

Paralleling the central horst along the entire rift zone from Lake Superior to Kansas are linear gravity minima that mark the site of thick deposits of Keweenaw sedimentary rock. In Wisconsin the most prominent of these minima, the Bayfield low, appears to be on trend with the horst axis gravity maxima. This anomaly may represent a rift flank sedimentary basin offset by right-lateral faulting. Immediately to the southwest of the Bayfield low, the Midcontinent Gravity High appears to bifurcate (fig. 1). The southern bifurcated branch traces the Middle Keweenaw Portage Lake Volcanic Group outcrop up the center of the Keweenaw Peninsula; the northern branch outlines the Duluth Gabbro Complex and the North Shore Volcanic Group northeastward to the Canadian border.

The geometry of the flanking basins is usually depicted as resembling the Kay (1951) taphro-geosyncline, "sediment filled, deeply depressed rift blocks bounded by one or more high angle faults." In northwestern Wisconsin the northern flanking basin sedimentary rocks are identified in outcrop as type strata of the Bayfield Group, composed of from oldest to youngest, the Orienta Sandstone, Devils Island Sandstone, and the Chequamegon Sandstone. These three formations average 89 percent quartz; the middle unit is classified as an orthoquartzite. The Bayfield Group is subhorizontal, mineralogically and texturally more mature and much thinner than the Oronto Group. Minimum thickness is 815 m (Myers, 1971); overall total subsurface thickness for the Bayfield Group may approach 2,100 m. In Minnesota and Iowa the presence of Bayfield Group equivalent strata is based on deep well, refraction seismic, and gravity data analysis.

LITHOSPHERIC FLEXURE AND EVOLUTION OF THE MIDCONTINENT RIFT

Jonathan E. Nyquist and Herbert F. Wang

In 1984 Petty Ray Geophysical ran a speculative seismic reflection survey across the Midcontinent Rift System crossing the Wisconsin-Minnesota border near St. Croix Falls, Wisconsin. The basement profile suggests that the sedimentary basins flanking the Midcontinent Rift System formed by flexure of the lithosphere rather than as half grabens. We modeled the lithosphere as an elastic plate of thickness (h) floating on a fluid mantle. A line load of magnitude (V_0) acting at the center of the plate deforms the lithosphere and sediments fill the depression (fig. 1). The elastic thickness of the lithosphere is a modeling fiction. It is the thickness of an elastic plate that approximates the long-term behavior of the lithosphere and is always thinner than the thermal lithosphere.

The best model fit to the seismic data is for a flexural parameter of $a = 35$ km and a load of 6.3×10^{12} N/m (fig. 2). This surprisingly low value is reflected in the narrow basin width and indicates that the lithosphere was thinned at the time of basin formation, possibly by a combination of extension and high heat flow. The magnitude of the central load required to produce the flexure is too great to be explained by volcanics; a major mountain range would be required. We suggest that mantle material intruded the lower crust, an idea supported by the anomalously high compressional velocities seen in the lower crust by deep refraction.

Deep seismic refraction data disclose that the Moho "basin" beneath the rift has also been deformed by flexure. However, the Moho is much wider, implying that the lithosphere cooled and thickened after rifting. Compensation for the intracrustal load now occurs at a greater depth.

The seismic reflection and refraction data give two snapshots of basin evolution. The reflection data show the sedimentary basin shape, which probably formed within the first 50 m.y. after rifting; the surface flexure represents the situation when the plate cools. The refraction data show the present shape of the Moho a billion years later. We suggest the following scenario for the evolution of the Midcontinent Rift System in this region:

- (1) Extension and high heat flow thins the lithosphere, and the mantle material intrudes the lower crust. Isostatic adjustment creates a gently dipping basin that fills with sediments and fissure-fed volcanics (fig. 3).
- (2) Volcanic activity ceases and the cooling intrusion contracts, increasing in density and loading the crust; sedimentation keeps pace with the deepening basin. The elastic thickness of the lithosphere rapidly increases with cooling (fig. 4).
- (3) Subsidence stops when the intrusive body has cooled. The St. Croix Horst is thrust up along the Douglas and Lake Owen Faults. The intracrustal body is preserved by the stable cratonic environment, but as the lithosphere thickens compensation occurs at a greater depth and with a longer wavelength reflected in the present day deformation of the Moho (fig. 5).

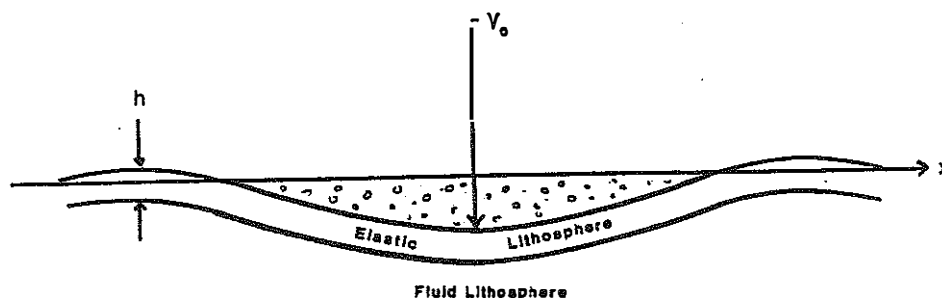


Figure 1. Flexural model.

