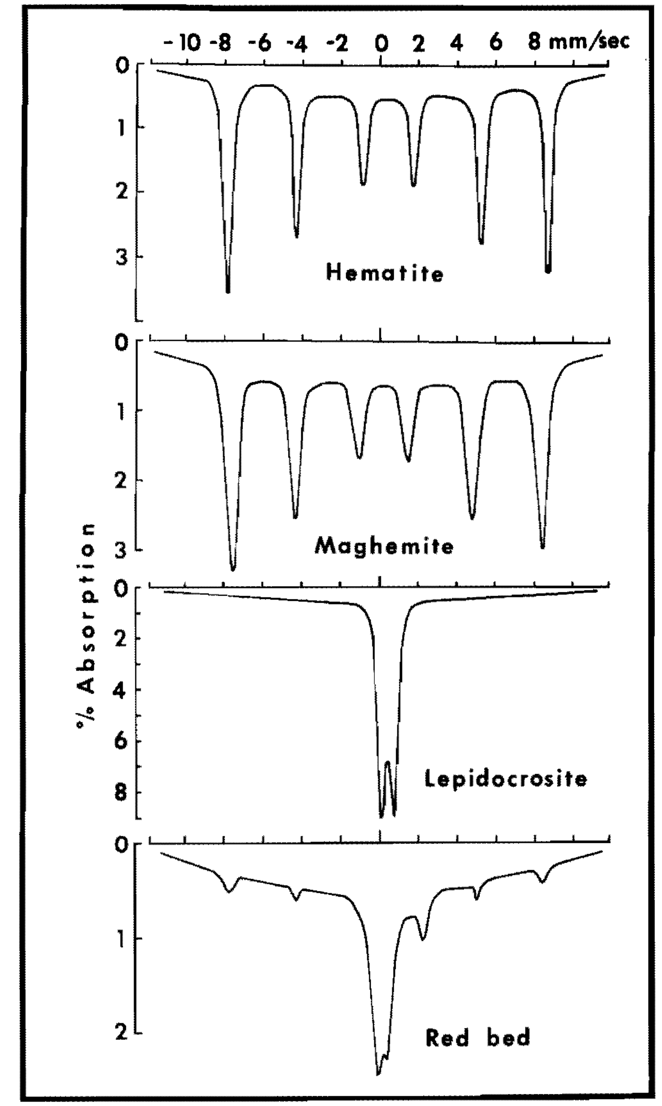

Figure 5E-2. Mossbauer spectra of (a) hematite, (b) maghemite, (c) lepidocrosite, (d) Pleistocene red bed from Baja California.

The advantages of this experiment are that the only sample preparation needed is grinding, and that one can work with much smaller crystallites than can be measured by X-ray techniques. In particular, Mössbauer spectroscopy makes it possible to investigate the nature of the staining of red sandstones. Preliminary studies of red beds from Baja California (Recent to Pliocene) yield rather intriguing results. Figure 5E-2 shows the spectrum of a Pleistocene sample together with spectra of three pure minerals, hematite, maghemite and lepidocrosite. Hematite can clearly be excluded as a constituent of this rock sample, as can goethite. The spectrum is tentatively interpreted as being due to lepidocrosite, biotite and maghemite. Other samples will be studied, for this tentative interpretation could have rather far reaching implications with respect to the genesis of red beds and the mechanism of their magnetization.

6. MAGNETIC DEEP SOUNDING

Hartmut Porath

The program of mapping variations in the electrical conductivity of the upper mantle in the western United States by observing differences in geomagnetic variations of periods of 15 minutes or more and relating these differences to variations in other geophysical parameters, such as heat flow and mantle seismic velocities, which are indicative of upper mantle inhomogeneities, has been continued. The program began with the development of a low cost magnetic variometer by Gough and Reitzel (1967a) to record simultaneously geomagnetic variations with a large number of instruments. This makes it possible to separate the observed variation field into an external and an internal component, thus improving prospects of a quantitative interpretation of the conductivity anomalies.

Twenty-two variometers were completed by the summer of 1967. The first eight of these instruments were put out by Reitzel in October 1966 in Colorado along a profile crossing the eastern front of the Rocky Mountains in an effort to locate a northward continuation of the conductivity anomaly discovered by Schmucker (1964) in southern New Mexico. Schmucker found the vertical variation (z) to increase by a factor of three east of 106° Long. (about 100 km west of the Rocky Mountain Front) and interpreted this to be due to a rise of mantle conductivity west of 106° Long., or, because of the close relationship between temperature and electrical conductivity in the mantle, to a rise in the mantle isotherms. A similar increase in Z was also observed by Reitzel in Colorado east of 106° Long. (Gough and Reitzel, 1967b), indicating the variation anomaly to be associated with the eastern front of the Rockies and marking the boundary between the Southern Rockies and the Great Plains.

In the summer of 1967, 42 variometers were put out in the western U.S. by the Center and the University of Alberta, Edmonton, where Dr. Gough had constructed another 20 variometers. The instruments were arranged along four east-west profiles crossing the Southern Rockies and Colorado Plateau, and extending well into the Great Plains and the Basin and Range Province (see Figure 6-1). Previous geophysical studies had indicated that the boundaries of these three provinces are marked by decreases in mantle seismic velocities and increases in heat flow going from the Great Plains west to the Basin and Range Province.

The summer of 1967 was not magnetically active, but a few bays as well as a moderate storm were recorded by about 80 per cent of the instruments. A computer plot of a bay on September 1, 1967, is shown in Figure 6-2 for the two southern lines operated by the Center. Line 3 shows the increase in Z from CIM to WAL associated with the eastern front of the Rockies. Most remarkable, however, are the high Z variations observed on both profiles over the Wasatch Front in Utah (EME, SLN, MCJ, GCC), which forms the eastern boundary of the Basin and Range Province. The fact that upward vertical variations of stations near the Wasatch Front correlate with westerly horizontal variations and the very low Z amplitudes of stations west of the Wasatch Front (EUR, BAK, VEY, HIK) suggests high mantle conductivities in the Basin and Range Province in accordance with the high heat flow of this region.

The eastern front anomaly is absent on Line 4 indicating that it swings towards the east in northern New Mexico. A small increase in Z for station TUC is, however, observed for the storm on September 20, 1967, and a bay on September 28, 1967, which have azimuths of the horizontal field different from the bay on September 1, 1967. This might indicate that TUC lies near the edge of the eastern front anomaly, but that its presence in the vertical variation depends on the direction of the inducing horizontal field. A reversal in Z is observed at CUB, which might be due to a conductivity anomaly associated with the boundary between the Colorado Plateau and the Southern Rockies.

Fourier transforms have been computed for the bay of September 1, 1967, and the amplitudes and phases of the vertical variation for various periods are shown in Figure 6-3 for the two southern lines. The eastern front anomaly is present for periods up to 60 minutes, whereas the Wasatch Front anomaly persists for a period of 90 minutes. Phase differences between stations near the boundaries of the three provinces, Great Plains, Southern Rockies and Basin and Range, are due to the additional internal vertical field induced by the external horizontal field perpendicular to the lateral inhomogeneities in conductivity.

The horizontal variations H and D vary substantially over the Center's array. The N-S component H increases, whereas the E-W component D decreases from east to west, which can be mainly attributed to spatial gradients in the external horizontal fields. The induced internal part of the horizontal field increases the external field and is apparent in the steepening of the gradient in H and a local increase superposed on the general decrease in D over the eastern front of the Rockies and the Wasatch Front. The results of both horizontal and vertical variations support, therefore, the interpretation that the mantle conductivity rises in two steps from the Great Plains to the Basin and Range Province.

Similar results have been obtained for the two northern lines operated by the University of Alberta, indicating that the observed variation anomalies are north-south trending features over the Center's array. It is intended to separate the internal from the external field to arrive at a more quantitative interpretation of the observed conductivity anomalies.

To investigate the course of the eastern front anomaly in New Mexico 12 instruments were put out in eastern New

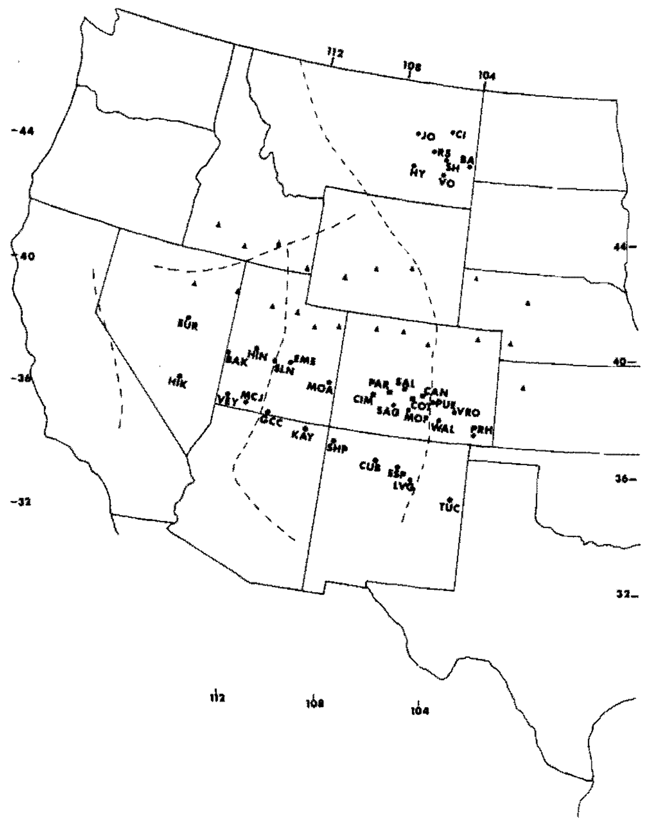

Figure 6-1. Map of western U.S. showing locations of variometer stations. Triangles denote stations operated by the University of Alberta. Also shown are the stations of Reitzel's Colorado line and the Montana array (see Annual Report 1966-1967).

