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PRECAMBRIAN DEEP HOLE TARGETS IN MINNESOTA

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It is becoming increasingly evident from active research in the Lake Superior region that two Archean terranes of fundamental significance are juxtaposed along a major crustal suture (Morey and Sims, 1976; Sims, 1976a). The suture is marked by a northeast-trending line of modern earthquake epicenters in western Minnesota (Walton, 1977). It passes beneath Proterozoic rocks in eastern Minnesota and coincides with the axis of the early Proterozoic Animikie basin (Morey, 1977; in prep.). It is offset by transform faults associated with the middle Proterozoic Keweenawan rift system at the head of Lake Superior and continues across northern Wisconsin and upper Michigan as a mappable boundary between early Archean gneisses and late Archean greenstone belts (Sims, 1976a). A deep trough in the crystalline basement beneath Lake Superior may also have some relationship to this feature (Richard K. Wold, personal communication).

The Archean terranes north and south of the suture contrast dramatically in lithology, ages of major components, tectonic styles and history, grade of metamorphism and mineralization. Fundamental geodynamic differences in these terranes have persisted through geologic time.

The problem of the relationships between the Archean terranes is more easily visualized if the Proterozoic and Phanerozoic supracrustal terranes are swept away. Of the five Precambrian terranes recognized in Minnesota, two are basins or platform deposits of sedimentary rocks, in some respects not unlike many later Phanerozoic basins on the craton. These are the Animikie basin of east-central Minnesota (ca. 2,000 m.y.) and the Sioux Quartzite of southwestern Minnesota (ca. 1,700-1,600 m.y.). Removing these along with the Phanerozoic sedimentary rocks from the geologic map of Minnesota leaves the two Archean terranes split by the mafic igneous rocks within the Keweenawan rift system, which formed ca. 1,100 m.y. ago (Figure 1).

Terrane I is exposed in a long strip down the Minnesota River Valley in southwestern Minnesota. It is characterized by gneisses of high-amphibolite to granulite metamorphic facies which have had a long, complex history. Certain components of the gneiss yield radiometric ages of ca. 3,700 m.y. (Goldich and Hedge, 1974). There appear to be metamorphic overprints at ca. 3,500 m.y. and 3,000 m.y. (Goldich and others, 1976). Widespread migmatization and invasions by synkinematic to late-kinematic granite occurred ca. 2,600 m.y. (Goldich and others, 1970). Another episode of granitic plutonism occurred ca. 1,800-1,700 m.y. especially in east-central Minnesota (Goldich, 1968; Morey, 1977), and about the same time basins of volcanogenic sedimentary and volcanic rocks appear to have formed in the old gneiss terrane in northern Wisconsin and upper Michigan (Sims, 1976a). In short, the terrane has been characterized by repeated strong magmatic and tectonic activity over a period of 2 billion years.

By contrast terrane II, north of the suture, appears to have formed during a single relatively brief episode of intense volcanic and plutonic activity ca. 2,700 m.y. ago. This is the terrane of greenstone and granite belts of the so-called Superior province of the Canadian Shield. It is characterized by steeply tilted and strongly to moderately deformed, but weakly metamorphosed belts of mafic pillow lavas and volcanogenic sedimentary rocks lying between elongated granitic plutons with seemingly diapiric relationships to the volcanic belts (Sims, 1976b). Numerous radiometric ages on a variety of major rock units all fall within the range of 2,700 $\pm$ 50 m.y. (for a summary see Morey and others, in prep.). Metamorphism reaches the upper amphibolite facies in some gneiss and migmatite associated with granitic belts, but metamorphism is mainly within the greenschist facies (for a summary see Morey, in press).

What then, is the relationship between these profoundly different major components of the North American Craton? How have they come into juxtaposition? Are they genetically related or related only by plate movements? If we knew the answers, we would know a lot more than we now do about the early history of the crust and its imprint on later geodynamic events. As it is, we can only speculate.

The boundary zone is not known to be exposed anywhere. Water-well drillers' logs from a few wells in central Minnesota imply that there may be a broad zone of shearing north of the line on Figure 1. One exploratory hole drilled last summer in connection with the U.S. Department of Energy NURE program near Morris, Minnesota, at the epicenter of an earthquake which occurred July 9, 1975 (the westernmost epicenter shown on Figure 1), encountered very weak, highly fractured granular leucogranite beneath less than a hundred meters of glacial drift (D.L. Southwick, 1978, personal communication). Both the aeromagnetic (Zietz and Kirby, 1970) and gravity (Craddock and others, 1970) maps of Minnesota show strong gradients and distinct changes in trends along the zone.

The line of suture is drawn on Figure 1 to coincide with the epicenters of four of the seven earthquakes in Minnesota that have been reported in historic time (about 140 years). On this basis it seems reasonable to presume that at present the suture is a fault along which small movements occur from time to time, which may have interesting implications for various structural trends and linears that have been projected in younger terranes (Warner, 1978), but ideas of what and where terranes I and II were, relative to each other 2,700 m.y. ago, and when and how they formed the present suture remain conjectural.

