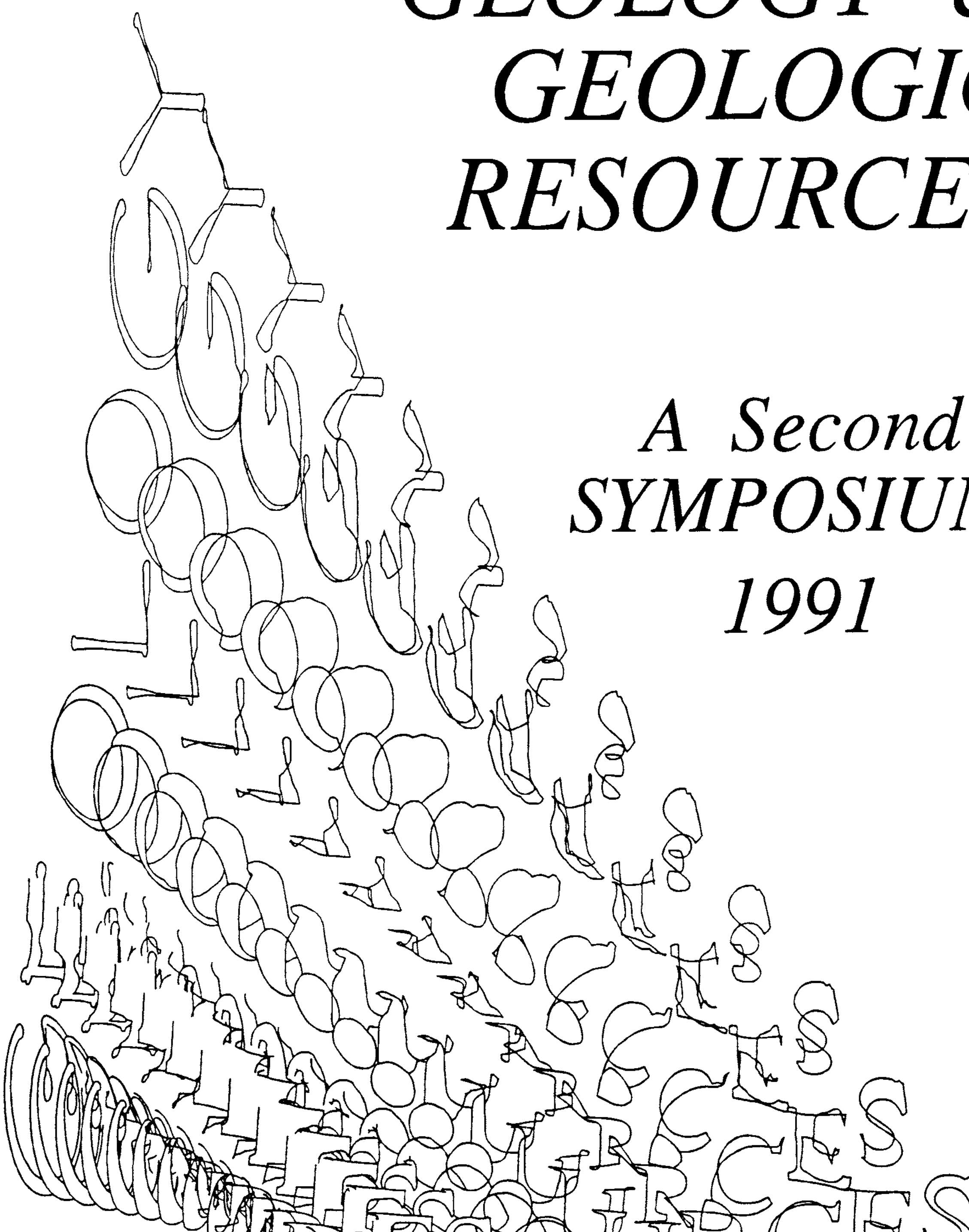
GEOLOGY

MICHIGAN: ITS GEOLOGY & GEOLOGIC RESOURCES



A Second SYMPOSIUM

1991

RESOURCES

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A Second Symposium

Michigan:

Its Geology and Geologic Resources

Program and Abstracts

March 14 and 15, 1991

Hosted by :

Geological Survey Division
Michigan Department of Natural Resources

DNR

at

Kellogg Center
Michigan State University
East Lansing, Michigan

FOREWARD

For over 150 years the Michigan Geological Survey has been mandated to keep current on ideas and information pertaining to the geology of Michigan. Gathering and disseminating this information to others interested in Michigan geology and its geological resources is an important function that this agency can and should provide.