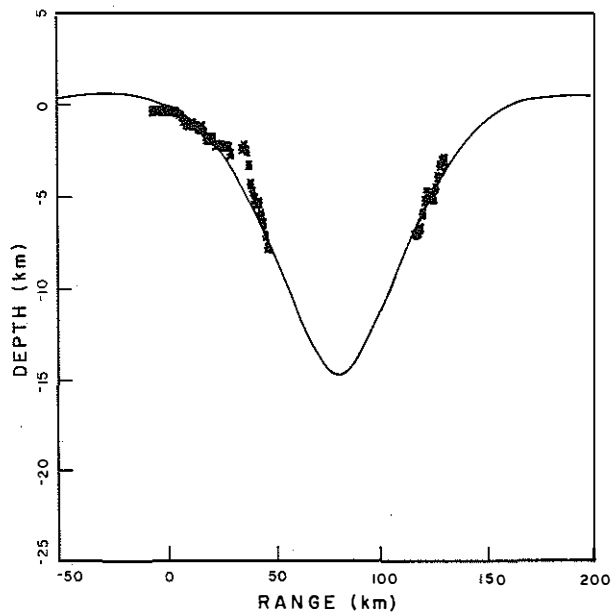


Figure 2. Least squares fit of unbroken plate model to seismic data, $a=35$ km; load, $v_0 = 6.3 \times 10^{13}$ N/M.

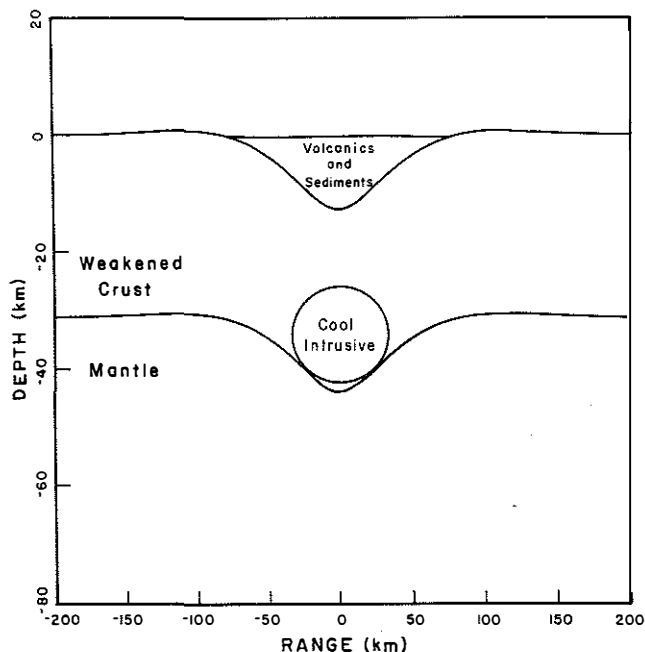


Figure 3. Extension and high heat flow thin the elastic lithosphere. The weight of hot, dense material intruding the lower crust flexes the lithosphere and produces a gentle basin.

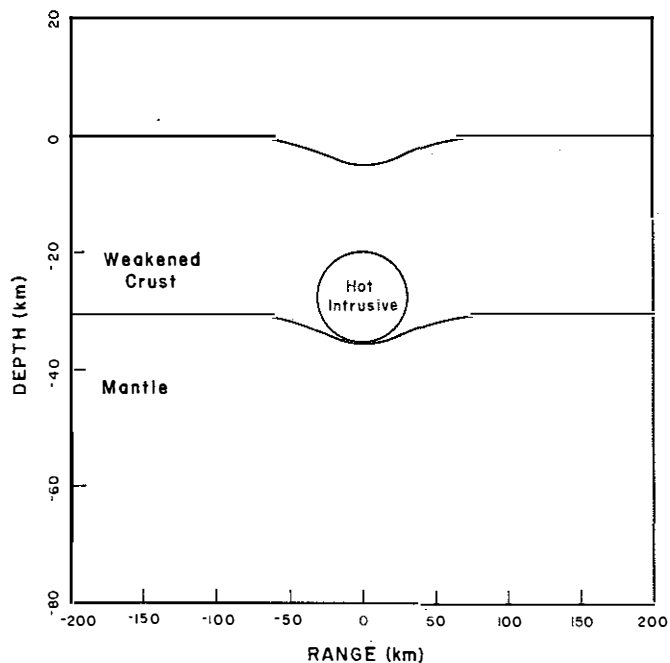


Figure 4. The intrusive cools and increases in density flexing the lithosphere further. Volcanics and sediments accumulate in the basin.

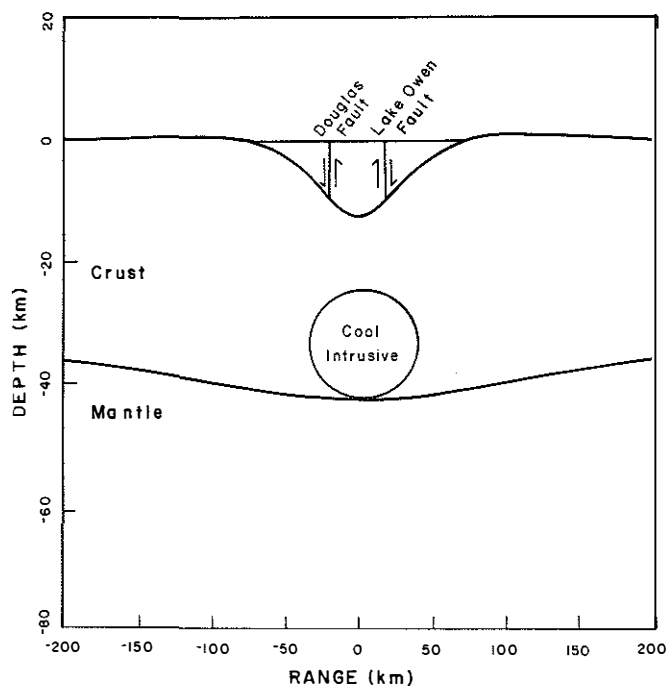


Figure 5. The elastic lithosphere thickens as the normal geothermal gradient is restored. The surface deformation is frozen in, but intrusive body is preserved by the stable cratonic environment and is now compensated at great depth over a wider region. The St. Croix Horst is uplifted along the Douglas and Lake Owen Faults in a later compressional event.

