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Background Paper - C.1

PIGGY-BACKING ON THE McCLURE *et al* SPARKS #1 DEEP TEST

GRATIOT COUNTY, MICHIGAN

L. L. Sloss

The following paper (starting on page C.1.3) is a preprint of the introduction to a forthcoming issue of JGR devoted to the scientific results obtained from a deep borehole in the Michigan Basin. Workshop participants may be interested in a narrative review of events and actions that led to participation by academic scientists in data gathering and experimentation in the borehole.

In the late spring of 1975 William Hinze, consultant to and friend of Harold McClure, Michigan oil operator, informed Sloss (as reporter on plate interiors to USGC) that a deep wildcat near the center of the Michigan Basin had penetrated Precambrian sediments and was approaching contract depth. Hinze raised the question of bottom-hole money to permit coring and testing for scientific purposes. After discussions with the operators (McClure, Amoco, and Shell) Shoemaker and Sloss met with ERDA and NSF administrators in mid-June to urge fast funding action to take advantage of the opportunities offered.

A key issue was: Could adequate funding be obtained for the proposed piggy-backing prior to the completion of the commercial operators' objectives and removal of the rig? The available time window was a matter of days or weeks. Initially, the time constraints seemed too severe, but it emerged on July 25 that NSF might be able to provide funding if a proposal could be submitted by August 1. This coincided with an easing of the operators' time constraints. At this point, as the well was nearing 15,000' (about a thousand feet into presumed Precambrian sediments), the operators changed their objective to 18,000' or basement, set 7 5/8" pipe at 15,080', and proceeded with drilling. Total depth was anticipated to be reached within the month of October.

After some tens of telephone hours, Sloss and Sleep determined that the major investigative expense would involve stress measures; in recognition of this Haimson (University of Wisconsin) was identified as P.I. and a proposal draft (20pp + budget matter) was forwarded to Madison on July 30 to be processed in record time and sent to Washington on August 8, or about one week after John Lance took over the NSF Geology Program from Dick Ray. Drilling continued at about 50'/day while seemingly intractable problems in the piggy-backing proposal emerged. Paramount among these was the question of responsibility for the rig, which was already drilling beyond its rated depth capacity, and for thousands of feet of drill pipe, casing, and liner after operations were taken over by NSF and the University of Wisconsin -- perhaps $1 million in all.

Proving that one person's dark cloud is another's silver lining, a twist-off and prolonged fishing job further postponed achievement of the industrial objectives. During this period, the grant (in amount of $250,300) was finalized on October 22, no more than ten weeks after primary submittal. The grant, very large by NSF Geology/Geophysics standards, is small in terms of the investment by industry at the point of turnover; yet the products gained are beyond price and demonstrate unequivocally the value of piggy-backing for scientific purposes.

It is important, however, that the Michigan experience does not become a model for future efforts. Such success as was realized depended on the concatenation of a nonreproducible set of circumstances: 1) close communication with the operators via Bill Hinze; 2) cooperative and concerned operators (Harold McClure and Amoco); 3) NSF personnel (Bert Carey, Bill Benson, Dick Ray, John Lance et al.) willing and able to rise above and beyond, especially to achieve fast action for a worthy cause; 4) Principal Investigators (Haimson and Wang) who rose to the occasion with vigor and skill; 5) a university research administration (Wisconsin) prepared to move with dispatch; 6) underemployed geologists and geophysicists (Sloss and Sleep) with nother better to occupy their time; and, not least, 7) an interruption of industrial effort (twist-off) to provide absolutely essential time without which the rig would have been stacked and moved for gainful employment elsewhere.

MORAL # 1 -- Lead time for future piggy-back efforts should not be less than a year.

MORAL # 2 -- Methods must be developed within granting agencies whereby very large risks, commonly self-insured by industry, can be covered when scientists take over drilling, coring, logging, and experimentation in boreholes.