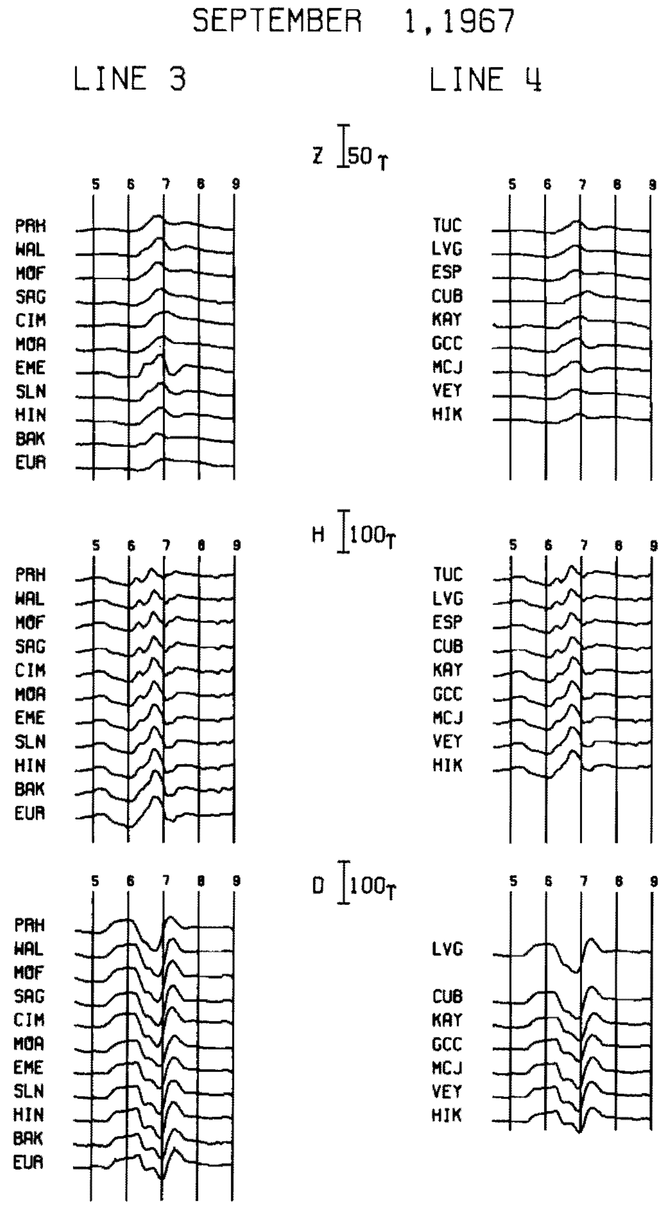

Figure 6-2. Computer plot of bay on September 1, 1967. The stations are plotted from east to west. Positive amplitudes represent upward vertical variations, and north (H) and east (D) represent horizontal variations.

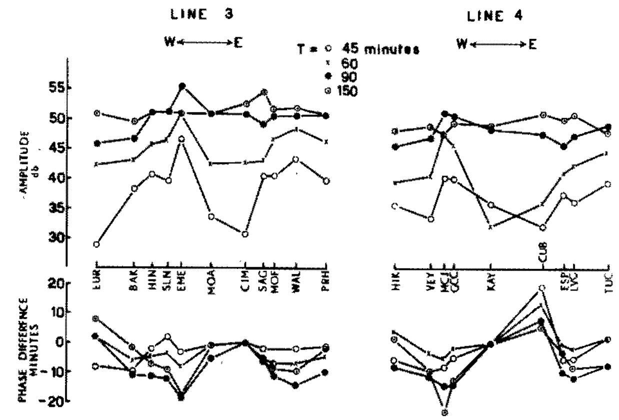

Figure 6-3. Amplitudes and phases of a Fourier analyzed bay of September 1, 1967.

Mexico, west Texas and Oklahoma in the spring of 1968. The lack of sizeable magnetic events during the time of recording will, however, prevent more than a preliminary analysis of variation anomalies in this region.

Forty-two instruments will be recording in the summer of 1968 in eastern California, Arizona, New Mexico and west Texas to map the southward continuation of the eastern front and Wasatch Front anomalies.

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7. ORGANIC GEOCHEMISTRY

Richard M. Mitterer

It has been estimated that in one year plants synthesize about 10^{17} grams of organic matter (Vallentyne, 1957). Thus the total weight of all organic compounds formed since life originated is almost equal to the weight of the Earth. The fate of this vast amount of organic matter, whether metabolized by other organisms, incorporated into sediments, or transformed into coal or petroleum, is one of the major concerns of organic geochemistry.

Proteins and their constituent amino acids comprise about one-third of all organic compounds being biologically synthesized. Their occurrence in materials of geologic interest, such as modern and fossil mollusk shells, sediments, and rocks, suggests that they may be of some significance from the geologic viewpoint.

This year a program in organic geochemistry was begun at the Center. Much of the early effort was given to building an amino acid analyzer. With this instrument, now in full operation, it is possible to detect as little as 10^{-10} mole of amino acid. In checking out the amino acid analyzer a survey was made of the amino content of various types of carbonates. Modern shells, fossil shells, worm tubes and oolites were analyzed. Some representative chromatograms illustrating the variety of carbonates which contain protein and amino acids are shown in Figure 7-1.

Figure 7-1A depicts the amino acid composition of protein from a modern mollusk shell, in this case from the inner, nacreous layer of the pearl oyster *Pinctada*. The outer, non-nacreous layer has a strikingly different composition with about half of the protein consisting of a single amino acid, glycine. *Pteria*, a mollusk closely related to *Pinctada*, has a very similar protein composition in its nacreous and non-nacreous layers. Both genera have a geologic range extending at least back to Devonian, making them two of the most primitive pelecypods still in existence. It may be that the protein composition of these shells resembles that of the earliest calcified mollusks.

The amino acid remnants in fossil shells are illustrated for *Mercenaria* in Figure 1B. Significant changes have occurred in the protein as a result of fossilization of the shell. The total amino acid content has been found to vary inversely with age of shell. Relative changes in the amino acid content have also occurred. Threonine, serine, cystine and arginine have disappeared completely in Early Pleistocene and older shells. Some new, non-protein amino acids such as alloisoleucine and ornithine have appeared. The relative changes in the amino acid content of fossil shells are sufficiently systematic to offer a means for determining approximate ages of unknown shells.

Mollusks are not the only invertebrate group capable of forming hard parts. Serpulid worms are colonial forms living in tubular carbonate structures which they fabricate by secreting a mucous upon which $CaCO_3$ is deposited. Figure 1C depicts the amino acid composition of the protein isolated from the wall structure of these worm tubes.

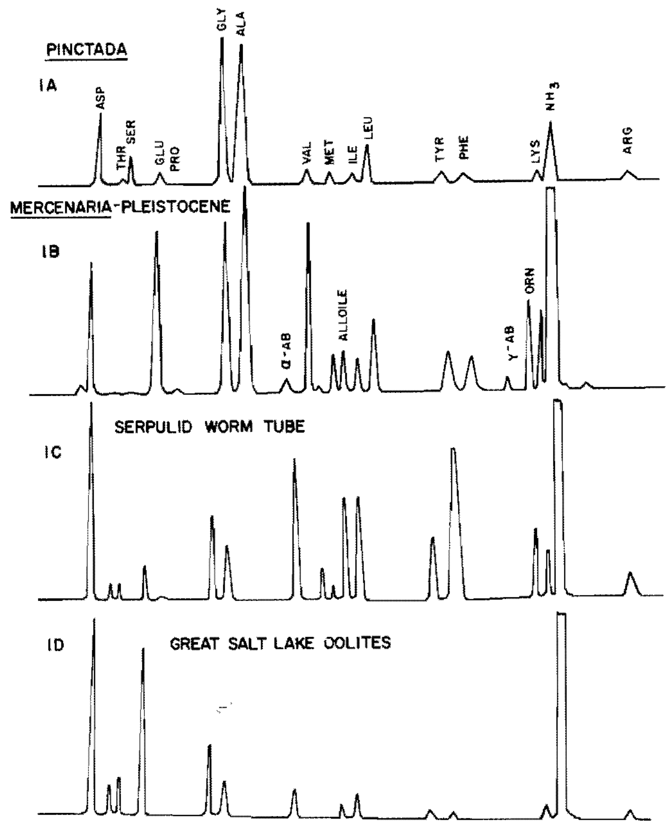

Figure 7-1. Amino acid composition of selected carbonates. Asp – Aspartic acid, Thr – Threonine, Ser – Serine, Glu – Glutamic acid, Pro – Proline, Gly – Glycine, Ala – Alanine, Val – Valine, Met – Methionine, Ile – Isoleucine, Leu – Leucine, Tyr – Tyrosine, Phe – Phenylalanine, Lys – Lysine, Arg – Arginine, α-AB – α-Aminobutyric acid, Alloile – Alloisoleucine, γ AB – γ Aminobutyric acid, Orn – Ornithine.

These examples illustrate the well-known association of an organic matrix with hard parts in biological systems. Such a relationship has not heretofore been recognized in inorganic systems. Figure 1D represents a chromatogram of an acid hydrolyzate from the outer portion of an oolite sample from Great Salt Lake. Oolites are spheroidal, concentric carbonate particles formed around a nucleus of foreign material such as quartz grains or shell fragments. Various theories have been proposed for their origin. One suggests that they are chemical precipitates. Another theory is that organisms living in the environment cause the deposition of $CaCO_3$ in some as yet unknown manner. The presence of boring algae and uncharacterized organic matter, noted in Bahamian oolites (Newell, Purdy and Imbrie, 1960), supports the latter view. The proteinaceous material found in Great Salt Lake and Bahamian oolites is the first reported occurrence of a specific organic substance in oolitic samples. No significant amount of free amino acids was detected. The source of the proteinaceous material could be either the algae or the uncharacterized organic matter. Regardless of the source, however, the important question is whether or not the proteinaceous substance is involved in the formation of the oolites. This question cannot be answered at the present time.