REFERENCES

- Aldrich, H.R., 1929, The geology of the Gogebic Iron Range of Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 71, 279 p.
- Anderson, R.R., and Black, R.A., 1982, Geologic interpretations from geophysical models of the Midcontinent geophysical anomaly in southwest Iowa, *in* Regional tectonics and seismicity of southwestern Iowa: Annual Report of U.S. Nuclear Regulatory Commission NUREG/CR-2548, p. 27-41.
- Arvidson, R.E., Guinness, E.A., Strebeck, J.W., Davies, G.F., and Schulz, K.J., 1982, Image processing applied to gravity and topography data covering the continental U.S.: EOS, Transactions of the American Geophysical Union, 63, p. 261-265.
- Austin, G. S., 1970, Deep stratigraphic test well near Hollandale, Minnesota: Minnesota Geological Survey Report of Investigations 12, 52 p.
- Balashova, M.M., Koblova, A.Z., and Provorov, V.M., 1983, Late Precambrian petroleum formation in the northern Ural-Volga region: International Geology Review, v. 25, p. 1455-1458.
- Barghoorn, E.S., Meinschein, W.G., and Schopf, J.W., 1965, Paleobiology of a Precambrian shale: Science, v. 148, p. 461-472.
- Barghoorn, E.S., and Schopf, J.W., 1966, Micro-organisms three billion years old from the Precambrian of South Africa: Science, 152, p. 758-763.
- Becker, L.E., and Patton, J.B., 1968, World occurrence of petroleum in Pre-Silurian rocks: American Association of Petroleum Geologists Bulletin, v. 52, p. 224-245.
- Brown, A.C., 1971, Zoning in the White Pine copper district, Ontonagon County, Michigan: Economic Geology, v. 66, p. 543-573.
- Brown, L., Jensen, L., Oliver, J., Kaufman, S. and Steiner, D., 1982, Rift structure beneath the Michigan Basin from COCORP profiling: Geology, v. 10, p. 645-649.
- Butler, B.S., and Burbank, W.S., 1929, The copper deposits of Michigan: U.S. Geological Survey Professional Paper 144, 238 p.
- Cannon, W.F., and Davidson, D.M., Jr., 1982, Bedrock geologic map of the Lake Superior region *in* Wold, R.J. and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, plate 1, scale 1:1,000,000.
- Catacosinos, P.A., 1981, Origin and stratigraphic assessment of pre-Mt. Simon clastics (Precambrian) of Michigan Basin: American Association of Petroleum Geologists Bulletin, v. 69, p. 1617-1620.
- Chase, C.G. and Gilmer, T.H., 1973, Precambrian plate tectonics: the Midcontinent Gravity High: Earth and Planetary Science Letters, 21, p. 70-80.

- Chaudhuri, S., and Faure, G., 1967, Geochronology of the Keweenawan rocks, White Pine, Michigan: *Economic Geology*, v. 62, p. 1011-1033.
- Compton, W., and Arriens, P.A., 1968, The Precambrian geochronology of Australia: *Canadian Journal Earth Sciences*, v. 5, p. 561-583.
- Coons, R.L., 1966, Precambrian basement geology and Paleozoic structure of the Mid-Continent gravity high: University of Wisconsin, Madison, unpublished Ph.D. dissertation, 167 p.
- Cooper, J.D., Miller, R.H., and Patterson, J., 1986, A trip through time: principles of historical geology: Merrill Publishing Company, 469 p.
- Craddock, C., 1972a, Regional geologic setting, *in* Sims, P.K., and Morey, G.B., eds., *Geology of Minnesota: A centennial volume*: Minnesota Geological Survey, p. 281-291.
- Craddock, C., 1972b, Keweenawan geology of east-central and southeastern Minnesota, *in* Sims, P.K., and Morey, G.B., eds., *Geology of Minnesota: A centennial volume*: Minnesota Geological Survey, p. 416-424.
- Craddock, C., Mooney, H.M., and Kolehmainen, V., 1970, Simple Bouguer gravity map of Minnesota and northwestern Wisconsin: Minnesota Geological Survey, Miscellaneous Map Series, Map M-10, scale 1:1,000,000.
- Craddock, C., Thiel, E.E., and Gross, B., 1963, A gravity investigation of the Precambrian of southeastern Minnesota and western Wisconsin: *Journal of Geophysical Research*, v. 68, p. 6015-6032.
- Daniels, P.A., Jr., 1982, Upper Precambrian sedimentary rocks: Oronto Group, Michigan-Wisconsin, *in* Wold, R.J., and Hinze, W.J., eds., *Geology and tectonics of the Lake Superior basin*: Geological Society of America Memoir 156, p. 107-133.
- Davidson, D.M., Jr., 1982, Geological evidence relating to interpretation of the Lake Superior basin structure, *in* Wold, R.J., and Hinze, W.J., eds., *Geology and tectonics of the Lake Superior basin*: Geological Society of America Memoir 156, p. 5-14.
- Davidson, D.M., Jr., and Mudrey, M.G., Jr., 1986, Mid-Continent Rift: New Frontier in an Old Area (abs): American Association of Petroleum Geologists Bulletin, v. 70, p. 579.
- Denning, R.M., 1949, The petrology of the Jacobsville sandstone, Lake Superior: Michigan College of Mineral Technology, Houghton, unpublished Master's thesis.
- Dickas, A.B., 1984, Midcontinent rift system: Precambrian hydrocarbon target: *Oil and Gas Journal*, October 15, 1984, p. 151-159.
- Dickas, A.B., 1986, Comparative Precambrian stratigraphy and structure along the Midcontinent Rift: American Association of Petroleum Geologists Bulletin, v. 70, p. 225-238.