A DEEP BOREHOLE IN THE MICHIGAN BASIN

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ABSTRACT

Heat flow, _in situ_ stress, _in situ_ S-wave and P-wave velocities, and _in situ_ density from borehole gravity were successfully measured in a 5.3 km deep borehole in the Michigan basin. Precambrian (?) redbeds and two altered basic igneous bodies were encountered beneath the known Cambrian succession of the basin. Petrological and paleomagnetic studies were undertaken on oriented samples obtained from the igneous body at the base of the hole and on other samples. The igneous body appears to have undergone greenschist metamorphism, probably about 600 - 800 m.y. ago. The redbeds are correlated with the Keweenawan "series" of northern Michigan on the basis of paleomagnetism and lithology. No evidence was found of a post-Cambrian heating event which might be expected if thermal contraction had caused basin subsidence in a manner analogous to the subsidence of the mid-oceanic ridges.

INTRODUCTION

The Michigan basin (fig. 1 and fig. 2) is a well-documented interior basin that has subsided at varying rates for 500 m.y., accumulating about 4 km of Phanerozoic sediments at its center. The basin has been under active exploration for oil, gas, salt, and brines for the last 40 years and all but the lower portion of the stratigraphic succession is thoroughly drilled and known to be relatively undisturbed by later events. Post-Early Ordovician units generally tend to be thickest at the center of the basin (near or west of Saginaw Bay) where they exhibit deeper-water facies. Early Ordovician and Cambrian units show thickening within the basin and are in part continuous with similar age units to the south (Catacosinos, 1973).

The basin is crossed by a northwest striking strongly positive gravity anomaly. By analogy to the Midcontinent Gravity High and by tracing of the anomaly into outcrop areas near Lake Superior, this anomaly has been generally attributed to a rift system filled with dense Keweenawan age (ca. 1100 m.y.) rocks (Hinze _et al_., 1975). The borehole described in this volume provided the first large scale sampling of this feature in the subsurface. Limited sampling and analogy to southern Wisconsin, northern Illinois, and northern Indiana indicates that the basement away from the rift valley is composed of granitic and metamorphic rocks of about 1200 to 1500 m.y. age (Hinze _et al_., 1975; Van Schmus, 1976). The Grenville front, which is the northern boundary of a region of 1100 m.y. old tectonism, is probably 100 to 200 km southeast of the borehole (Baer, 1976). Alkaline igneous activity and faulting occurred in the North Bay region of Ontario and eastward in early Cambrian time (565 m.y., Doig, 1970).

HISTORY OF PROJECT

A deep hole was drilled in the Michigan basin by the Shell, Amoco, and McClure petroleum companies (fig. 1). At 3715 m depth the hole penetrated below the known Cambrian formations and into a section of firmly lithified red mudstones with interbeds of arkosic sandstone. Metabasic rocks* were encountered at 4790 m depths and between 5250 m depths and the bottom of the hole at 5324 m depth. An oriented, 17 m long core was obtained from the bottom of the hole. Experiments conducted within the borehole and on recovered samples are described in this issue of JGR.

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* Called metabasite herein so as not to imply either instrusive or extrusive origin.

The mid-continent members of the Plate Interiors group of the U.S. Geodynamics Project were alerted to the possibility of "piggy backing" scientific experiments onto the drilling operation in the late spring of 1975 when an early autumn completion of the well was projected. Once the National Science Foundation had given preliminary approval to organize a proposal for scientific studies, numerous scientists with potential interest in the project were contacted. A proposal involving several investigators from different universities, service companies, and the operators of the well was organized and submitted to the National Science Foundation by Bezalel C. Haimson and Herbert F. Wang of the University of Wisconsin who agreed to act as principal investigators and coordinators of the project. Many officials of the National Science Foundation and the University of Wisconsin assisted in handling the proposal more rapidly than is usual. Because of the limited time available it was necessary to use only those techniques which were operational at the time of the planning and to eschew any development of technology for the project.