The diverse carbonate forms described above appear to have one common relationship. All have been found to contain proteinaceous material. The universal association of an organic matrix and hard parts in living systems, such as mollusk shells and worm tubes, has suggested a possible genetic relationship (Wilbur, 1964). It is intriguing, however, that supposedly inorganic forms such as oolites have now also been found to contain proteinaceous material.

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8. MICROPALEONTOLOGY

A. Upper Cretaceous Planktonic Foraminifera and Biostratigraphy of the Western Gulf Coastal Plain

Emile A. Pessagno, Jr.

The work described in this section is a continuation of work begun at the University of California, Davis.

(1) An Analysis of the Morphology, Phylogeny and Classification of Upper Cretaceous *Globigerinacea.* [A more complete account of this research has been published (Pessagno, 1967).]

The importance of foraminifera particularly in economic paleontology and stratigraphy was recognized in the 1920's and 1930's by Cushman, White and other American workers. The planktonic foraminifera were sadly neglected in the United States until the advent of the classical work of Bolli, Loeblich and Tappan, et al. (1957). The Europeans, however, were impressed by the biostratigraphic potential of the planktonic foraminifera at a much earlier date. The work of Bolli (1945, 1951), Subbotina (1952), Bronnimann (1952), Reichel (1950), Mornod (1950), Sigal (1952), Dalbiez (1955), and that of other European workers did much to foster an interest in planktonic foraminifera among American workers.

The last comprehensive survey of Upper Cretaceous foraminifera from the Gulf Coastal Plain Area was made by Cushman (1946). Although some planktonic foraminifera were described and figured by Cushman, his monographic study devoted itself largely to the benthonic foraminifera. In addition, changes in the taxonomy of planktonic foraminifera have been so great within the last 20 years that most of Cushman's data are now obsolete, and thus are not very useful to those studying the Upper Cretaceous stratigraphy of the coastal plains.

The present study concerned itself primarily with an analysis of the Upper Cretaceous planktonic foraminifera from the western Gulf Coastal Plain Area. Over 1200 Upper Cretaceous samples were collected from the coastal plain area of México, Texas, and southwest Arkansas (Figure 8A-1). The principal objectives of the work are two-fold: (1) to study the external and internal morphology of Upper Cretaceous planktonic foraminifera, and thereby bring about a better definition of taxa, and (2) to determine the phylogenetic relationship of the Upper Cretaceous taxa studied.

Two new families of Upper Cretaceous planktonic foraminifera have been erected: (1) the Marginotruncanidae Pessagno (Turonian to Santonian) and (2) the Abathomphalidae Pessagno (Maestrichtian). Both of these new families are morphologically distinct and have great significance in the phylogeny of the planktonic foraminifera.

The Marginotruncanidae Pessagno, n. fam. are characterized (1) by having extraumbilical-umbilical apertures and (2) by having large portici (not tegilla) with infralaminal accessory apertures. This family includes *Whiteinella* Pessagno, n. gen. and *Marginotruncana* Hofker (emended). *Whiteinella* lacks a well developed keel, whereas *Marginotruncana* Hofker may be either single or double keeled. There seems little doubt that the Marginotruncanidae represent an intermediate group forming an important phylogenetic link between the Rotaliporidae Sigal and the Globotruncanidae Brotzen.

The Abathomphalidae are characterized (1) by having extraumbilical-umbilical apertures and (2) by possessing true tegilla with infralaminal (not intralaminal insofar as is known) accessory apertures. This family includes *Abathomphalus* Bolli, Loeblich and Tappan, and *Globotruncanella* Reiss (emended). *Abathomphalus* possesses a weakly developed double keel, whereas *Globotruncanella* is keelless, sometimes possessing an imperforate peripheral band. The Abathomphalidae evolved either from the Globotruncanidae or the Rotaliporidae and may well have given rise to the "Globorotaliidae" Cushman of the Early Tertiary.

Two new species have been erected among the Planomalinidae: *Globigerinelloides bollii* Pessagno and *Globigerinelloides prairiehillensis* Pessagno. One new genus, *Loeblichella* Pessagno, and one new species, *Praeglobotruncana bronnimanni* Pessagno have been erected under the Rotaliporidae. One new genus, *Whiteinella* Pessagno has been erected under the Marginotruncaidae Pessagno, n. fam. Three new species: *Whiteinella archaeocretacea* Pessagno, *Marginotruncana bouldinensis* Pessagno, and *Marginotruncana pseudolinneiana* Pessagno have been erected under the Marginotruncanidae. At the generic level, one new genus, *Archaeoglobigerina* Pessagno, has been added under the Globotruncanidae. The latter family includes the following new species: *Archaeoglobigerina blowi* Pessagno, *Archaeoglobigerina bosquensis* Pessagno, *Rugoglobigerina tradinghousensis* Pessagno, *Globotruncana hilli* Pessagno, *Globotruncana loeblichi* Pessagno and *Globotruncana stephensoni* Pessagno.

A neotype has been erected for *Rosalina canaliculata* Reuss, 1854. Where necessary, lectotypes have been established for species described by workers in syntypic series.

The more important Upper Cretaceous planktonic species have been illustrated (Pessagno, 1967). Hundreds of planktonic specimens were thin-sectioned both for form analysis studies and phylogenetic studies. Means and standard deviations were calculated for many of the form analysis measurements. Such studies have greatly enhanced the definition of many taxa and have given the investigator a clearer insight into their phylogenetic relationships.

(2) Upper Cretaceous Stratigraphy of the Western Gulf Coast. [A complete account of this work is in press (Pessagno, 1969).]

The Upper Cretaceous strata of the Gulf Coast region of México, Texas and southwestern Arkansas contain a rich, abundant, well-preserved and hitherto poorly studied assemblage of planktonic foraminifera. The rapid evolution and cosmopolitan nature of these planktonic microfossils make them an ideal biostratigraphic tool for the development of detailed, long distance systems of zonation. In the present study the planktonic foraminifera have been utilized to subdivide the Upper Cretaceous of the western Gulf Coast region into the following biostratigraphic units (see Figures 8A-1 through 5):

(1) The *Rotalipora* s.s. Assemblage Zone: *Rotalipora evoluta* Subzone to *Rotalipora cushmani – greenhornensis* Subzone. Late Washitian to early Eaglefordian (early to late Cenomanian).

(2) The *Marginotruncana helvetica* assemblage Zone: *Marginotruncana sigali* Subzone to *Whiteinella archaeocretacea* Subzone. Middle to late Eaglefordian (Early to late Turonian).

(3) The *Marginotruncana renzi* Assemblage Zone: early Austinian (Coniacian).

(4) The *Globotruncana bulloides* Assemblage Zone: *Marginotruncana concavata* Subzone to *Globotruncana fornicata* Subzone. Middle to late Austinian (early to late Santonian).

(5) The *Globotruncana fornicata – stuartiformis* Assemblage Zone: *Archaeoglobigerina blowi* Subzone *(Dictyomitra multicostata* Zonule to *Planoglobulina glabrata* Zonule); *Globotruncana elevata* Subzone *Pseudotextalaria elegans* Zonule to *Globotruncana calcarata* Zonule); and *Rugotruncana subcircumnodifer* Subzone *(Globotruncana lapparenti* s.s. Zonule to *Rugotruncana subpennyi* Zonule). *Archaeoglobigerina blowi* Subzone: early Taylorian (early Campanian); *Globotruncana elevata* Subzone: late Taylorian (late Campanian); and *Rugotruncana subcircumnodifer* Subzone: early Navarroan (early Maestrichtian).

(6) The *Globotruncana contusa – stuartiformis* Assemblage Zone: *Globotruncana gansseri* Subzone to *Abathomphalus mayaroensis* Subzone. Middle to late Navarroan (middle to late Maestrichtian).

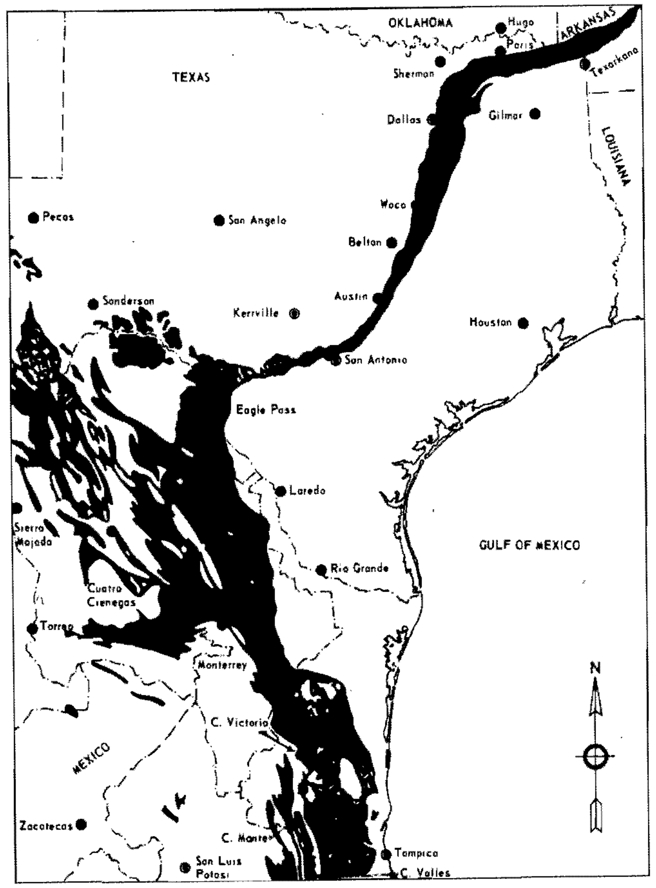

Figure 8A-1. Index Map. Distribution of UK deposits in Arkansas, Texas and eastern Mexico.