This biennial symposium is meant to provide a unique forum to exchange and share ideas and information on a formal and informal basis. It is most gratifying to me to find such broad-based interest in this symposium. I wish to thank the participants and organizers for their time and effort and give special recognition and gratitude to college and university students who show interest in Michigan geology.

R. Thomas Segall
Chief, Geological Survey Division

COMPLETION OF TOPOGRAPHIC MAPPING IN MICHIGAN

Once-over primary (7 1/2 minute quadrangle) topographic mapping was completed by the U.S. Geological Survey, Mid-Continent Mapping Center, Rolla, Missouri in 1990. This "benchmark" occasion concluded an effort which began in 1902, nearly 90 years ago. In Michigan, there are approximately 1,250 7 1/2 minute quadrangles on a scale of 1:24,000 or 1:25,000. Topographic maps with other scales were also provided including 1:62,500, 1:100,000, 1:250,000, 1:500,000 and 1:1,000,000.

Early in our Second Symposium program, this completion event will be eulogized. Representatives of the U.S. Geological Survey, National Mapping Division, will present a certificate to commemorate the completion of primary topographic quadrangle mapping in Michigan and a framed map of a selected topographic quadrangle.

The Michigan Geological Survey and the U.S. Geological Survey had a cooperative program of topographic mapping from 1961 through 1981 during which time the Michigan Survey contributed approximately 1 1/3 million dollars to this venture.

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Wednesday Evening Program

Pre-registration check-in, cash-bar ice breaker and Poster Session at the Kellogg Center from 6:00 to 8:00 PM.

Thursday - March 14 - Morning Presentations

6:30 to 7:30 AM First Day Speakers buffet breakfast

7:00 AM. Pre-registration check-in and registration opens

Time	Location	Name	Organization	Title
8:00	Auditorium	R. Thomas Segall	WELCOMING REMARKS and USGS Presentation,	
9:00 AM	Auditorium	Oliver, S. J. P.	ICF Resources Incorporated	GRI's Antrim Shale Research Project
	Big 10 A	Esparza, L. E.	U. S. Bureau of Mines	Recent Developments in Michigan's Mineral Industry
9:30 AM	Auditorium	Bailey, D. J. and Maness, T. R.	Tomball, TX Maness Petroleum	Stratigraphic Framework of the Antrim Shale in the Michigan Basin
	Big 10 A	Brozdowski, R. A.	Callahan Mining Corp.	Ropes Gold Deposit, Marquette Greenstone Belt, Michigan: Gold Concentration in a Dilational Bend in a Shear Zone.
10:00	BREAK			
10:15 AM	Auditorium	Butka, R. T. and McGuire, D.	Daniel R. McGuire Inc.	Quality Control of Wellsite Data in the Antrim Shale
	Big 10 A	Wilkin, R. T., and Bornhorst, T. J.	Michigan Technological University	Economic Potential and Geological Relationships in the Granitoids of the Northern Complex, Michigan
10:45 AM	Auditorium	Curtis, J. B., Manger, K. C., & Vessell, R. K	ICF Resources D. K. Davies & Assoc.	Geologic Factors Affecting Antrim Shale Production I - Stratigraphy and Geochemistry
	Big 10 A	Matty, D. J., *et al.*	Central Michigan University	Development of the Peavy Pond Complex, Iron County, Michigan
11:15 AM	Auditorium	Manger, K. C., and Oliver, S. J. P.	ICF Resources	Geologic Factors Affecting Antrim Shale Gas Production II - Geologic Mapping and Fracture Analysis
	Big 10 A	Slitor, W. and Mancuso, J.	Cleveland Cliffs, Inc. Bowling Green Univ.	Stratigraphic Differences Within the Negaunee Iron Formation: Empire Mine Area
11:45	LUNCH			