The scientific investigations conducted in this project can be conveniently grouped as follows:

(1) determination of the age, origin, and thermal and tectonic history of the Precambrian (?) rocks recovered from the hole;

(2) measurement of geophysical parameters including heat flow and stress which may be perturbed by near-surface effects in shallow experiments;

(3) measurement of the <u>in situ</u> properties of the rocks at depth for use in the above items and for evaluatin g theories on the origin of mid-continental basins in general and the Michigan basin in particular.

ROCK SAMPLES

In addition to the well cuttings the operating companies obtained an oriented core from the bottom 17 m of the hole in metabasite and three sections of unoriented core from the overlying redbeds. No core includes the top boundary of either igneous body encountered in the hole.

The chemical and mineralogical composition of the samples provides constraints on possible thermal events and constitutes a natural petrological experiment, as the Michigan basin has been stable for the last 300 m.y. The current bottom hole temperature of 125°C (Brewster and Pollack, 1976) has probably affected the lower metabasite during that inverval.

Attempts to determine the ages of emplacement and metamorphism of the igneous rocks using radiometric methods were largely unsuccessful (Van Schmus, this volume). Well constrained paleomagnetic poles, however, were obtained from the redbeds and the lower metabasite. Comparison with established polar wandering curves indicates that the redbeds acquired their remanent magnetism during late Keweenawan time. The paleomagnetic pole of the lower metabasite corresponds to that of latest Precambrian to Cambrian time (500-800 m.y., van der Voo and Watts, this volume). An extensive metamorphic event must have affected the rock if the lower metabasite is Keweenawan extrusive or shallow intrusive.

Except for clinopyroxenes and opaques the original minerals have been extensively altered to greenschist facies. Honnorez, McCallister et al., and Stakes, (all in this volume) have performed whole-rock and mineral chemical and x-ray analyses, and petrography on the samples. More than one generation of secondary minerals and of vein minerals appears to exist. Smectites, which are common in oceanic metabasites and are produced in experimental alteration of basalt by seawater, are absent.

The metamorphic mineral assemblage of the lower metabasite is believed to have formed at temperatures significatnly hotter (up to 400°C) than the present 125°C.

A general lack of retrograde metamorphism is exhibited in the metabasite samples even though there has been much time for such reactions to occur. The pore water in the Michigan rocks was probably more reducing than the water at mid-oceanic ridges so that alteration of chlorite to vermiculite did not occur (Stakes, this volume). The access of fluids into the metabasite after metamorphism may have been highly restricted, as open natural cracks are absent and appear to have healed or been filled with vein deposits (Wang and Simmons, this volume).

Fowler and Kuenzi (this volume) have investigated the core and geophysical logs obtained from the redbeds. The entire 1538 m thick sequence consists of undeformed recurring beds of arkosic sandstone that grade upward into laminated and cross-laminated mudstone units that display micro-grading, fluid escape structures, and soft sediment deformation and compaction structures. These features are compatible with deposition by turbidity currents and associated processes, and have been interpreted by Fowler and Kuenzi (this volume) to record submarine fan deposition in an elongate, broadly-subsiding protoceanic basin which foundered following arrestment of Keweenawan rifting.

Additional work on the samples obtained is likely to provide further interpretation of the history of these older rocks. The most must be made out of these samples, as the Precambrian (?) rocks encountered in the well do not appear to encourage additional petroleum exploration. It is conceivable that there may be further drilling in other fault-bounded deep basins, some of which can be located with publicly available gravity and magnetic data (Hinze and Merritt, 1969). The deep subsurface of Michigan is also a possible site for deep waste disposal and low temperature geothermal heat. Much can be done to integrate the publicly available data on the Phanerozoic formations into a form useful for tectonic studies.

GEOPHYSICAL MEASUREMENTS

Near-surface conditions often interfere with geophysical measurements intended to determine the properties of the interior of the earth. Additional information thus may be gained by making measurements in deep boreholes (Shoemaker, 1975). As part of the Michigan well experiment in situ stress and temperature were measured at various depths in the well.