- Dorr, J.A., and Eschmann, D.F., 1973, *Geology of Michigan*: University of Michigan Press, Ann Arbor, 476 p.
- DuBois, P.M., 1962, Paleomagnetism and correlation of Keweenawan rocks: *Geological Survey of Canada Bulletin* 71, 75 p.
- Dunlop, J.S.R., Muir, M.D., Milne, V.A., and Groves, D.I., 1978, A new microfossil assemblage from the Archean of western Australia: *Nature*, v. 274, p. 676-678.
- Dunshi, Y., and Guangning, Z., 1980, Exploration practice in and prospects of the buried-hill oil fields in north China *in* Mason, J.F., ed., *Petroleum Geology in China*: Penn Well Publishing Company, Tulsa, Oklahoma, 263 p.
- Durkee, E.F., 1982, Oil and gas developments in Australia in 1981: *American Association of Petroleum Geologists Bulletin*, v. 66, p. 2321-2348.
- Durkee, E.F., 1983, Oil and gas developments in Australia in 1982: *American Association of Petroleum Geologists Bulletin*, v. 67, p. 1827-1848.
- Dutton, C.E., and Bradley, R.E., 1970, Lithologic, geophysical, and mineral commodity maps of Precambrian rocks in Wisconsin: U.S. Geological Survey Miscellaneous Geologic Investigations Map 1-631, sheet 3 of 6, scale 1:500,000.
- Eglinton, G., Scott, P.M., Belsky, T., Burlingame, A.L., and Calvin, M., 1964, Hydrocarbons of biological origin from a one-billion years old sediment: *Science*, v. 145, p. 263-264.
- Elmore, R.D., and Daniels, P.A., Jr., 1980, Depositional system model for Upper Keweenawan Oronto Group sediments, northern peninsula Michigan (abs): *American Geophysical Union Transactions*, v. 61, p. 1195.
- Engel, A.E.J., Nagy, B., Nagy, L.A., Engel, C.G., Kremp, G.O.W., and Drew, C.M., 1968, Alga-like forms in Onverwacht Series, South Africa: oldest recognized lifelike forms on earth: *Science*, v. 161, p. 1005-1008.
- Farnham, P.R., 1967, Crustal structure in the Keweenawan province of east central Minnesota and western Wisconsin: University of Minnesota, St. Paul, unpublished Ph.D. dissertation, 464 p.
- Fowler, J.H., and Kuenzi, W.D., 1978, Keweenawan turbidites in Michigan (deep borehole red beds): A foundered basin sequence developed during evolution of a protoceanic rift system: *Journal of Geophysical Research*, v. 83, p. 5833-5843.
- Galloway, W.E., and Hobday, D.K., 1983, Terrigenous clastic depositional systems: Springer-Verlag, 423 p.
- Gardner, F.J., 1963, Amadeus next Aussie oil producer?: *Oil and Gas Journal*, September 16, 1963, 157 p.

- Glaessner, M.F., 1961, Pre-cambrian animals: Scientific American, v. 204, p. 72-78.
- Grant, U.S., 1901, Preliminary report on the copper-bearing rocks of Douglas County, Wisconsin (2nd ed.): Geological and National History Survey Bulletin 6, 83 p..
- Green, J.C., 1977, Keweenawan plateau volcanism in the Lake Superior region, *in* Baragar, W.R.A., ed., Volcanic regimes in Canada: Geological Association of Canada Special Paper 16, p. 407-422.
- Green, J.C., 1982, Geologic and geochemical evidence for the nature and development of the Middle Proterozoic (Keweenawan) Midcontinent Rift of North America: Tectonophysics, 94, p. 413-437.
- Green, J.C., 1983, Geologic and geochemical evidence for the nature and development of the Middle Paleozoic (Keweenawan) Midcontinent Rift of North America: Tectonophysics, v. 94, p. 413-437.
- Halbouty, M.T., King, R.E., Klemme, H.D., Dott, R.H., Sr., and Meyerhoff, A.A., 1970, Factors affecting formation of giant oil and gas fields and basin classification, *in* Halbouty, M.T., ed., Geology of giant petroleum fields: American Association of Petroleum Geologists Memoir 14, p. 528-555.
- Halls, H.C., 1966, A review of the Keweenawan geology of the Lake Superior region, *in* Steinhart, J.S., and Smith, T.J., eds., The earth beneath the continents: American Geophysical Union Geophysical Monograph 10, p. 3-27.
- Halls, H.C., 1982, Crustal thickness in the Lake Superior region, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 239-243.
- Halls, H.C., and West, G.F., 1971, A seismic refraction survey in Lake Superior: Canadian Journal of Earth Science, v. 8, p. 610-630.
- Hamblin, W.K., 1958, Cambrian sandstones of northern Michigan: Michigan Geological Survey Publication 51, 149 p.
- Hamblin, W.K., 1961, Paleogeographic evolution of the Lake Superior region from Late Keweenawan to Late Cambrian time: Bulletin of the Geological Society of America, v. 72, p. 1-18.
- Hamblin, W.K., 1965, Basement control of Keweenawan and Cambrian sedimentation in Lake Superior region: Bulletin of the American Association of Petroleum Geologists, v. 49, p. 950-958.
- Hatch, J.R., and Morey, G.B., 1985, Hydrocarbon source rock evaluation of Middle Proterozoic Solor Church Formation, North American Mid-Continent Rift System, Rice County, Minnesota: American Association of Petroleum Geologists Bulletin, v. 69, p. 1208-1216.