This system of zonation (see Figures 8A-3 through 5) is based on: (1) the association of diagnostic taxa at given stratigraphic horizons, (2) the range zones and concurrent range zones of the various taxa, (3) the relative abundance of important taxa at various stratigraphic horizons, and (4) the phylogeny and evolution of Upper Cretaceous planktonic foraminifera. It has become established through the analysis of more than 1200 fossiliferous samples from the surface and subsurface in both the western part of the Gulf Coast region and in the Caribbean region. Where possible samples were collected within the framework of measured sections of the lithic units under study.

Samples for planktonic foraminifera were collected as far south in the western Gulf Coast region as the approximate latitude of Tampico, México (22°N Lat.) and as far north as Brownstown, Sevier County, Arkansas (34°N Lat.) (Figure 8A-1). At a given stratigraphic horizon such as the *Globotruncana elevata* Subzone, there are few species of planktonic foraminifera which do not occur in both the Tethyal faunal province and southern part of the Boreal faunal province. In most cases planktonic species which do not occur in both areas are new species whose stratigraphic and geographic distribution are yet unknown. The present study indicates that the aforementioned system of zonation is applicable at the zonule level at least as far north as the latitude of Brownstown, Arkansas. Furthermore, Olsson's (1964) work in New Jersey together with work in progress in California by the writer, Douglas (in progress), and others suggests that the system of zonation introduced herein can be applied at the subzone level at least as far north as 40°N Lat. in eastern North America and as far north as 34° in western North America.

One of the chief by-products of this study is the creation of a regional correlation chart (Figure 8A-2) for the Upper Cretaceous of the western Gulf Coast region based on planktonic foraminiferal zonation. Accurate biostratigraphic dating of lithic units in eastern México utilizing planktonic foraminifera indicates that a number of formational units are time-transgressive from north to south. Units like the San Felipe Formation and Agua Nueva Formation are considerably older in northern México near Monterrey than they are in southern México near Tampico. The present study has yielded but a few radical changes in the dating of lithic units in Texas and Arkansas previously established on the basis of megafossils (Stephenson *et al.*, 1942). Notable among these changes are Navarroan ages for the Upson Clay and San Miguel Formation of the Rio Grande area of Texas (approximate latitude of Eagle Pass) and all but perhaps the lowermost part of the Marlbrook Marl of Arkansas.

Correlation with the type European Upper Cretaceous stages is rendered difficult by the imprecise and often obsolete definition of the stages in their type areas, and by a lack of accurate data concerning the stratigraphic distribution of planktonic foraminifera in the type sections of the stages. The first of these problems affects all Upper Cretaceous biostratigraphy regardless of the group of organisms used for correlation. It can perhaps only be solved by an international stratigraphic commission chosen to modernize the definition of the European stages. The second problem can be solved by detailed sampling of strata included in the type sections of each European stage for planktonic foraminifera. Until a detailed reanalysis of the majority of the type European stages is made the writer prefers to use North American stage names, particularly those of the standard Gulf Coast section.

The Eaglefordian Stage of the standard Gulf Coast Upper Cretaceous section has been subdivided into three new substages: (1) the Lozierian, (2) the Bocian, and (3) the Sycamorian.

The Boquillas Formation in Val Verde and Terrell Counties, Texas, has been subdivided into a lower unit termed the Rock Pens Member and an upper unit termed the Langtry Member. The terms Atco Chalk and Bruceville Chalk-Marl, first used informally by Durham (1957) have been formally described herein.

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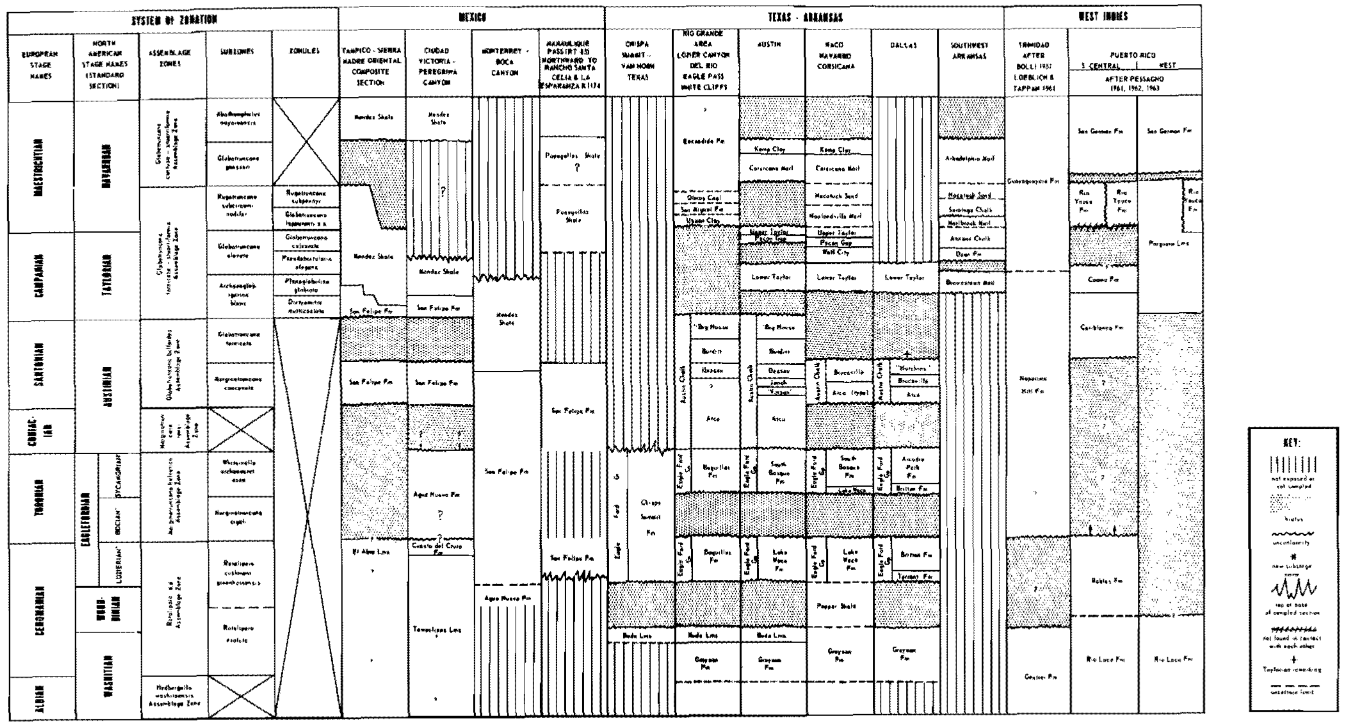

Figure 8A-2. Upper Cretaceous Correlation Chart for Western Gulf Coastal Plain and Caribbean Areas.

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B. Studies of Planktonic Foraminiferal Wall Structure

Emile A. Pessagno, Jr.

It has always been assumed that planktonic foraminifera have primary test walls which are completely radial hyaline in character. The term radial hyaline has a two-fold connotation to the majority of workers: (1) a more or less morphologic connotation which describes the crystals comprising the test wall as being equidimensional, euhedral microprisms oriented with their long axes normal to the surface of the test, and (2) a crystallographic connotation which states that the c-axes of the crystals are oriented normal to the surface of the shell (Towe and Cifelli, 1967, p. 744). This two-fold definition undoubtedly evolved from the work of Sorby (1879, p. 64) who noted that many hyaline foraminifera have their shells composed "--of small prisms of calcite having their principal axis perpendicular to the surface of the shell."

The term *radial hyaline* itself was first formally defined by Wood in 1949 who stated that the radial hyaline test is comprised of crystals of calcite oriented with their c-axes normal to the surface of the test. Towe and Cifelli (1967) suggest that the terms radial hyaline and granular hyaline be stripped of all morphological implications and be restricted to describing the preferred orientation of c-axes or the lack of such a preferred orientation.

It seems obvious that a revised and more precise terminology is needed in discussing foraminiferal wall structure. However, considering the rapid advances in knowledge as a result of numerous studies being undertaken with both the scanning and transmission-type electron microscopes, it is felt that any change in terminology at the moment would be premature. The following terminology is used on an interim basis:

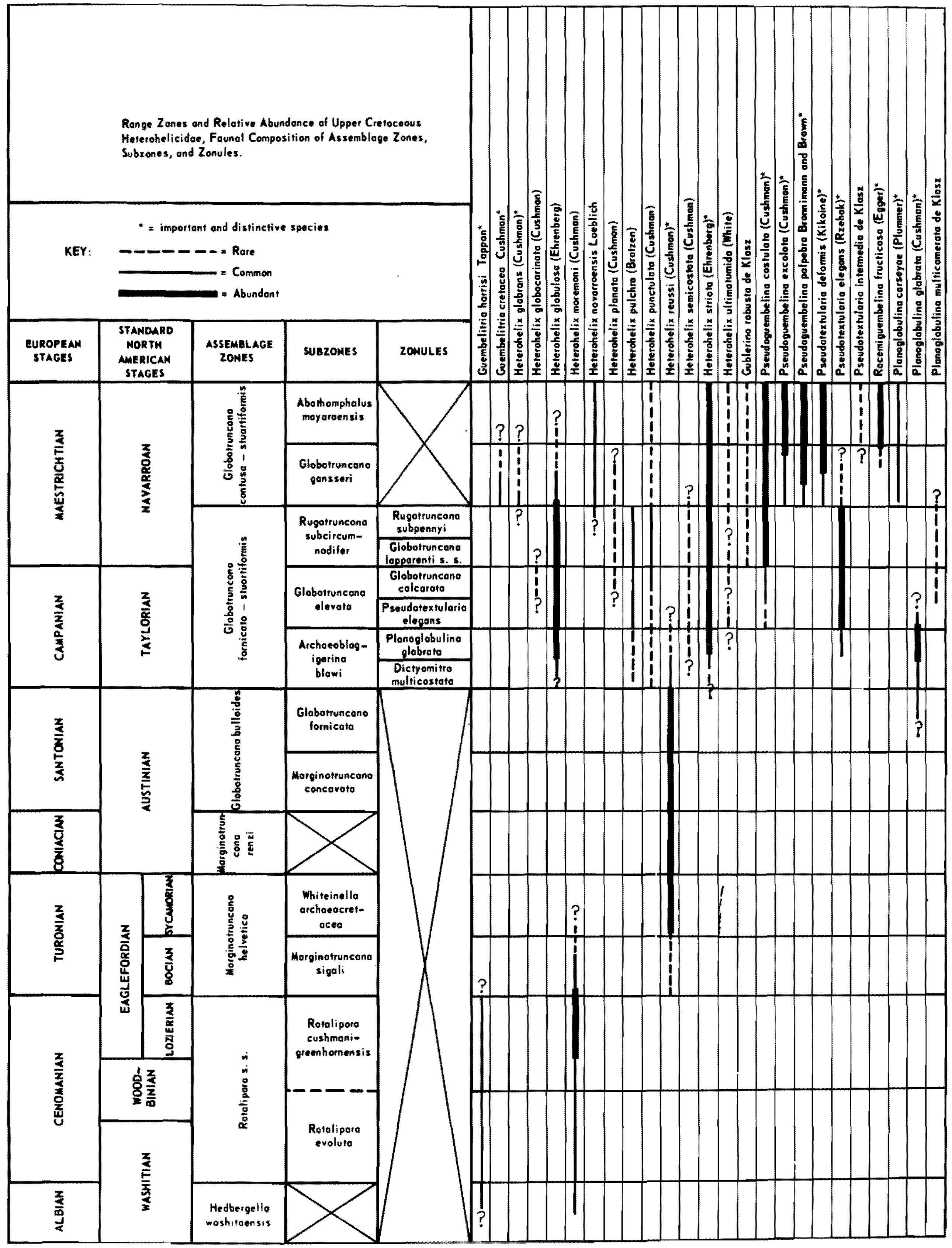

Figure 8A-3. Range Zones and Relative Abundance of Upper Cretaceous Heterohelicidae. Faunal Composition of Assemblage Zones, Subzones, and Zonules.

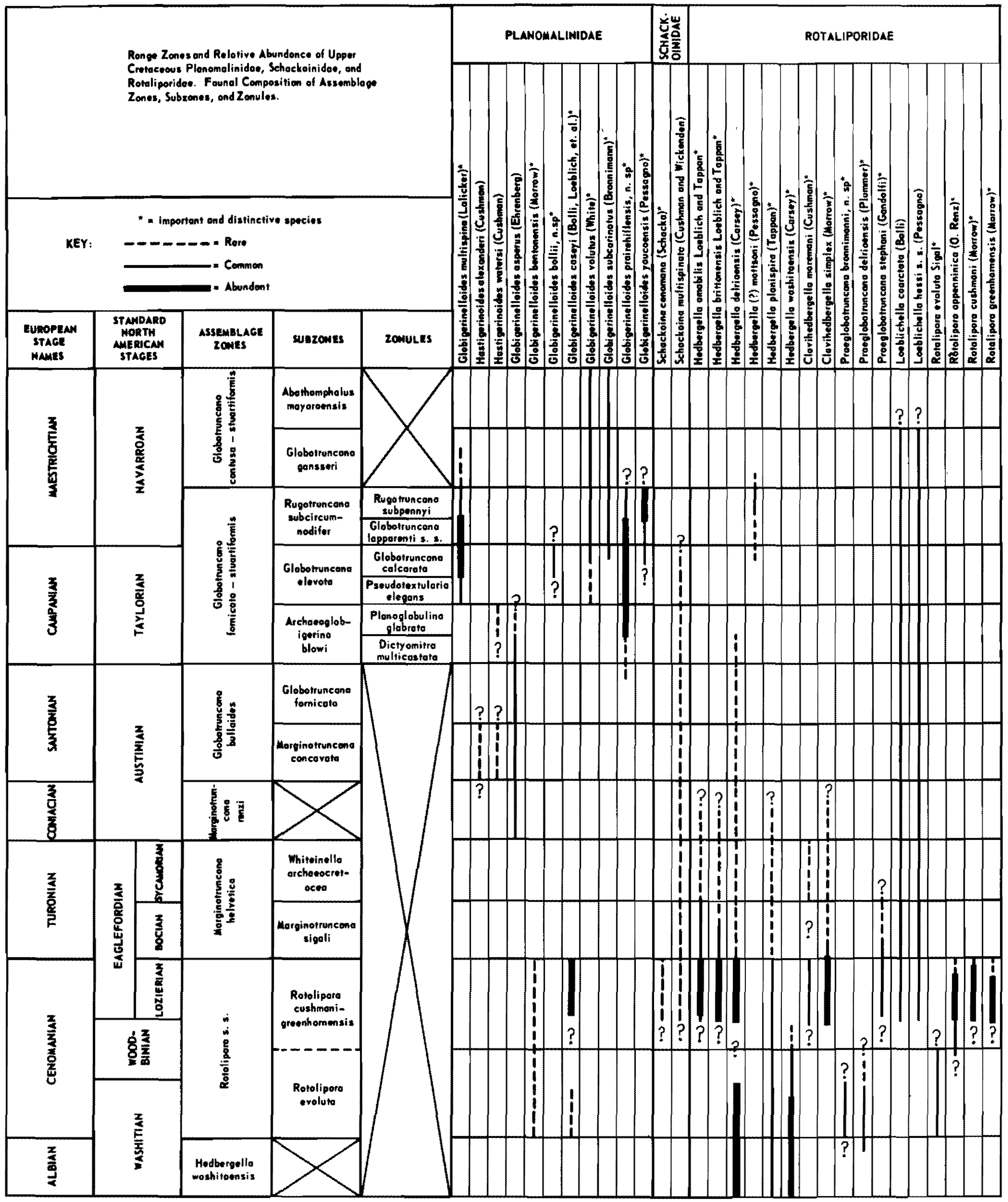

Figure 8A-4. Range Zones and Relative Abundance of Upper Cretaceous Planomalinidae, Schackoinidae, and Rotaliporidae. Faunal Composition of Assemblage Zones, Subzones, and Zonules.

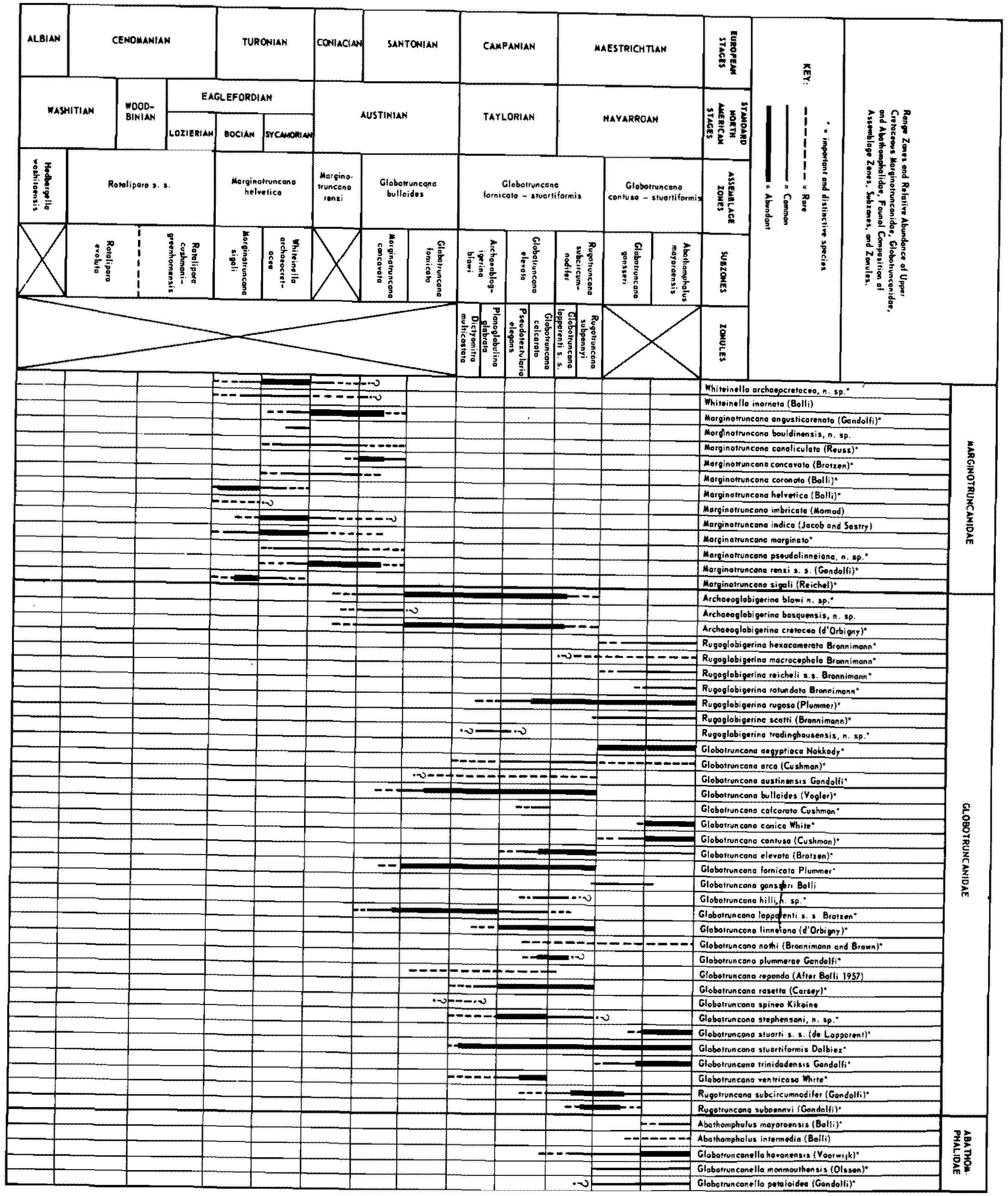

Figure 8A-5. Range Zones and Relative Abundance of Upper Cretaceous Marginotruncanidae, Globotruncanidae, and Abathomphalidae. Faunal Composition of Assemblage Zones, Subzones, and Zonules.