It has of course been speculated that old gneisses of terrane I type formed a basement for terrane II volcanism--that remobilization and anatexis of the old basement generated diapiric granitic masses which rose upward while belts of volcanic rocks subsided in between, creating a kind of clothes-wringer vertical tectonics. Although the tectonic aspects of this model are plausible, isotopic ratios and quantative trace-element studies in the terrrane II rocks of Minnesota do not favor recycling of materials that are much older than 2,700 m.y. or are sialic in composition (Arth and Hanson, 1975).

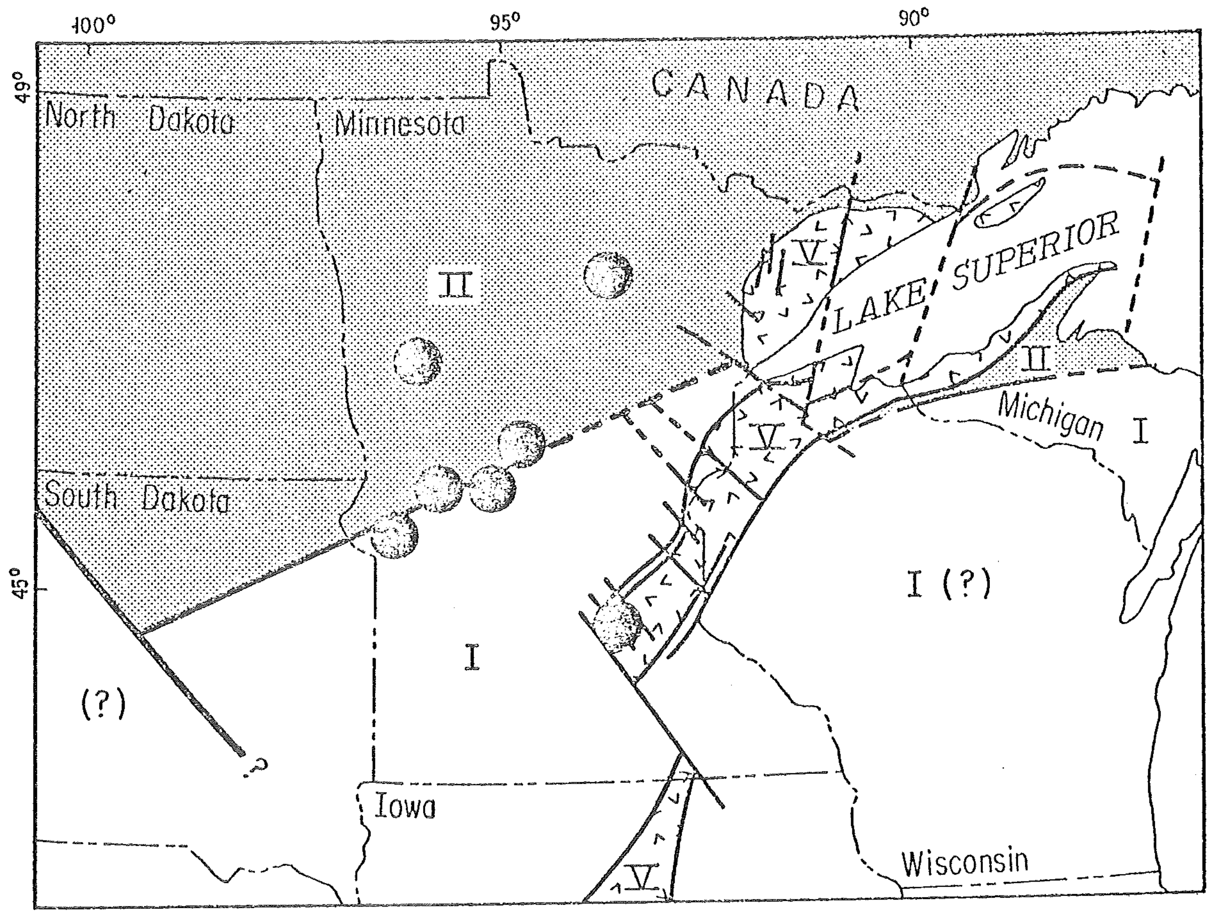

Figure 1. The fundamental Precambrian basement terranes of Minnesota and adjacent areas as they would appear if overlying sedimentary strata were removed. Black circles are the locations of historic earthquakes within Minnesota. The map does not show the lower Proterozoic rocks of terrane III (Animikie basin), terrane IV (Sioux Quartzite) or rocks of Phanerozoic age.