- Hinze, W.J., Kellogg, R. L., and O'Hara, N.W., 1975, Geophysical studies of basement geology of southern peninsula of Michigan: American Association of Petroleum Geologists Bulletin, v. 59, p. 1562-1584.
- Hinze, W.J., Wold, R.J., and O'Hara, N.W., 1982, Gravity and magnetic anomaly studies of Lake Superior, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 203-222.
- Hite, D.M., 1968, Sedimentology of the Upper Keweenawan sequence of northern Wisconsin and adjacent Michigan; University of Wisconsin, Madison, unpublished Ph.D. dissertation, 202 p.
- Holmes, A., 1965, Principles of physical geology: Ronald Press Company, 1288 p.
- Hubbard, H.A., 1975, Keweenawan geology of the North Ironwood, Ironwood and Little Girls Point quadrangles, Gogebic County, Michigan: U.S. Geological Survey Open-file report OF 75-152, 23 p.
- Irving, R.D., 1883, The copper-bearing rocks of Lake Superior: U.S. Geological Survey Monograph 5, 464 p.
- Johns, R.B., Belsky, T., McCarthy, E.D., Burlingame, A.L., Haug, P. Schoes, H.K., Richter, W., and Calvin, M., 1966, The organic geochemistry of ancient sediments - Part II; Geochimica Cosmochimica Acta, v. 30, p. 1191-1222.
- Jones, D.J., 1956, Introduction to microfossils: Harper and Brothers Publishers, 406 p.
- Kalliokoski, J., 1975, Chemistry and mineralogy of Precambrian paleosols in northern Michigan: Geological Society of America Bulletin, v. 86, p. 371-376.
- Kalliokoski, J., 1982, Jacobsville Sandstone, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 147-155.
- Kay, M., 1951, North American geosynclines: Geological Society of America Memoir 48, 143 p.
- Kelly, W.C., and Nishioka, G.K., 1985, Precambrian oil inclusions in late veins and the role of hydrocarbons in copper mineralization at White Pine, Michigan: Geology, v. 13, p. 334-337.
- Kemp, A.L.W., Dell, C.J., and Harper, N.S., 1978, Sedimentation rates and a sediment budget for Lake Superior: Journal of Great Lakes Research, p. 276-287.
- King, E.R. and Zietz, I., 1971, Aeromagnetic study of the Midcontinent Gravity High of central United States: Bulletin of the Geological Society of America, v. 82, p. 2187-2207.

- Kingston, D.R., Dishroon, C.P., and Williams, P.A., 1983, Hydrocarbon plays and global basin classification: American Association of Petroleum Geologists Bulletin, v. 67, p. 2194-2198.
- Klasner, J.S., King, E.R., and Jones, W.J., 1985, Geologic interpretation of gravity and magnetic data for northern Michigan and Wisconsin, *in* Hinze, W.J., ed., The utility of regional gravity and magnetic anomaly maps: Society of Exploration Geophysicists, p. 267-286.
- Lane, A.C., and Seaman, A.E., 1907, Notes on the geological section of Michigan, Part 1. The pre-Ordovician: Journal of Geology, v. 15, p. 680-695.
- Lee, C.K., and Kerr, S.D., Jr., 1984, Midcontinent rift - a frontier oil province: Oil and Gas Journal, August 13, 1984, p. 145-150.
- Levin, H.L., 1983, The earth through time: Saunders College Publishing, 513 p.
- Lidiak, E.G., 1972, Precambrian rocks in the subsurface of Nebraska: Nebraska Survey Bulletin 26, 41 p.
- Linder, A.W., 1984, Oil and gas development in Australia in 1983: American Association of Petroleum Geologists Bulletin, v. 68, p. 1600-1616.
- Linder, A.W., 1985, Oil and gas development in Australia in 1984: American Association of Petroleum Geologists Bulletin, v. 69, p. 1856-1870.
- Long, D.G.F. and Young, G.M., 1978, Dispersion of cross-stratification as a potential tool in the interpretation of Proterozoic arenites: Journal Sedimentary Petrology, v. 48, p. 857-862.
- Luetgert, J.H. and Meyer, R.P., 1982, Structure of the western basin of Lake Superior from cross structure refraction profiles, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 245-255.
- Lyons, P.L., 1959, The Greenleaf anomaly, a significant gravity feature, *in* Hambleton, W.M., ed., Symposium on the geophysics of Kansas: Kansas State Geological Survey Bulletin 137, p. 105-120.
- Lyons, P.L., and O'Hara, N.W., 1982, Gravity anomaly map of the United States (exclusive of Alaska and Hawaii): Society of Exploration Geophysicists, scale 1:2,500,000, 2 sheets.
- McCulloh, T.H., 1973, Oil and gas, *in* D.A. Brobst and W.P. Pratt, eds., United States mineral resources: U.S. Geological Survey Professional Paper 820, p. 477-496.
- McKirdy, D.M., 1974, Organic geochemistry in Precambrian research: Precambrian Research, v. 1, p. 75-137.
- Meinschein, W.G., 1965, Soudan Formation: Organic extracts of early Precambrian rocks: Science, v. 150, p. 601-605.