(1) *Radial hyaline:* Tests comprised of euhderal prisms of calcite oriented with their c-axes normal to the surface; usually comprising "calcite crusts" of the outer test wall (Bé and Ericson, 1963).

(2) *Micrograular hyaline:* Tests comprised of minute anhedral grains of calcite having uncertain crystallographic orientation; usually comprising lamellar portion of primary test walls and septa as well as portici, tegilla and apertural flaps.

(3) *Ultragranular hyaline:* Large, generally euhedral crystals of calcite oriented with their c-axes normal to the surface of the test. One or more isolated crystals of calcite usually comprising secondary structure such as coarse spines.

Pessagno (1968; see also Pessagno and Miyano, 1968) has studied the wall structure of planktonic foraminifera with (1) the transmission-electron microscope, (2) the scanning electron microscope, (3) dark field illumination and (4) phase contrast. The results obtained using these four independent methods of investigation are as follows:

(1) Upper Cretaceous Globigerinacea have primary test walls, septal walls, portici and tegilla which are microgranular hyaline in character. Some ornamental structures such as the rugosities and beads of the Globotruncanidae are ultragranular hyaline in character and are essentially plastered down on a microgranular hyaline base. Others, such as the costae of the Heterohelicidae, microgranular hyaline.

(2) Cenozoic planktonic foraminifera possess primary outer walls which are either entirely microgranular hyaline or both microgranular hyaline and radial hyaline (prismatic).

Work by Bé and Ericson (1963) at Lamont indicates that epipelagic (i.e. near surface) individuals of *Globorotalia truncatulinoides* (d'Orbigny) possess thin shell walls, whereas mesopelagic individuals (living at depths of 500 meters) develop thick "calcite crusts." The present investigations demonstrate that the thin-walled epipelagic tests are entirely micrograular hyaline in character. The thicker walled tests of mesopelagic individuals consist of an inner laminated, microgranular hyaline layer and an outer radial hyaline (prismatic) "calcite crust" (Figure 8B-2; Plate 8B-1, Figures 2 and 4).

The anhedral microgranules of calcite in the lamellar part of the test average about 0.5 microns in size and are far too small to isolate optically (Plate 8B-1, Figure 1). Their precise orientation can only be determined through electron diffraction and X-ray diffraction techniques. A composite picture of the orientation of such crystals optically can perhaps be obtained by examining planktonic foraminiferal wall structure with dark field illumination. With dark field illumination the microgranular laminated layer of mesopelagic specimens of *G. truncatulinoides* (d'Orbigny) appears opaque (see Plate 7, Figure 2 of Pessagno and Miyano, 1968) suggesting refraction of light as a result of the random orientation of the microgranules. The radial hyaline "calcite crust" on the other hand appears perfectly translucent, undoubtedly reflecting the preferred orientation of the euhedral prisms.

It is hypothesized that since Upper Cretaceous planktonic foraminifera possess microgranular hyaline primary test walls, it is quite conceivable that they were all epipelagic or surface dwellers. "Calcite crusts" seem to have first appeared among Early Tertiary (Late Paleocene?) foraminifera. It is possible that the large euhedral prisms of calcite comprising the "calcite crusts" of Cenozoic planktonic foraminifera may serve as a protective coating to mesopelagic individuals living in the bathypelagic zone at depths of about 500 meters. Conceivably, at such depths the solution of $CaCO_3$ would be more rapid due to increased pressure and decreased pH. Park (1966) indicates that a pH minimum (7.5 to 7.7) exists between 200 meters and 1200 meters in the northeastern Pacific. It is postulated that under such conditions larger crystals comprising the "calcite crust" might dissolve less readily than the minute granules of calcite comprising the microgranular hyaline part of the test. It is further postulated that severe ecological changes may have led the planktonic foraminifera to assume a mesopelagic as well as an epipelagic way of life during the Cenozoic.

Plate Description

Plate 8B-1: Description

1 *Globorotalia truncatulinoides* (d'Orbigny)
Electron micrograph of septal wall made from two-stage replica of horizontal section. Negative (reverse) print of portion of septum. Note microgranular character of test wall. x17,000.

2 *Globorotalia truncatulinoides* (d'Orbigny)
Electron micrograph of radial hyaline "calcite crust" of outer wall. Note euhedral prisms of calcite. Negative (reverse) print from two-stage replica of horizontal section. x3100.

3 Scanning electron micrograph of the test surface of *Hastigerina murrayi* Thomson. Note microgranular character of test. Some pores seem to be surrounded by rather high rims of microgranules. Other pores lack such rims. Node-like mounds of microgranules occur in interpore areas. Recent Atlantic Ocean. x3000.

4 Scanning electron micrograph of primary wall of *Globorotalia truncatulinoides* (d'Orbigny). Natural section. A = radial hyaline "calcite crust"; B = microgranular laminated layer. x2000.

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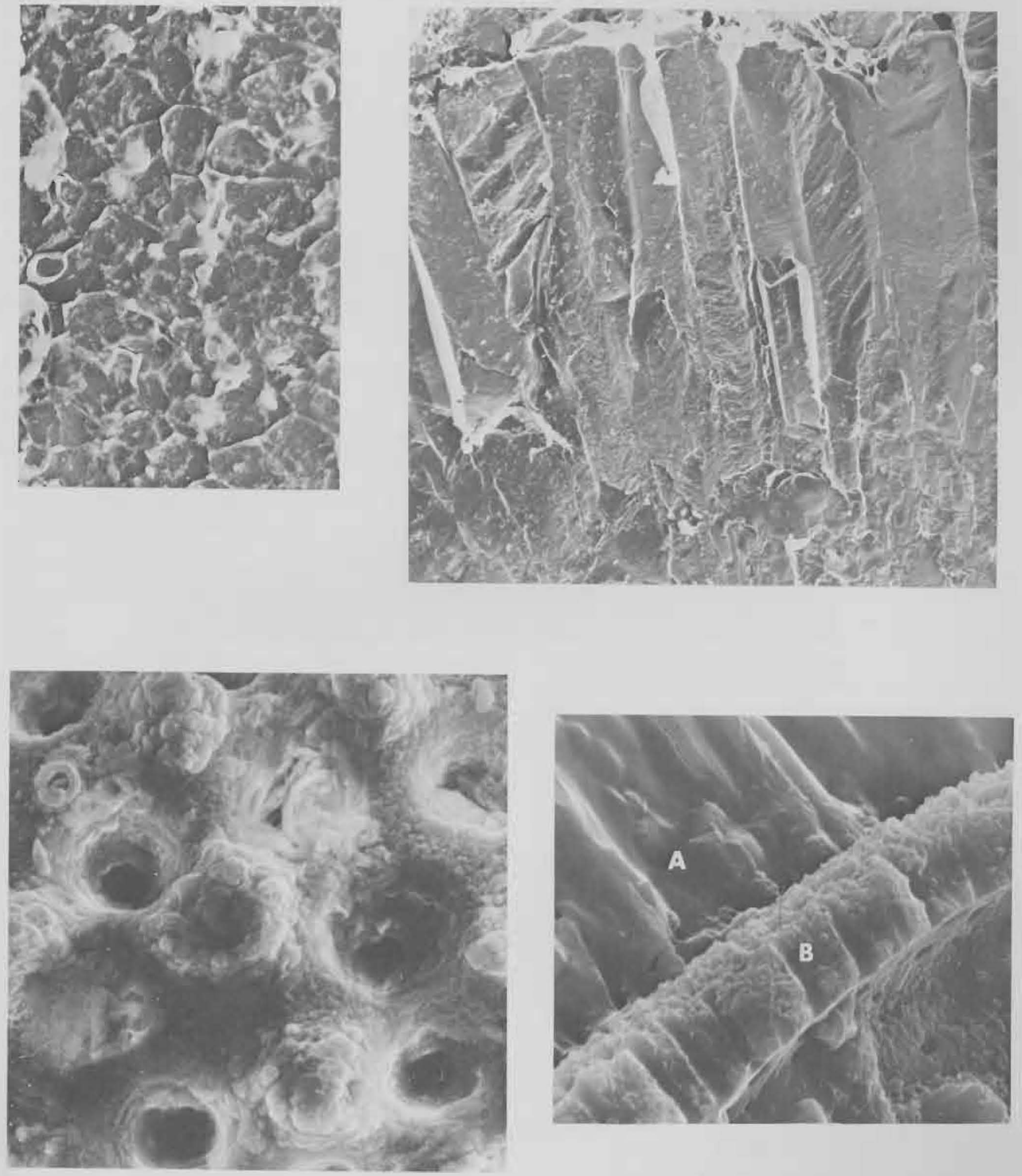

Plate 8B-1.

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C. Upper Cretaceous Radiolaria of the California Coast Ranges

Emile A. Pessagno, Jr.

Nearly 65 years ago Steinmann (1905) noted the association of serpentinites, spilitic lava and radiolarian chert in alpine "eugeosynclinal" strata. The radiolarian chert component of "Steinmann's trinity" is nearly as characteristic of "eugeosynclinal" rocks as the serpentinites and spilitic lava. "Eugeosynclinal" strata such as those of the Franciscan Complex of the California Coast Ranges are notorious for their paucity of marine invertebrates. Yet in California as elsewhere in the world, one group of invertebrate organisms with great stratigraphic potential, the radiolaria, has been sadly neglected. Because of their abundance, planktonic/cosmopolitan nature, and exceedingly great variety of form, the radiolaria should serve as a valuable biostratigraphic tool not only to the geologist attemption to disentangle the complex stratigraphy of orogenic belts, but also to the oceanographer attempting to determine the age of the oceanic crust (e.g. JOIDES Deep Sea Drilling program, JOIDES, 1967).