Thursday - March 14 - Afternoon Presentations

Time	Location	Name	Organization	Title
11:45	LUNCH			
2:00 PM	Auditorium	Nicol, J. E. and Oliver, S. J. P.	ICF Resources Incorporated	Reservoir Characterization of the Antrim Shale
	Big 10 A	Johnson, A. M.	Michigan Technological University	A Mechanism and Model for the Biogenic Origin of Sedimentary Iron Formations
2:30 PM	Auditorium	Smith, M. B.	NSI Technologies	Hydraulic Fracture Treatment Analysis in the Antrim Shale
	Big 10 A	Ho, E. S., Mauk, J. L., & Meyers, P. A.	University of Michigan	The Keweenawan Nonesuch Formation of the Midcontinent Rift, Northern Michigan: Copper-Silver Ore Deposition and Thermal History
3:00	BREAK			
3:15 PM	Auditorium	Bailey *et al*		Antrim Panel Discussion
	Big 10 A	Trow, J.	Michigan State University	Inductive Electrostatic Gradiometry Explains Keweenawan Native Copper Plumbing System
3:45 PM	Auditorium	Dellapenna *et al.*	Western Michigan University	New Stratigraphic Nomenclature for the Antrim Group, Michigan Basin
	Big 10 A	OPEN		
4:15 PM	Auditorium	J. Minthorn and T. Garvin	Halliburton Services	Successful Application of New Technology in Antrim Shale Completions
	Big 10 A	OPEN		

Poster Session 5:00 to 7:00PM

Cash Bar at 6:00PM

Symposium Banquet at 7:00PM
Big 10 Room of the Kellogg Center

The speaker is Dr. Robert L. Bates,
Ohio State University, who will elucidate
"GEOLITERARY FOLLIES"

Friday - March 15 - Morning Presentations

6:30 to 7:30 AM Second Day Speakers Buffet Breakfast

Time	Location	Name	Organization	Title
8:30 AM	Auditorium	Moline, G. R., Shepherd, L. D. and Bahr, J. M.	University of Wisconsin – Madison	The Implications of Multiple Scale Heterogeneity for Regional Hydrodynamic Modeling of the St. Peter Sandstone
	Big 10 A	Benton, S. E., and Passero, R. N.	Western Michigan University	Aquifer Vulnerability in Southwestern Michigan
9:00 AM	Auditorium	Smith, G. L.	University of Wisconsin – Madison	Evidence for Tidally-Influenced Deposition in the "Brazos Shale", Central Michigan Basin
	Big 10 A	Cousins-Leatherman, C. S. & Krause, P.	Kalamazoo County Environmental Health Program	Human Impacts on Groundwater in Kalamazoo County
9:30 AM	Auditorium	Vandrey, R., *et al*	University of Wisconsin – Madison	Geochemical Analysis of the Middle to Late Ordovician Strata in the Michigan Basin
	Big 10 A	Dannemiller, G.	Environmental Science and Engineering, Inc.	Remnant Glacial Groundwater in the Michigan Basin
10:00	BREAK			
10:15 AM	Auditorium	Westjohn, D. B.	United States Geological Survey	Hydraulic Conductivities of Pennsylvanian and Mississippian Sandstones from the Michigan Basin and their Relation to Mineralogy and Borehole Geophysical-Log Responses
	Big 10 A	Kehew *et al*	Western Michigan University	Ground-Water Flow Systems and Distribution of Agricultural Non-Point Source Contaminants in a Glaciofluvial Fan Aquifer
10:45 AM	Auditorium	Young *et al*	Michigan State University	Diagenesis of the Marshall Sandstone
	Big 10 A	Long, D. T. and Wilson, T. P.	Michigan State University	Sources for Water and Solutes in Subsurface Fluids: Michigan Basin
11:15 AM	Auditorium	Brooks, R. *et al*	Team Resources	New Frontier Exploration for Oil & Gas in the Upper Peninsula Michigan & Wisconsin
	Big 10 A	Regis, R. S.	Michigan Technological University	Satellite Image and GIS-Aided Analysis of Glacial Features in the Central Upper Peninsula, Michigan
11:45	LUNCH			