The temperature measurements were converted to heat flow values using conductivities measured from samples (Brewster and Pollack, 1976). The heat flow in the lower part of the hole is about 20% higher than the heat flow in the upper part, probably due to warming of the surface following the last glaciation. This difference can be safely applied to existing heat flow measurements in the area of the well for comparison with non-glaciated parts of the world.

Hydrofracture experiments to determine in situ stress were attempted at several depths in the hole (Haimson, this volume). No directions of principal stress were obtained because of equipment malfunctions on the experiments in the lower uncased portion of the hole. The principal extensile stress appears to be less than the lithostatic stress except in the shallowest measurement (1230 m). Flow in salt beds beneath the location of this measurement may have relieved any normal stress greatly different from the lithostatic pressure in the upoer beds through geologic time.

Hydrofracture in hard rocks at the depth of this well (5 km) will be necessary in the development of "hot dry" geothermal systems. The general difficulties encountered with equipment indicate a need for technical improvements.

MECHANISM OF SUBSIDENCE

Several mechanisms have been suggested for the subsidence of interior basins.

(1) Thermal contraction of the lithosphere following an initial heating event analogous to the subsidence of mid-ocean ridges (Sleep, 1971; Sleep and Snell, 1976; Haxby et al., 1976). A decrease of the buoyancy of the lithosphere either by subaerial erosion during uplift of the hot expanded lithosphere or by subsurface processes are needed to cause a net amount of subsidence. For the Michigan basin two heating and subsidence events are required (fig. 3).

(2) Loading by dense intrusions into the lower crust (McGinnis, 1970).

(3) Migration of melt in the uppermost asthenosphere (Scheidegger and O'Keefe, 1967; Sloss and Speed, 1974).

The subsidence in all these mechanisms is redistributed by flexure of the lithosphere (above references and Watts and Ryan, 1976).

The sedimentary succession in the Michigan basin can be divided into several sequences separated by unconformities of at least continent-wide extent (Sloss, 1963; Sloss and Speed, 1974). With the thermal contraction mechanism, these interruptions of sedimentation are attributed to world-wide eustatic sea-level changes. If the other mechanisms prevail each sequence is considered to have a distinct driving event.

The Michigan basin is nearly in isostatic equilibrium and presumably was in equilibrium, like the rest of the continental interior, before the initiation of basin formation. Thus, for subsidence to occur, a net load must have been added to the lithosphere or its immediate substratum. The load of sediments would enlarge any depression once initiated,

$$S = S_o \rho_m / (\rho_m - \rho_s) \qquad /1/$$

where S is the amount of sediment depositied, S_o is the amount of subsidence that would occur in the absence of sedimentation, and ρ_m and ρ_s are the densities of the mantle and sediments. In situ gravity measurements in the Michigan borehole indicate that the average density of Phanerozoic sediments is 2.61 gm/cc (Hinze et al., this volume). The densities obtained for various formations in that study can be used to see how much of the variability of the subsidence pattern at different times is due to variations in density of sediments. For example, preferential accumulation of a low-density sediment such as salt in one part of the basin would tend to reduce the total accumulation of sediments in that part of the basin.

The records obtained for the Michigan borehole and by previous drilling are notable in exhibiting no evidence for post-Cambrian metamorphism or igneous activity. Support of the thermal-contraction and igneous-loading theories of Phanerozoic basin formation was thus not obtained. A simple relationship of the subsidence of the basin to the mid-Michigan gravity high as proposed by Hinze and Merritt (1969) seems less likely now that the age of the rift system is determined to be Keweenawan (van der Voo, this volume) about 600 m.y. before the most rapid Phanerozoic subsidence. Note that Hinze et al. (1972) explain this time lag by having the hot material which upwelled to form the rift different in composition from average mantle. The change to a more dense state can thus be slower than ordinary thermal contraction and triggered by later minor heating events.