- Meinschein, W.G., Barghoorn, E.S., and Schopf, J.W., 1964, Biological remnants in a Precambrian sediment: *Science*, v. 145, p. 262-263.
- Meyerhoff, A.A., 1980, Geology and petroleum field in Proterozoic and Lower Cambrian strata, Lena-Tunguska petroleum province, eastern Siberia, U.S.S.R., *in* Halbouty, M.T., ed., Giant oil and gas fields of the decade 1968-1978: American Association of Petroleum Geologists Memoir 30, p. 225-256.
- Mooney, H.M., Farnham, P.R., Johnson, S.H., Volz, G., and Craddock, C., 1970, Seismic studies over the Midcontinent Gravity High in Minnesota and northwestern Wisconsin: Minnesota Geological Survey Report of Investigations 11, 191 p.
- Moore, L.R., Moore, J.R.M., and Spinner, E., 1969, A geomicrobiological study of the Precambrian Nonesuch Shale: Yorkshire Geological Society Proceedings, v. 37, p. 351-394.
- Morey, G.B., 1967, Stratigraphy and petrology of the type Fond du Lac Formation, Duluth, Minnesota: Minnesota Geological Survey Report of Investigations 7, 35 p.
- Morey, G.B., Petrology of Keweenaw sandstones in the subsurface of southeastern Minnesota, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 436-449.
- Morey, G.B., 1974, Cyclic sedimentation of the Solor Church Formation (Upper Precambrian, Keweenaw) southeastern Minnesota: *Journal of Sedimentary Petrology*, 44, p. 872-884.
- Morey, G.B., 1977, Revised Keweenaw subsurface stratigraphy, southeastern Minnesota: Minnesota Geological Survey Report of Investigations 16, 67 p.
- Morey, G.B., 1978, Metamorphism in the Lake Superior region, U.S.A., and its relation to crustal evolution, *in* Fraser, J.A., and Heywood, W.W., eds., Metamorphism in the Canadian Shield: Geological Survey of Canada Paper 78-10, p. 283-314.
- Morey, G.B. and Green, J.C., 1982, Status of the Keweenaw as a stratigraphic unit in the Lake Superior region, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 15-25.
- Morey, G.B. and Ojakangas, R.W., 1982, Keweenaw sedimentary rocks of eastern Minnesota and northwestern Wisconsin, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 135-146.
- Morey, G.B. and Sims, P.K., 1976, Boundary between two Precambrian terranes in Minnesota and its geologic significance: Geological Society of America Bulletin, v. 87, p. 141-152.

- Morey, G.B., Sims, P.K., Cannon, W.F., Mudrey, M.G. Jr., and Southwick, D.L., 1982, Geologic map of the Lake Superior region - Minnesota, Wisconsin, and northern Michigan: Minnesota Geological Survey State Map Series S-13, scale 1:1,000,000.
- Mudrey, M.G., Jr., 1979, Geologic summary of the Ashland 2° Quadrangle: Wisconsin Geological and Natural Survey Open-file Report 79-1, 39 p.
- Mudrey, M.G. Jr., Brown, B.A. and Greenberg, J.K., 1982, Bedrock geologic map of Wisconsin: Wisconsin Geological and Natural History Survey, scale 1:1,000,000.
- Murray, G.E., 1965, Indigenous Precambrian petroleum: American Association of Petroleum Geologists Bulletin, v. 49, p. 3-21.
- Murray, G.E., Kaczor, M.J., and McArthur, R.E., 1980, Indigenous Precambrian petroleum revisited: American Association of Petroleum Geologists Bulletin, v. 64, p. 1681-1700.
- Myers, W.D. II, 1971, The sedimentology and tectonic significance of the Bayfield Group (Upper Keweenawan?) Wisconsin and Minnesota: University of Wisconsin, Madison, unpublished Ph.D. dissertation, 259 p.
- Nanz, R.H., 1953, Chemical composition of Precambrian slates with notes on the geochemical evolution of lutites: Journal of Geology, v. 61, p. 51-64.
- Ocola, L.C., and Meyer, R.P., 1973, Central North American Rift System, 1. Structure of the axial zone from seismic and gravimetric data: Journal of Geophysical Research, v. 78, p. 5173-5194.
- Ojakangas, R.W., and Morey, G.B., 1982a, Keweenawan pre-volcanic quartz sandstones and related rocks of the Lake Superior region, *in* Wold, R.J., and Hinze, W.J., eds., Geology and Tectonics of the Lake Superior Basin: Geological Society of America Memoir 156, p. 85-96.
- Ojakangas, R.W., and Morey, G.B., 1982b, Keweenawan sedimentary rocks of the Lake Superior region: A summary, *in* Wold, R.J., and Hinze, W.J., eds., Geology and Tectonics of the Lake Superior Basin: Geological Society of America Memoir 156, p. 157-164.
- Ostrom, M.E., and Slaughter, A.E., 1967, Correlation problems of the Cambrian and Ordovician outcrop areas of the Northern Peninsular [sic] of Michigan: Annual Field Excursion, Michigan Basin Geological Society, p. 1-5.
- Patenaude, R.W., 1966, A regional aeromagnetic survey of Wisconsin, II *in* Steinhart, J.S., and Smith, T.J., eds., The earth beneath the continents: American Geophysical Union Geophysical Monograph 10, p. 111-126.
- Pettijohn, F.J., 1957, Sedimentary rocks (2nd ed.): New York, Harper and Row, 718 p.
- Potter, P.E. and Pettijohn, F.J., 1977, Paleocurrents and basin analysis (2nd ed.): New York, Springer-Verlag, 425 p.