Friday - March 15 - Afternoon Presentations

Time	Location	Name	Organization	Title
11:45	LUNCH			
2:00 PM	Auditorium	Prouty, C. E.	Michigan State University	The Role of Shear Faulting in Fluid Flow Mechanics in the Michigan Basin
	Big 10 A	Rieck, R. L.	Western Illinois University	Bedrock Topography of the Eastern Two-Thirds of Michigan's Northern Peninsula
2:30 PM	Auditorium	Meyers, P. A. *et al*	University of Michigan	Organic Geochemical Reassessment of Petroleum Sources and Thermal History in the Michigan Basin
	Big 10 A	Herman, J. D.	Geospectra Corporation	Surface Expressions of Subsurface Structures in the Northeastern Part of the Michigan Basin
3:00	BREAK			
3:15 PM	Auditorium	Herman, J. D.	GeoSpectra Corporation	Surface Expression of Buried Precambrian Basement Geology on the Northeastern Flank of the Michigan Basin
	Big 10 A	Blewett, W. L. and Winters, H. A.	Shippensburg University Michigan State University	A Reinterpretation of the Inner Port Huron Moraine: Implications for the Northern Great Lakes Region
3:45 PM	Auditorium	R. Turpening and C. Caravana	MIT	Viewing a Hydrofrac in the Antrim Shale with Shear Wave VSPs
	Big 10 A	Winters, H. A. and Rieck, R. L.	Michigan State University	Terrain Characteristics in the Grand Rapids Area Prior to Late Wisconsinan Glaciation
4:15 PM	Auditorium	OPEN		
	Big 10 A	OPEN		

ABSTRACTS of PRESENTATIONS by AUTHOR

STRATIGRAPHIC FRAMEWORK OF THE ANTRIM SHALE IN THE MICHIGAN BASIN

D. J. Bailey – Tomball, Texas and T. R. Maness – Maness Petroleum Corporation

A basinwide network of 14 regional correlation cross-sections was constructed to trace the vertical and lateral changes in the black, highly radioactive shales of the Antrim and the less radioactive gray-green shales of the Ellsworth Formation. Correlations were greatly facilitated by "normalizing" the gamma ray response in over 400 digitized logs used in the data base.

The Antrim/Ellsworth Group can be divided into three formations that can be traced throughout the basin. The lowest Antrim Formation, composed of mainly black shale, can be further subdivided into 4 members. The middle formation is the Ellsworth Formation of western Michigan that steadily increases in radioactivity as it is traced into eastern Michigan. The upper formation (unnamed) is mainly black shale and is confined to the eastern two thirds of the basin.

There appears to be little interfingering of these units. The distribution of the shales suggests that the main source of these sediments was from the north and west into an oxygen stratified water body where dysaerobic to anerobic conditions fluctuated periodically on a regional scale.

AQUIFER VULNERABILITY IN SOUTHWESTERN MICHIGAN

Steven E. Benton and Richard N. Passero – Western Michigan University

Several methods have been developed to determine the vulnerability of aquifers to contaminants discharged on the land surface or at shallow depths. Two methods currently in use are the National Water Well Association's DRASTIC system and the U.S. Soil Conservation Services' SEEPPAGE system. These systems use weighted factors to generate a number that indicates the relative vulnerability of an aquifer. The factors used account for many of the physical and chemical processes that control the movement and fate of contaminants, however, this data may be difficult to obtain and quantify. Another system currently in development is the AQUIPRO model. AQUIPRO (Aquifer Protection) uses data reported on water well records to generate a number (score) that indicates the relative protection or vulnerability of an aquifer. The factors used are well depth, lithology (clay and clay-sand-gravel mixtures), and numbers of these lithologic units. The AQUIPRO program was written for IBM-compatable microcomputers and uses well records from WELLKEY available from the Michigan DNR Geological Survey, MIRIS, and other sources.

The AQUIPRO model is being tested in southwestern lower Michigan by correlating AQUIPRO scores with groundwater contamination related to Act-307 sites, suburban housing plats, agricultural areas, and a proposed landfill site. In Kalamazoo County AQUIPRO scores were calculated for wells near 49 Act-307 groundwater contamination sites. Scores reflect the fact that there are not significant amounts of clay and/or partial clay beneath the sites. An exception is the KL landfill where a thick layer of till protects a deep uncontaminated aquifer. AQUIPRO scores for wells screened below the till are greater by a factor of ten than wells screened above the till.

The model was also tested on three suburban residential plats with relatively high nitrate concentrations in the ground water, presumably from septic tank systems. Well records, partial chemical analyses, and septic tank system permits were available for 95 residences. Nitrate concentrations were compared to AQUIPRO scores, well depths, clay and partial clay thicknesses, depths to static water level (SWL), well depths below SWL, and the time from well installation to the date of sampling. Neither the Meadow Wood or Prairie Brook plats had significant thicknesses of clay or partial clay and SWLs were relatively close to the surface. No significant correlations were found in these plats. At Cooper Hills, significant correlations were found for AQUIPRO scores, well depths, clay thicknesses, and well depths below SWL. Isopach maps and cross-sections were constructed to show the distribution of nitrate, clay, and partial clay.