The higher heat flow during the heating event would imply higher temperatures at depth which might produce noticeable metamorphic and paleomagnetic effects. A heat flow during the mid-Ordovician greater by a factor of two than present would have been necessary to resolve a separate heating event in the hole because the depth to the base of the Middle Ordovician (2658 m) is about half total depth (5324 m). Calculations by Haxby et al. (1976), predict that detection of an Ordovician heating event is at best marginal.

Eocambrian or Cambrian metamorphic activity is indicated by the paleomagnetic study of the lower metabasite (van der Voo and Watts, this volume). The heat could be related to Cambrian and Early Ordovician subsidence but not to later subsidence. If significant subaerial erosion of a thermally-induced uplift accompanied the Cambrian (?) heating, the depth and hence the temperature of the rocks at the base of the Michigan borehole could have been greater in the Cambrian than in the postulated pre-Middle Ordovician event.

AFTERTHOUGHTS

The Michigan experiment is a highly successful example of what can be achieved by close cooperation between industry and the academic community with the support of federal funding. An expenditure of about 7% of the cost of drilling and maintaining the hole has produced data that could not otherwise be obtained and furnished experience with the technical and organizational aspects of such projects. Advance funding and selection of holes as they become available would permit development of in-hole technology and collection of additional samples.

Some of the experiments in the Michigan borehole might prove useful in holes drilled on the sea-floor, although at a cost far above that of the Michigan project. In particular borehole gravity data would be very useful in interpreting marine gravity data and for determining the average porosity of oceanic sediments and crust. Hydraulic fracturing measurements which proved useful for measuring stress at the plate boundary in Iceland (Haimson, 1977) would be useful toward determining intro-plate stresses in the ocean, and in understanding seismic processes at submerged plate boundaries.

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Appendix: Well Description

Permit number - 29739

Gratiot County, Section 10 of TION-R2W (North Star Township)
McClure Oil Company, Sparks *et al.*, #1-8, total depth 17466 feet (16,704 feet below sea level), completed 1975.

General Michigan Literature:

1. A list of wells to the Precambrian in lower Michigan is given on page 62 of *Annual Statistical Summary 24, Michigan's Oil and Gas Fields*. This publication as well as other literature can be obtained from Publications Room, Dept. of Natural Resources, Box 30028, Lansing, Michigan 48909. This department also maintains an open file of drillers logs.

2. The annual field trip guides of the Michigan Basin Geological Society include useful descriptive papers on subsurface and surface geology of the Michigan region.

3. A general level text on Michigan geology has been written by Dorr and Eschman (1970).

4. The gravity and magnetic maps of Michigan are reproduced in Hinze *et al.* (this vol.).

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FIGURE CAPTIONS

Fig. 1. The site of the deep borehole discussed in this volume shown on a preglacial subcrop map of the Michigan basin, after Stonehouse (1969). Note the progressive outcrop of older beds away from the basin center. (By permission of the Michigan Basin Geological Society).

Fig. 2. Structural contours, in kilo feet, on the Precambrian basement surface in Michigan, after Hinze and Merritt (1969). Note the gradual increase in depth to basement toward the center of the basin. The deep borehole discussed in this volume is indicated by a triangle. The boreholes on Beaver Island discussed by Fowler and Kuenzi (this volume) are indicated by circles. (By permission of the Michigan Basin Geological Society).

Fig. 3. The depths of strata in the deep Michigan borehole plotted as a function of absolute age. Time intervals missing due to non-deposition or to erosion are indicated by dashed lines. Theoretical 50 m.y. exponentials, expected if subsidence is due to thermal contraction of the lithosphere, are fit to the present surface and to the bases of the Cambrian and Middle Ordovician sections (solid curves). One thermal event followed by cooling cannot explain the observed subsidence. The time scale is modified after the 50 m.y. time scale of Lambert (1971) and the time scale of Churkin *et al*. (1977).