For several years Dr. Pessagno has been engaged in a study of the stratigraphic distribution, morphology and phylogeny of California Upper Cretaceous radiolaria. In the thick, relatively unfossiliferous, and often highly disturbed Upper Cretaceous sequence of the California Coast Ranges, radiolaria are the only invertebrate fossils that are consistently abundant. A large number of well preserved specimens have been extracted from limestone nodules, mudstones and radiolarites occurring in the Upper Cretaceous portion of the Great Valley Sequence. Nearly 1200 samples have been collected from measured sections of strata cropping out in the Coast Ranges from Contra Costa County (near Mt. Diablo) northward to Tehama County.

The results of this study thus far can be summarized as follows:

(1) A rich, diversified radiolarian assemblage containing well over 250 species, the majority of which are new, has been recovered from strata ranging in age from early Cenomanian to early Maestrichtian (dating based on associated planktonic foraminifera and mollusca). At a given horizon, such as the Upper Campanian, the radiolarian assemblage shows far greater diversity than either the planktonic foraminiferal or molluscan assemblages. For example, whereas more than seven species of planktonic foraminifera seldom occur in late Campanian strata at this latitude, it is not unusual to find more than 70 species of radiolaria at the same horizon.

(2) The California radiolarian assemblage underwent a rapid evolution during the course of Late Cretaceous time. Many species are short ranging and highly distinctive (see Plate 8C-1), often being restricted to a single stage or parts of a single stage.

(3) The rapid evolution displayed by radiolaria at the specific, generic and family levels indicates that they can be used to subdivide the Upper Cretaceous portion of the Great Valley Sequence into at least ten basic zonal units. This system of zonation can be readily integrated with those based on tried zone fossils such as the planktonic foraminifera, ammonites, and Inoceramids. When a system of radiolarian zonation has been established for the less structurally complex Great Valley Sequence in the eastern portion of the California Coast Ranges, it is likely that it can be utilized to work out the stratigraphic succession of the highly complicated Franciscan Complex to the west. In fact, some Franciscan red cherts which were chemically disentegrated during the course of this project have yielded Upper Cretaceous radiolaria whose range zones have been established through this study of the Great Valley Sequence.

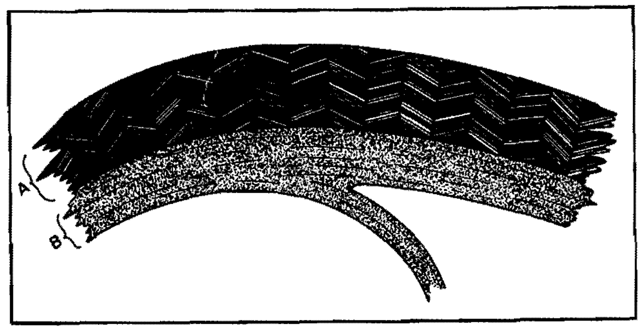

Figure 8B-2. Schematic diagram showing the structure of the outer wall of a mesopelagic specimen of Globorotalia s.s. as seen in horizontal section. (A) radial hyaline "calcite crust" composed of euhedral calcite prisms oriented with their C-axes normal to the test surface; (B) microgranular hyaline laminated inner portion of outer wall.

Plate 8C-1: Description

All figures are scanning electron micrographs of Upper Cretaceous radiolarians from the Coast Ranges of northern California.

1 Distinctive bean-shaped Spongodiscid. Late Campanian to early Maestrichtian age. Marker equals 50 microns.

2 Aberrant Nasselline from strata of early Cenomanian age. Marker equals 50 microns.

3 Three raged Spongodiscid restricted to strata of Cenomanian and early Turonian age. (3) Marker equals 50 microns. (6) Marker equals 25 microns.

4 Cenomanian Nasselline of the *Sciadiocapsa* family group. Marker equals 50 microns.

5 Late Campanian Nasselline of the *Sciadiocapsa* family group. Marker equals 100 microns.

7 Early Maestrichtian Nasselline of the *Sciadiocapsa* family group. Marker equals 25 microns.

8 Early Maestrichtian Nasselline of the *Sciadiocapsa* family group. Marker equals 25 microns.

9 Spongodiscid restricted to strata of Turonian and Coniacian age. Central portion of test depressed; quite thin, showing spiral arrangement of meshwork in transmitted light. Marker equals 50 microns.

10 Cenomanian Nasselline of the *Sciadiocapsa* family group. Marker equals 25 microns.

11 Coniacian Spongodiscid; perhaps related to *Hagiastrum* Haeckel. Marker equals 25 microns.

12 Distinctive Cenomanian Nasselline of the *Sciadiocapsa* family group. Marker equals 50 microns.

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9. PALYNOLOGY

Palynologic Studies of the Devonian

James B. Urban

Palynologic studies have been conducted on Devonian fossils recovered from the Calloway Formation of Missouri, the Woodford Formation of Oklahoma and strata from Iowa that have been identified as belonging in the Cedar Valley Formation.

(1) Palynology of the Cedar Valley Formation

Five localities in the supposed Cedar Valley Formation of Iowa have been sampled and all have palynologic fossils present. Ten samples taken as segments of a complete channel of the rocks exposed in Pavlovec's Spillville Quarry, SE 1/4 Sec. 20, T. 97N, R. 9W, Winneshiek County, Iowa, have been the primary object for study to date. Spores, chitinozoans, acritarchs, and scolecodonts are present in the section. Relative percentages of the four groups are shown in Figure 9-1. Samples A through E were taken from the "*Productella* zone;" F through I were taken in the "Rhombohedral calcite zone;" and sample J was taken from the marl at the top of the section (Tri-State Guidebook, 1966, p. 18).

Samples A through E are indicative of a near shore, lagoonal environment, and open circulation marine is indicated in the remainder of the section.

The spore assemblage of the studied section consists of 28 genera and 40 species; 7 genera and 21 species are considered to be new. A complete assemblage list follows the text. Comparison with previously reported assemblages from Canada (McGregor, 1960) and the Old Red Sandstone of England (Richardson, 1960, 1962, 1965) indicates an age assignment of Upper Eifelian or Lower Givetian. This age assignment differs from previous determinations made on the basis of invertebrate fossils which usually place the Cedar Valley in the Upper Givetian or Lower Frasnian. A Frasnian age assignment has been made for supposed Solon member rocks by N. Norton (personal communication). The Solon member designation of the section used in this study was according to the Iowa Geological Survey usage; however, D. Koch (personal communication) reports some workers favor placing the section in the Wapsipinicon Formation.

Two sections each of the Rapid and Coralville members have fossils indicating a close similarity to the Calloway Formation of Missouri and an age assignment of Upper Givetian or Lower Frasnian.

The aforementioned differences necessitate a study of material from the Cedar Valley and Wapsipinicon Formation type sections in order to determine meaningful stratigraphic information.

Assemblage List:

Acanthotriletes multisetus (Naumova) Potonie and Kremp, 1954
Acanthotriletes sp. a new species
Ancyrospora ancyrea (Eisenack) Richardson, 1962
Ancyrospora cf. grandispinosa Richardson, 1960
Apiculatisporis elegans McGregor, 1960
Acinosporites sp. a new species
Acinosporites sp. b new species
Archaeozonotriletes sp. a new species
Biharisporites sp. a new species
Calyptosporites proteus (Naumova) Allen, 1965
Diaphanosporites sp. a new species
Diatomozonotriletes sp. a new species

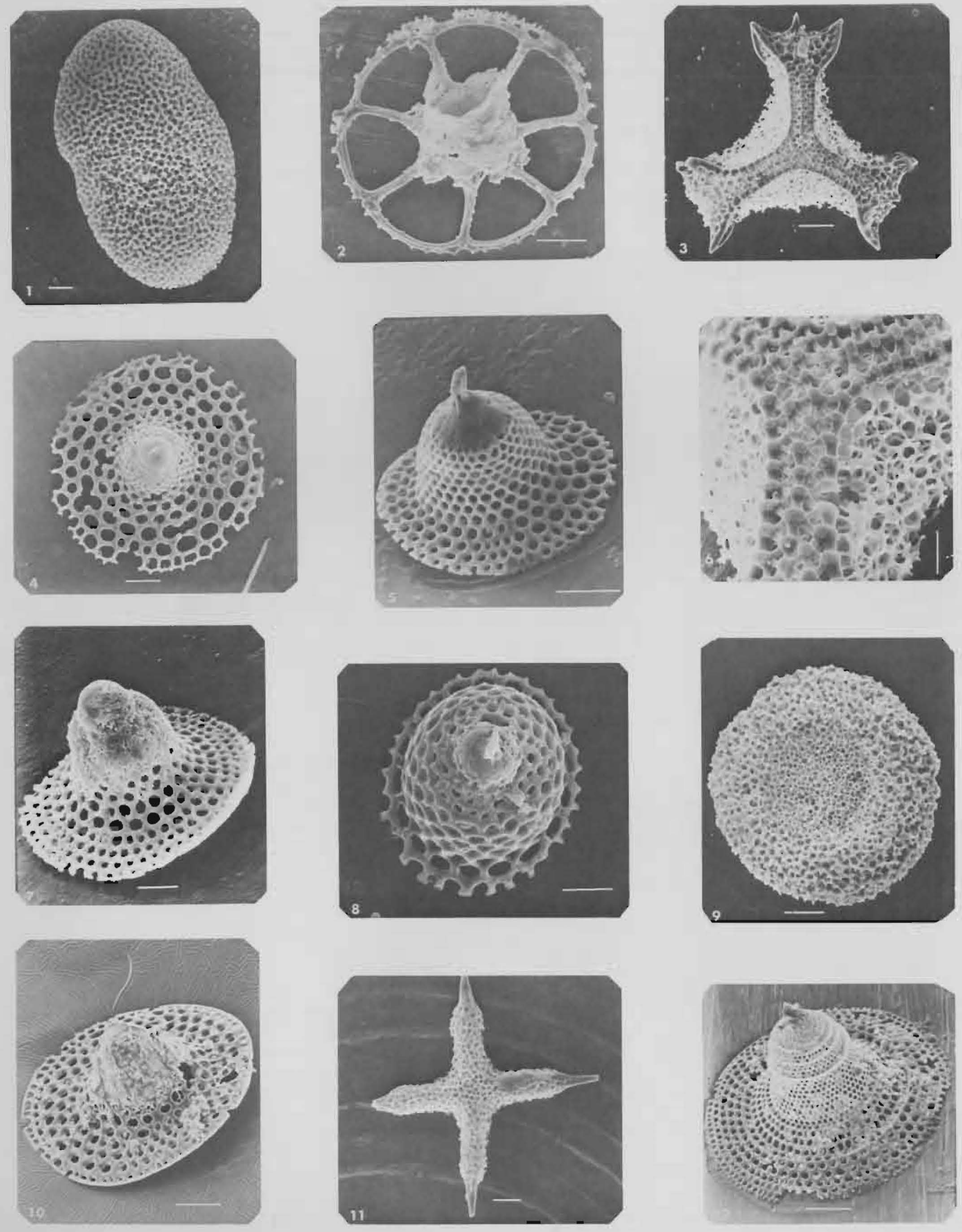

Plate 8C-1.