In Wakeshma Township statistical analyses were used to determine the relationship between ground-water nitrate concentrations in an agricultural area and AQUIPRO scores, well depths, clay and partial clay thicknesses, depths to SWL, and well depths below SWL. Partial chemical analyses were used for 41 wells, 18 of which had nitrate concentrations above detectable limits. Significant correlations were found for AQUIPRO scores, clay thicknesses, well depths, and well depths below SWL. Isopach maps and cross-sections were constructed to show the distribution of nitrate, clay and partial clay thickness, and clay in the upper 50 feet of the wells.

AQUIPRO scores were calculated for an area in which a Type II landfill has been proposed and the hydrogeology of the area has been studied in detail. Significant correlations were observed between AQUIPRO, AQUIPRO factors, and tritium and nitrate concentrations in the groundwater.

AQUIPRO scores were calculated for monitoring wells and private wells on or near Act-307 sites in Calhoun County. The data was obtained from hydrogeologic reports. Presently, AQUIPRO is being used in Van Buren County as it relates to the distribution of nitrates from agriculture and chloride from oil field brines. In the near future, AQUIPRO will be compared to over 400 nitrate values and a recently produced U.S. Geological Survey DRASTIC map for Kalamazoo County.

A REINTERPRETATION OF THE INNER PORT HURON MORAINE: IMPLICATIONS FOR THE NORTHERN GREAT LAKES REGION

William L. Blewett – Department of Geography-Earth Science, Shippensburg University and – Harold A. Winters, – Department of Geography, Michigan State University

On the basis of reconnaissance mapping in northwestern southern Michigan, Leverett and Taylor (1915) identified a northeast- southwest trending topographic complex they named the Inner Port Huron Moraine, flanked by an associated valley train complex of similar orientation called the Mancelona Plain. Recent analysis based on 1) detailed field mapping, 2) soil maps, 3) topographic quadrangles, 4) water and petroleum well logs, and 5) aerial photographs indicates that these morainic tracts are actually hummocky proximal topography associated with an especially prominent and important head of outwash graded to the Mancelona Plain. Evidence includes 1) landforms with distinct asymmetrical profiles, 2) surficial formations containing thick (80 m) glaciofluvial deposits (but no till) in areas mapped as moraine, and 3) uppermost glaciofluvial sediments that show a transition from coarse, poorly sorted proximal deposits dominated by longitudinal bars to distal, fine-textured, well-sorted braided stream deposits displaying sandy bedforms. Morphologic and sedimentologic similarities among the Inner Port Huron feature and other topographic complexes mapped as moraine in northern Michigan (Blewett and Rieck, 1987) suggest that the present findings may have wide applicability throughout the northern Great Lakes region.

NEW FRONTIER EXPLORATION FOR OIL AND GAS IN UPPER PENINSULA, MICHIGAN AND WISCONSIN

Robert A. Brooks, and Robert T. Stolzle – Team Resources Corp., and Earl Haney – Roze Energy

The Michigan Basin has produced in excess of 1.75 billion barrels of oil and 2.75 trillion cubic feet of gas from Paleozoic formations. Much of the hydrocarbon has come from the Ordovician and Silurian formations. These formations occur throughout the basin. At their deepest known location, the base of the Paleozoic is about 16000 feet below sea level. On the southern periphery, the Ordovician and Silurian drape over various folds such as the Findlay Arch and extend into other basins. To the East, North, and West, however, these units outcrop.

The portion of the Michigan Basin that is located in Eastern Wisconsin and Michigan's Upper Peninsula contains a rapidly thinning wedge of lower Paleozoic sediments. Despite the fact that Ordovician and Silurian sediments are prolific oil producers elsewhere in the Michigan Basin, very few drill holes have penetrated deeper than the Silurian system north of the Northern Reef Trend in Michigan. There have been documented oil shows from the few exploratory wells drilled in this area from the 1930's to the present.

The sparse well control can provide only a minimal structural and stratigraphic framework. However, gravity and magnetic data indicate large anomalies that are believed to represent large untested structural closures. Satellite imagery, geomorphic analysis and geochemistry are some of the tools that have been applied to further the understanding of the geology of this area of the Michigan Basin and aid in the selection of the most prospective drill sites.