- Qi, F., and Xie-Pei, W., 1984, Significant role of structural fractures in Renqui buried-hill oil field in eastern China: American Association of Petroleum Geologists Bulletin, v. 68, p. 971-982.
- Quanheng, Z., 1984, Jizhong depression, China -- its geologic framework, evolutionary history, and distribution of hydrocarbons: American Association of Petroleum Geologists Bulletin, v. 68, p. 983-992.
- Raasch, G.O., 1950, Current evaluation of the Cambrian-Keweenawan boundary (Wis.): Transactions of Illinois State Academy of Sciences, v. 43, p. 137-150.
- Rudman, A.J., Summerson, C.H., and Hinze, W.J., Geology of basement in Midwestern United States: Bulletin of the American Association of Petroleum Geologists, v. 49, no. 7, p. 894-904.
- Ruiz, J., Jones, L.M., and Kelly, W.C., 1984, Rubidium-strontium dating of ore deposits hosted by Rb-rich rocks, using calcite and other common Sr-bearing minerals: Geology, v. 12, p. 259-262.
- Schopf, J.W., 1968, Microflora of the Bitter Spring Formation, late Precambrian, central Australia: Journal of Paleontology, v. 42, p. 651-688.
- Serpa, L., Setzer, T., Farmer, H., Brown, L., Oliver, J., Kaufman, S., Sharp, J. and Steeples, D.W., 1984, Structure of the southern Keweenawan rift from COCORP survey across the Midcontinent Geophysical Anomaly in northeastern Kansas: Tectonics, 3, p. 367-384.
- Shaw, D.M., Reilly, G.A., Muysson, J.R., Pattenden, G.E., and Campbell, F.E., 1967, An estimate of the chemical composition of the Canadian Precambrian shield: Canadian Journal of Earth Sciences, v. 4, p. 829-853.
- Shicong, G., Dungzhou, Q., Xiaqun, C., Fungten, Y., Huaiyu, Y., Shoude, W., Jingcai, Z., and Sioche, C., 1980, Geologic history of late Proterozoic to Triassic in China and associated hydrocarbons, *in* Mason, J.F., ed., Petroleum Geology in China, Penn Well Publishing Company, Tulsa, Oklahoma, p. 142-153.
- Shirley, K., 1985, Wildcat test Precambrian gas: American Association of Petroleum Geologists Explorer, August, p. 1, 12, and 13.
- Sims, P.K., Cannon, W.F., and Mudrey, M.G., Jr., 1978, Preliminary geologic map of Precambrian rocks in part of northern Wisconsin: U.S. Geological Survey Open-file report 78-318, scale 1:250,000, 3 sheets.
- Sims, P.K., Card, K.D., Morey, G.B., and Peterman, Z.E., 1980, The great lakes tectonic zone - a major crustal structure in central North America: Geological Society of America Bulletin, v. 91, p. 690-698.
- Sloan, R.E., [1965], A teacher's guide for geologic field investigations in southeastern Minnesota: Minnesota Department of Education, 19 p.
- Sloan, R.E. and Danes, Z.F., 1962, A geologic and gravity survey of the Belle Plaine area, Minnesota: Minnesota Academy of Science Proceedings, v. 30, p. 49-52.