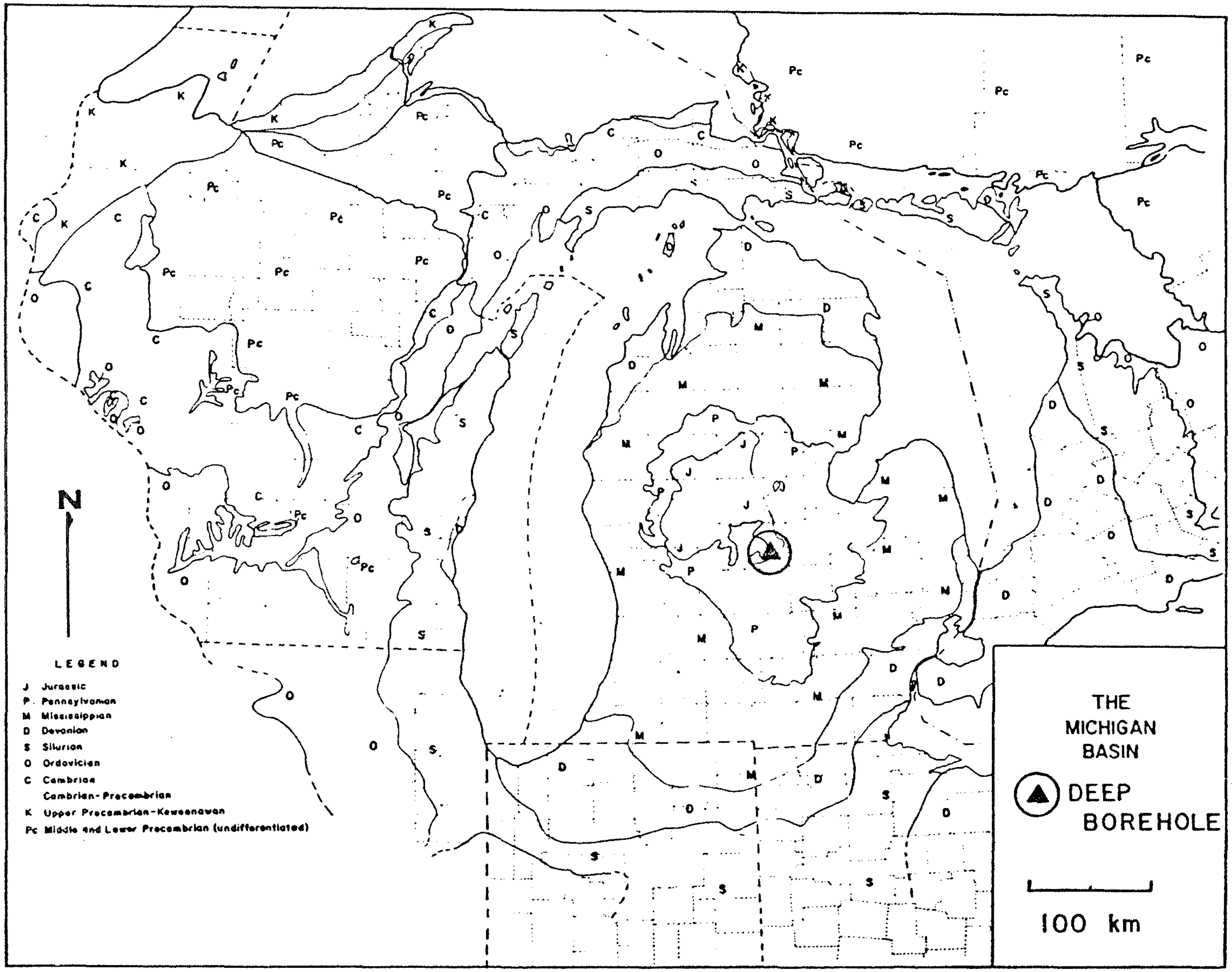
N
LEGEND
J Jurassic
P Pennsylvanian
M Mississippian
D Devonian
S Silurian
O Ordovician
C Cambrian
Cambrian-Precambrian
K Upper Precambrian-Keweenawan
Pc Middle and Lower Precambrian (undifferentiated)
THE MICHIGAN BASIN
DEEP BOREHOLE
100 km