Dibolisporites sp. a new species
Dibrochosporites nodosus Urban, 1968
Emphanisporites sp. a new species
Emphanisporites rotatus McGregor, 1960
Geminospora sp. a new species
Geminospora svalbardiae (Vigran) Allen, 1965
Granulatisporites muninensis Allen, 1965
Leiotriletes dissimalis McGregor, 1960
Leiotriletes marginalis McGregor, 1960
Leiotriletes microdeltoides McGregor, 1960
Leiotriletes sp. a new species
Planisporites delucidus McGregor, 1960
Rhabdosporites sp. a new species
cf *Raistrichia sp. a* new species
Retusotriletes dubius (Eisenack) Richardson, 1965
Retusotriletes distinctus Richardson, 1965
Retusotriletes laevigatus Guennel, 1963
Retusotriletes sp. a new species
Tholisporites sp. a new species
Verrucosisporites uncatus (Naumova) Richardson, 1965

Plus seven new genera each with a single species

(2) A Study of the Morphology of the Spore Genus *Ancyrospora* Richardson

Specimens referable to the spore genus *Ancyrospora* Richardson were encountered during palynologic studies of the Cedar Valley Formation of Iowa and the Calloway Formation of Missouri. Examination of specimens with the scanning electron microscope reveals differences in morphology not reported to date. Further, the differences in morphology have a relationship to stratigraphic and geographic differences. Forms referrable to *A. grandispinosa* Richardson, 1960, and *A. ancyrea* (Eisenack) Richardson, 1962, have been noted only from the lower 40 feet of the Solon member of the Cedar Valley Formation. The associated assemblage indicates an age assignment of Upper Eifelian or Lower Givetian. *Ancyrospora simplex* Guennel, 1963, has been recovered from the Calloway Formation. The associated assemblage appears to be correlative to the Middle Frasnian, Albertensis Zone of Canada.

(3) Chitinozoa of the Calloway Formation (Devonian) of Missouri

Palynologic fossils have been recovered from six sections of the Calloway Formation in north-central Missouri. One section exposed in a quarry (four miles north of Williamsburg, Missouri, SW 1/4 Sec. 9, T.48N, R.7W) has yielded a diverse chitinozoan assemblage consisting of four genera and eight species. One interesting aspect of distribution is the restriction of the chitinozoans to a single interval four feet thick in 35 feet of section. All samples have spores present, but spore species diversity is greatest in the interval containing the Chitinozoa.

Morphologic studies with the scanning electron microscope have shown Chitinozoa to have one to three wall layers. The variation in number of layers appears to be related to other morphologic variations of taxonomic importance.

Plate 9-1: Description

All figures are scanning electron micrographs except 17 which is a transmitted light photograph. All specimens were photographed at magnifications twice the given figure and subsequently reduced by half.

1 Proximal side of *Ancyrospora* cf *ancyrea* (Eisenack) Richardson, 1962. x250.

2 Distal side of (1). x250.

3 Section broken along the flange. The inner exoexine is shown consisting of an inner solid layer changing outward to a net-like part, thin on the distal but built up in successive concentric layers along the equator to form the flange. The homogeneous outer exoexine is present on the distal and flange surfaces. x1100.

4 Spines of *Ancyrospora simplex* Guennel, 1963, with anastomosing bases and multifucate tips. x1500.

5 Equatorial view of a specimen of *Ancyrospora simplex* Guennel, 1963. Note prominent triradiate ridges. x250.

6 *Ancyrochitina sp. a.* x250.

7 *Ancyrochitina sp. b.* Note operculum. x300.

8 Operculum of (7). x800.

9 Section of a wall of *Angochitina sp.* showing a single homogeneous layer. x2500.

10 Section of a wall of *Ancyrochitina sp.* showing three layers present. x5000.

11 *Acinosporites sp. a* (new species). Proximal view. x250.

12 Distal ornamentation of 11. x1500.

13 *Ancyrochitina sp.* x250.

14 Spines on the neck of (13). x2250.

15 *Ancyrochitina cf. spinosa* Eisenack. x250.

16 *Genus A sp a.* Gen. et sp. nov. x250.

17 Transmitted light photomicrograph of (16). Note trilete structure developed on the under side of the proximal side. x250.

18 *Geminospora svalbardiae* (Vigran) Allen, 1965. x250.

19 *Leiotriletes microdeltoides* McGregor, 1960. x250.

20 *Calyptosporites proteus* (Naumova) Allen, 1965. Distal view. x250.

21 *Emphanisporites rotatus* McGregor, 1960. Proximal view. x250.

22 *Acinosporites sp.* Proximal view. x250.

23 *Genus B sp. a.* Gen. et sp. nov. Proximal view. x250.

24 *Genus B sp. b.* Gen. et sp. nov. Proximal view. x250.

25 Double wall layer and ornament of (26). x5000.

26 *Dibrochosporites nodosus* Urban, 1968. Proximal view. x250.

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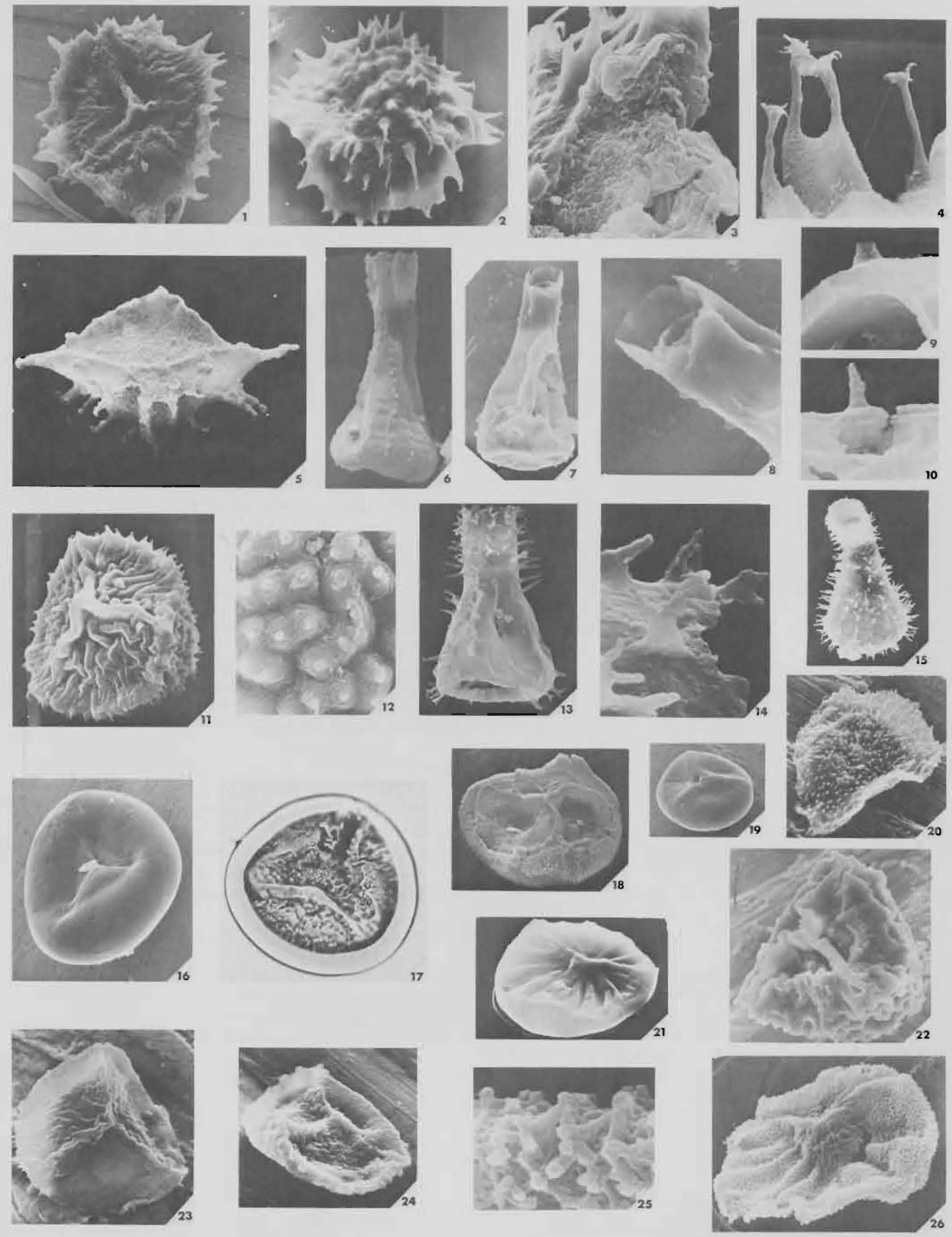

Plate 9-1.

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