ROPES GOLD DEPOSIT, MARQUETTE GREENSTONE BELT, MICHIGAN: GOLD CONCENTRATION IN A DILATIONAL BEND IN A SHEAR ZONE

Robert A. Brozdowski – Callahan Mining Corporation, Negaunee, Michigan

The Ropes gold deposit is in the Late Archean Marquette greenstone belt in Michigan's Upper Peninsula. The deposit is near a northeast striking transition between basalt flows and dacite tuffs, along which serpentinized peridotite is emplaced. A tabular trend of quartz-sericite-chlorite rock, which is altered dacite tuff, strikes east-northeast from this transition and hosts ore. Carbonate- quartz-chlorite rock, which is sheared and altered peridotite, immediately bounds the quartz-sericite-chlorite rock. This is bounded on north and south by carbonate-talc rock, then outward by serpentinized peridotite.

The deposit is 2.8 million tonnes with 3.7 g/tonne Au; near vertical, 335 m in strike, 600 m down dip, and 12 m average thickness. 95% of the ore is characterized by dispersed sub-100 micron pyrite, with micron gold included or attached, in quartz- sericite-chlorite rock. This type of ore is zoned longitudinally into three subtypes with differing proportions of quartz, sericite, chlorite, and pyrite. Silver is with tetrahedrite, galena, and electrum. Au/Ag is 0.65. Five per cent of the ore is layered auriferous quartz veins at the south side of the deposit.

The deposit is in a 080 degree striking dilational bend in a steeply south dipping, high angle reverse, oblique dextral, brittle-ductile shear zone which strikes 070 degrees overall. Shear was along a line plunging 60 degrees east, indicated by oblique shear quartz veins and by zones of gold concentration with dispersed pyrite, which are oriented in right stepping en echelon, low angle sigmoidal fashion, and by S-C kinematic indicators. Sericite, chlorite, and auriferous pyrite aligned along schistosity indicate hydrothermal alteration and gold deposition were contemporaneous with simple shear deformation. Contacts of the quartz-sericite-chlorite rock with bounding rocks were weaknesses which localized shear. Quartz-sericite-chlorite rock which hosts the ore dips less steeply near surface, and narrows up dip and eastward: this constriction may have focussed ascending hydrothermal fluids. Carbonatization of serpentinized peridotite, and sericite alteration of dacite tuff were, respectively, sinks for carbon dioxide and potassium. Simple mineral assemblages and limited compositional ranges of the rock- forming minerals suggest homogenization of the system by pervasive fluid flow, which was promoted by the dilational characteristics of the shear zone.

QUALITY CONTROL OF WELLSITE DATA IN THE ANTRIM SHALE

R. T. Butka and D. McGuire – Daniel R. McGuire Inc.

The Devonian Antrim Shale of the Michigan Basin continues to be one of the most active gas plays in the United States. Although the Antrim Shale has been productive in the Otsego County area for over forty years, the introduction of gas lift technology substantially improved economics and encouraged current activity, as well as exploration into adjacent counties.

Antrim reservoir characteristics, and hence gas production, varies considerably between wells. To better understand the factors affecting gas production, we have collected substantial quantities of data at the wellsite during drilling. Of the utmost importance is quality control while gathering data; basic knowledge of factors such as formation tops and gross lithology can ensure best data possible.

This paper presents procedures and formats for gathering essential wellsite geological data in a timely and cost effective manner. Such data can provide critical information, not only on a single well basis, but also at the field level.

HUMAN IMPACTS ON GROUND WATER IN KALAMAZOO COUNTY

C. S. Cousins-Leatherman and P. Krause – Kalamazoo County Environmental Health Program

Thick glacial and alluvial deposits provide the drinking water for more than 95% of the residents, industries, and commerical operations located in Kalamazoo County. The current population for the county is over 215,000 people, growing at a projected rate of 3.8% per year. For the last four years this growth has resulted in an average of 600 new wells and 900 new septic systems installed each year. While the ground water reserves total more than an estimated 144 million gallons per year, the quality and quantity of ground water (priority use is drinking water) is being impacted by human activities in the county. As of this date, more than $2 million have been spent from State Act 307 funds on alternative water supplies for homes and businesses that had contamination incidents such as spills, on-site sewage discharges, leaking underground tanks and the disposal of hazardous waste.