Figure 1

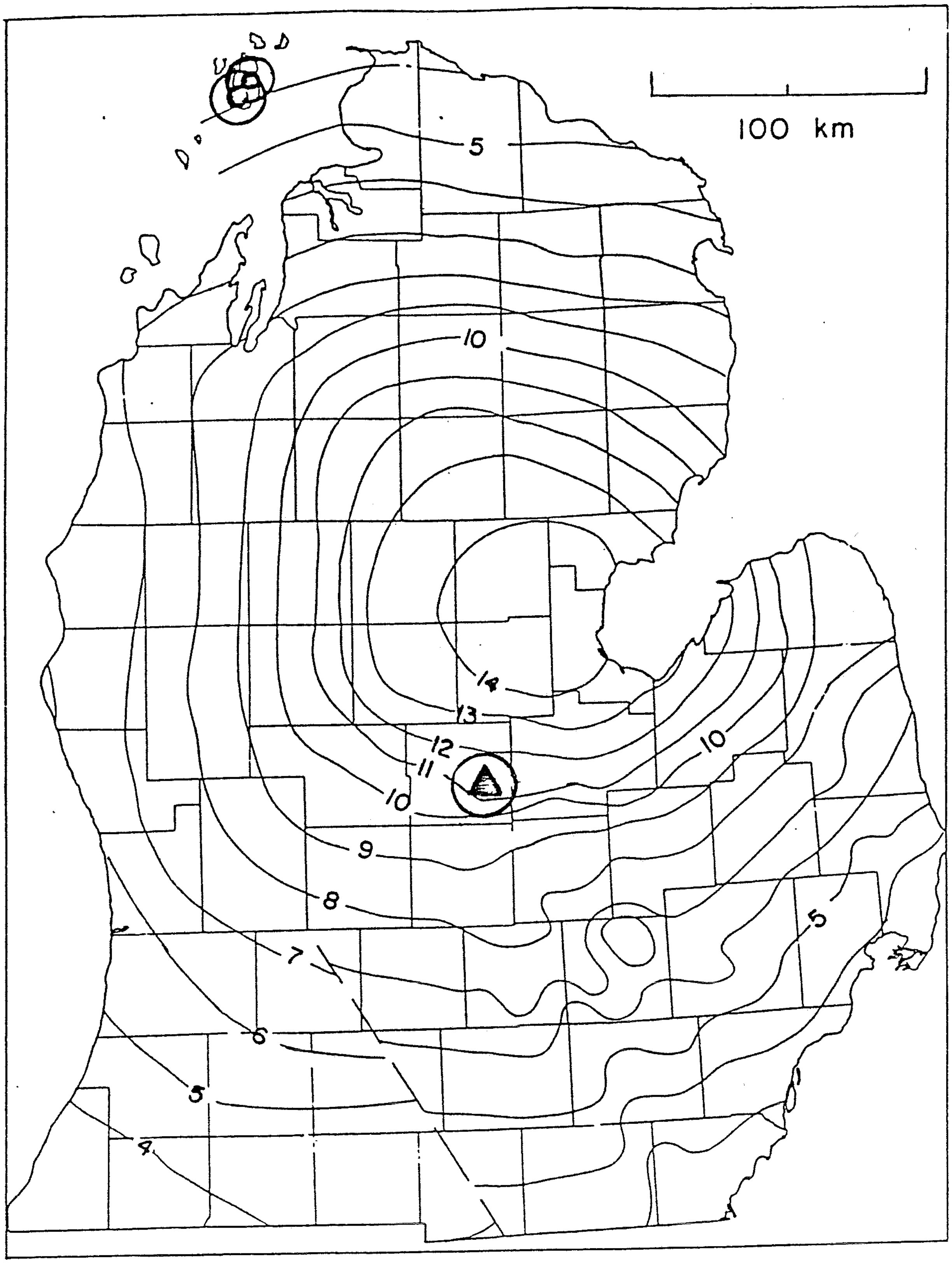