Another line of reasoning speculates that terrane I represents a remnant of a very early piece of proto-continental crust whose evolution may be related to early impact processes (Weiblen and Schulz, in press). This crust might have became rigid enough to fracture on a large scale 2,700 m.y. ago, so that oceanic crust began to form with pillow lavas, island arcs and other phenomena related to interactions between newly formed oceanic plates, as represented by greenstone belts, and older crust, as represented by gneissic terrane rocks. It is conceivable that both the oceanic and older crustal segments were welded together by the diapiric addition of large volumes of granite during a period of major crustal thickening 2,650-2,700 m.y. ago (Sims and Morey, 1973). Conversely, it is also conceivable that terranes I and II were unrelated 2,700 m.y. ago and drifted together later perhaps at the time of the so-called Penokean orogeny which generated plutonism and volcanism in those parts of the Animikie basin underlain by terrane I rocks (Van Schmus, 1976). Regardless terranes I and II clearly were joined together by at least 1,800 m.y. ago to form a single large craton. Shortly thereafter, terrane II was elevated relative to terrane I, for the Sioux Quartzite, which occupies a basin in terrane I, has current directions and sediment composition indicating that it formed from very mature sediments derived from the north (Weber, 1977).

No doubt there are other possibilities, and the game of model building could go on indefinitely within the not too limiting constraints of present knowledge. Clearly the ultimate answer to the nature and origin of the suture will have a strong bearing on geodynamic concepts, but equally important would be an answer to the question of what it is about the fundamental structure and composition of terrane I that has caused it to have been tectonically active over a prolonged period of geologic time while the adjacent rocks of terrane II remained virtually inert except for the subsidence involved in the formation of the Animikie basin. Two different kinds of Archean crust seem to be involved, and we need to characterize them petrologically, geochemically, structurally, and stratigraphically.

What then, from the standpoint of continental drilling programs, are the primary targets? First, in our opinion, is the need for a number of shallow holes to define the structure of the suture and the characteristics of the rocks of both terranes in contact along the suture (Morey, 1976). Glacial drift in the area ranges to several hundred meters in depth. A series of holes to bedrock with enough penetration of bedrock to get perhaps 50 meters of good core are needed along at least two traverses across the suture zone. Six to ten holes are needed for each traverse, making a total of twelve to twenty shallow holes.

Second is the question of a target for deep drilling. The classical method by which geologists project what lies at depth in the crust is to develop a stratigraphic succession and project it structurally. This works in principle until mapping reaches the lowest rocks exposed in the most deeply eroded uplift, at which point there is nothing more at the surface to tell you what is below. It is arguable that this point has been reached for the North American continent in the 3,000 m.y. old gneiss in the Minnesota River Valley. Further direct knowledge of what lies at depth can be obtained only by drilling. It is also arguable that this knowledge is critical for understanding the early origins and subsequent activity of the crust.

It has been conjectured, for example, that beneath the very oldest rocks now exposed, younger rocks may be encountered as the result of crustal thickening by a process of "underplating" (see for example Sims, 1976a). Prolonged buoyancy is implied by the continued uplift needed for the deep erosion of the highly metamorphosed old rocks, and this buoyancy in turn implies that the underplated materials be a lighter fraction of the mantle. If these younger, underplated materials exist, what might they be? Granite? Anorthosite? Whatever is found by deep drilling beneath the oldest rocks will have profound implications for geodynamic thought.

The Minnesota Geological Survey is actively engaged in a series of programs which provide a foundation for a drilling project. We are expanding our data base of subsurface information by collecting all useful water-well logs throughout the state. Special attention is being given to wells that penetrate Precambrian basement, and under a U.S. Department of Energy NURE Program contract with Union Carbide Nuclear Division, water samples from these wells are being collected and analyzed for about 30 elements. This will provide data for geochemical mapping of the drift-buried Precambrian areas. Under a contract with the Nuclear Regulatory Commission, crustal structure and seismicity are being investigated by means of a sensitive seismic monitoring array and portable seismometers connected by telephone or microwave in real time to a central recording station. The COCORP deep seismic profiling project has given high priority to a traverse across the terrane I-terrane II boundary in Minnesota. Several hundred high quality isotopic age determinations have been made on Precambrian rocks in Minnesota and we have just completed a thorough review of these data and entered them into the U.S. Geological Survey RADB system. Minnesota is one of the few states with published aeromagnetic and gravity maps at a scale of 1:1,000,000. We are nearly finished with a program to upgrade the gravity map so that most of the state will soon be covered by stations at one-mile intervals. Recommendations are being made to the legislature as the result of a state-funded conference on geophysics to make a new high-resolution aeromagnetic map and undertake a continuing program of other geophysical investigations. This program is funded for FY 1979. The Minnesota Geological Survey is part of the School of Earth Sciences at the University of Minnesota; with our own programs and resources and the resources of the Department of Geology and Geophysics, we are in a position to provide a strong program of coordinated research to back up a Continental Drilling Project in Minnesota and make maximum use of the materials and information obtained by drilling.

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