The Environmental Health Program (EHP) of the County Human Services Department has taken an active role in monitoring and evaluating the impacts humans have on the quality of drinking water in the county. Utilizing

a combination of software programs and computerized mapping systems, the EHP is mapping the shallow and deeper aquifers in the area. This information is overlayed with the locations of point and nonpoint sources of contamination and the known areas of contamination for several townships in the county, to provide a total picture of the resource and how badly it is contaminated.

The final maps and their descriptions are being presented to local boards of zoning and planning and to the local public water supplies for inclusion in long-term plans and wellhead protection programs. The information will also be utilized in the siting process for a non hazardous waste landfill.

GEOLOGIC FACTORS AFFECTING ANTRIM SHALE PRODUCTION I - STRATIGRAPHY AND GEOCHEMISTRY

John B. Curtis, – Colorado School of Mines; Katherine C. Manger – ICF Rescources; and Richard K. Vessell – David K. Daves and Associates Inc.

Drilling of the Antrim Shale has increased dramatically over the last few years. However, the effect of lithologic and geochemical variations on well performance is not well understood. Mineralogical, organic, geochemical, and textural differences between the Antrim lithologies influence the potential pay zones in the black shale units and their response to stimulation treatment. Four lithologies have been identified in the Antrim: an organic-rich black shale, two gray shales, one carbonate-rich shale with an almost crystalline texture and another with a more clastic texture; and a green shale found mostly in the Upper Antrim. The relative positions and relationships of these lithologies may affect response to stimulation treatment. Also, X-ray diffraction analysis has identified significant quantities of muscovite, previously unreported in the Antrim Shale. GRI has shown muscovite orientation in the Appalachian Basin shales to be indicative of porosity.

Geochemical analyses of wells in Otsego, Gladwin and Ogemaw counties identified the black shales as high quality source rocks, containing up to 30% organic carbon by volume. The source rocks appear to be actively generating gas with associated mudlog shows indicating the presence of permeable gas-filled zones. The organic carbon is probably of marine origin making it prone to generating oil. However, it is only marginally thermally mature and has not reached peak oil generation. Free oil was measured in cuttings and core samples but does not flow in commercial quantities probably due to the nature of the Antrim's microporosity network and low matrix permeability.

The geochemical data were used to construct GRI Hydrocarbon logs for each of the study wells. The Hydrocarbon log can be used to identify the location of free gas and oil, and relative permeability to gas. Readily constructed from drill cuttings canned on-site, GRI's Hydrocarbon Log provides useful information to aid in the selection of gross completion intervals and to predict the production potential of wells drilled outside the established play area.

REMNANT GLACIAL GROUND WATER IN THE MICHIGAN BASIN

Gary Dannemiller – Environmental Science and Engineering, Inc.

Ground water derived from bedrock in the Michigan and Saginaw lowlands contains high dissolved solids (1,000 to 100,000 mg/L). The ground water in these areas is also thought to be derived from glacial recharge water. Oxygen isotopic values (delta -13.8 to -18.19 per mil oxygen-18) are depleted by comparison (delta -11.6 to -9.9 per mil oxygen-18). The high dissolved solids content is not characteristic of glacially derived water which brings into question the origin of the ground water. Analysis of ground water in the lowland areas for carbon-14 resulted in apparent ages of 24,000 to over 32,000 years before present. A possible explanation for this can be found in a reversal of ground water flow paths from the last glacial event (13,000 years before present) to that presently existing. The lowland areas were ground water recharge areas during the glacial period and are now discharge areas. Glacially derived recharge ground water has been trapped since deposition beneath thick lacustrine clays and prevented from discharging or mixing with modern age surface derived recharge water. Mixing of the glacial waters with upwelling ground water of high dissolved solids content resulted in the ground water quality observable today. Glacial recharge ground water which was deposited throughout the remainder of the basin has since been diluted beyond isotopic recognition or flowed out of the ground water system since deposition.

Ground water in the northern areas of the basin which have a depleted oxygen-18 isotopic value (-14.5 to -12.6 per mil oxygen-18) in comparison to the southern part of the basin (-9.5 to -8.5 per mil oxygen-18) has a modern carbon-14 age date and is not the result of a glacial recharge event. These depleted isotopic values are the result of local climatic difference over the basin.