Figure 2

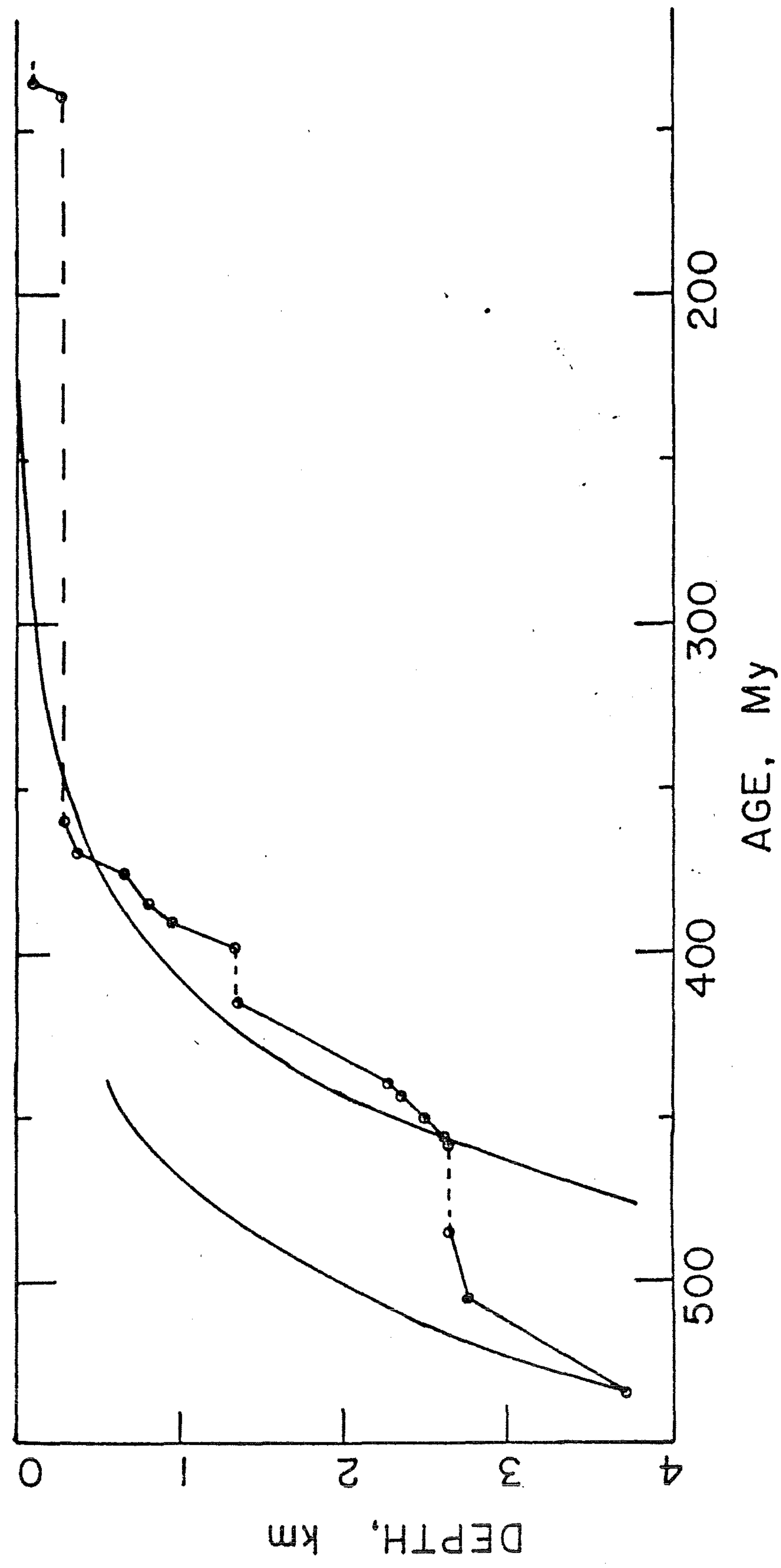

Figure 3