- Smith, T.J., Steinhart, J.S., and Aldrich, L.T., 1966, Lake Superior crustal structure: *Journal of Geophysical Research*, v. 71, p. 1141-1172.
- Somanas, C., 1984, A comprehensive geophysical interpretation of the Midcontinent Geophysical Anomaly in northeastern Kansas: University of Kansas, unpublished Master's thesis, 87 p.
- Stauffer, C.R., 1927, Age of the Red Clastic series of Minnesota: *Bulletin of the Geological Society of America*, v. 38, p. 469-478.
- Steeple, D.W., 1976, Preliminary crustal model for northwest Kansas (abs): EOS, *Transactions of the American Geophysical Union*, v. 57, p. 961.
- Steinhart, J.S. and Smith, T.J., eds., 1966, The earth beneath the continents: American Geophysical Union Geophysical Monograph 10, 663 p.
- Teselle, R.D., Box, G.L., Luebking, G.A., Bickel, D., and Thames, C.B., 1985, Oil and gas developments in northern Rockies in 1984: *American Association of Petroleum Geologists Bulletin*, v. 69, p. 1559-1566.
- Thiel, E., 1956, Correlation of gravity anomalies with the Keweenaw geology of Wisconsin and Minnesota: *Bulletin of the Geological Society of America*, v. 67, p. 1079-1100.
- Thwaites, F.T., 1912, Sandstones of the Wisconsin coast of Lake Superior: *Wisconsin Geological and Natural History Survey Bulletin* 25, 117 p.
- Thwaites, F.T., 1931, Geologic cross section of central United States, Michigan, Wisconsin, Illinois: Kansas Geological Society, 4th annual Field Conference Guidebook, p. 66-70.
- Thwaites, F.T., 1935, Post-conference day no. 2, Monday, September 2, 1935, Duluth, Minnesota, to Ironwood, Michigan, field trip description, *in* Guidebook of the ninth annual field conference: Kansas Geological Society, p. 221-234.
- Trofimuk, A.A., Vasil'yev, V.G., Oraasev, I.P., Kosaorotov, S.P., Mandel'baum, M.M., Mustafinov, A.N., and Samsnov, V.V., 1969, Main problems of prospecting the Markovo oil field in eastern Siberia: *Petroleum Geology*, v. 8, p. 13-18.
- Tryhorn, A.D., and Ojakangas, R.W., 1972, Sedimentation and petrology of the upper Precambrian Hinckley Sandstone of east-central Minnesota: *in* Sims, P.K., and Morey, G.B., eds., *Geology of Minnesota: A centennial volume*: Minnesota Geological Survey, p. 431-435.
- Tyler, S.A., and Barghoorn, E.S., 1954, Occurrence of structurally preserved plants in Precambrian rocks of the Canadian shield: *Science*, v. 119, p. 606-608.
- Tyler, S.A., Marsden, R.W., Grout, F.F., and Thiel, G.A., 1940, Studies of the Lake Superior Precambrian by accessory-mineral methods: *Bulletin of the Geological Society of America*, v. 51, p. 1429-1538.

- Van Hise, C.R. and Leith, C.K., 1911, The geology of the Lake Superior region: U.S. Geological Survey Monograph 52, 641 p.
- Van Schmus, W.R., and Bickford, M.E., 1981, Proterozoic chronology and evolution of the midcontinent region, North America, *in* Kroner, A., ed., Precambrian plate tectonics: Elsevier, Amsterdam, p. 261-296.
- Van Schmus, W.R., and Hinze, W.J., 1985, The midcontinent rift system: Annual Review Earth and Planetary Sciences, 13, p. 345-383.
- Vassoyevich, N.B., Vysotskiy, I.V., Sokolov, B.A., and Tatarenko, Y.I., 1971, Oil-gas potential of late Precambrian deposits: International Geology Review, v. 13, p. 407-418.
- Watts, D.R., 1981, Paleomagnetism of the Fond du Lac Formation and the Eileen and Middle River sections with implications for Keweenaw tectonics and the Grenville problem: Canadian Journal of Earth Science, v. 18, p. 829-841.
- Webb, E.A., 1965, Will Officer and Amadeus basins both be productive?: World Oil, June, p. 160-165.
- Weber, J.R. and Goodacre, A.K., 1966, A reconnaissance underwater gravity survey of Lake Superior, *in* Steinhart, J.S., and Smith, T.J., eds., The earth beneath the continents: American Geophysical Union Geophysical Monograph 10, p. 56-65.
- Weiblen, P.W., and Morey, G.B., 1980, A summary of the stratigraphy, petrology, and structure of the Duluth Complex: American Journal of Science, v. 280-A, pt. 1, p. 88-133.
- White, W.S., 1966a, Geologic evidence for crustal structure in the western Lake Superior basin, *in* Steinhart, J.S., and Smith, T.J., eds., The earth beneath the continents: American Geophysical Union Geophysical Monograph 10, p. 28-41.
- White, W.S., 1966b, Tectonics of the Keweenaw basin, western Lake Superior region: U.S. Geological Survey Professional Paper 524-E, p. E1-E23.
- White, W.S., Cornwall, H.R., and Swanson, R.W., 1953, Bedrock geology of the Ahmeek quadrangle, Michigan: United States Geological Survey Geologic Quadrangle Map GQ 27, scale 1:24,000.
- White, W.S., and Wright, J.C., 1954, The White Pine copper deposit, Ontonagor County, Michigan: Economic Geology, v. 49, p. 675-716.
- Wold, R.J., and Hinze, W.J., eds., 1982, Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, 280 p.
- Wold, R.J., Hutchinson, D.R., and Johnson, T.C., 1982, Topography and surficial structure of Lake Superior bedrock as based on seismic reflection profiles, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 257-272.

- Wold, R.J., and Ostenso, N.A., 1966, Aeromagnetic, gravity, and sub-bottom profiling studies in western Lake Superior, *in* Steinhart, J.S., and Smith, T.J., eds., The earth beneath the continents: American Geophysical Union Geophysical Monograph 10, p. 66-94.
- Wolff, R.G. and Huber, N.K., 1973, The Copper Harbor Conglomerate (Middle Keweenaw) on Isle Royale, Michigan, and its regional implications: U.S. Geological Survey Professional Paper 754-B, p. B1-B15.
- Woollard, G.P., 1943, Transcontinental gravitational and magnetic profile of North America and its relation to geologic structure: Bulletin of the Geological Society of America, v. 54, p. 747-790.
- Woollard, G.P., 1951, Annual report of the special committee on the geophysical and geological study of continents, 1950-1951: American Geophysical Union Transactions, 32, p. 634-647.
- Yarger, H.L., 1983, Regional interpretation of Kansas aeromagnetic data: Kansas Geological Survey Geophysics Series 1, 35 p.