NEW STRATIGRAPHIC NOMENCLATURE FOR THE ANTRIM GROUP, MICHIGAN BASIN

Timothy M. Dellapenna, Marnie Twynham, and William B. Harrison III – Western Michigan University

New stratigraphy is proposed for the previously known Antrim Shale and Ellsworth Shale. The Antrim Group is here devised to include three formations: the Sanilac, Ellsworth, and Antrim Formations. The Sanilac Formation contains the black shales which were formerly contained within the upper portion of the Ellsworth Shale in western Michigan and the upper black shales contained in the Antrim Shale of eastern Michigan. The Ellsworth Formation is composed of the gray shales below the upper black shales of what was formerly the Ellsworth Shale in western Michigan, and the gray shales of the "Upper" or "Light Antrim" of eastern Michigan. The Antrim

Formation is composed of black and gray shales below the Ellsworth Formation and includes the "Traverse Formation". The Antrim Formation has been subdivided into four members: the Chester Black Shale, previously known as the Upper Black Shale; the Crapo Creek Gray Shale, previously known as the Middle Gray Shale; the Charlton Black Shale, previously known as the Lower Black Shale; and the Mud Lake Gray Shale, previously known as the Traverse Formation. Type localities for the new stratigraphic units are also proposed.

RECENT DEVELOPMENTS IN MICHIGAN'S MINERAL INDUSTRY

Leon E. Esparza – U.S. Bureau of Mines

The estimated value of Michigan's nonfuel mineral production was $1.586 billion in 1989, a slight decline from the $1.588 billion reported in 1988. Value of output for 1990 also is expected to decrease slightly. The anticipated decline in 1990 is partially attributed to a labor dispute that idled the State's two iron ore mines in August. Another factor is a continued sluggish demand for nonresidential construction due to high interest rates and general caution by financial lenders because of the burgeoning nationwide savings and loan scandal. Michigan, in recent years, has ranked fourth, nationally, in value of nonfuel mineral production. The State leads the Nation in production of calcium compounds, crude iron oxide pigments, magnesium compounds, and peat. It is the Nation's second leading producer of iron ore, construction sand and gravel, and industrial sand behind Minnesota, California, and Illinois, respectively. Metallic minerals account for about 45% of the State's nonfuel mineral value; construction materials, approximately 40%; and commodities extracted from brines, about 15%. Iron ore is the State's leading commodity, followed by portland cement and construction sand and gravel.

Exploration for precious metals and diamonds has been at a modest pace in recent years. Diamond exploration on State and private lands continued in northern Michigan near Crystal Falls by Crystal Exploration Inc. and Exmin Corp. The State Department of Natural Resources held a metallic mineral lease sale in May 1989 for 14,000 acres in four counties. Iron ore producers at the Tilden and Empire Mines operated at capacity levels until a strike idled the mines in August 1990. A roof fall at the White Pine Mine, operated by Copper Range Company, temporarily halted copper production in February 1989; by June, however, operations resumed. In May 1989, Metall Mining Corp. purchased Copper Range and the White Pine operation. Gold production at the Callahan Mining Co. Ropes Mine was halted in September 1989 because of a soft market and unstable ground around the shaft. The operation remained idle during 1990. Demand for crushed stone used in iron ore pelletizing and steelmaking was at a high level throughout the 2-year period. In 1989, LaFarge Corp. announced a multi-year expansion and modernization plan for its Alpena cement plant with the intent to boost annual production capacity to 2.5 million short tons.

SURFACE EXPRESSION OF BURIED PRECAMBRIAN BASEMENT GEOLOGY ON THE NORTHEASTERN FLANK OF THE MICHIGAN BASIN

John D. Herman – GeoSpectra Corporation

Magnetic and gravity data imagery were used to identify the boundaries of 3 major buried Precambrian basement provinces on the eastern half of Manitoulin Island, including the Southern, Eastern Granite-Rhyolite, and Grenville Provinces. Automatic lineament mapping and automatic lineament trend mapping programs applied to LANDSAT MSS and digital elevation data revealed correlations between the trends of surface lineaments and the trends of buried basement structures and other boundaries mapped from potential field imagery. Within the area inferred to overlie the Grenville and Eastern Granite-Rhyolite Provinces, automatically

mapped LANDSAT lineaments have predominantly northeast trends, parallel to those in the basement. In the area inferred to overlie the buried Southern Province in which east-west basement trends are dominant, nearly east-west trending surface lineaments are more common than they are to the east in the area overlying the Eastern Granite-Rhyolite Province. Manual interpretation of the LANDSAT, digital elevation and potential field imagery shows correspondence in trends and locations between major coastal inlets and inferred buried basement boundaries. Several

positive magnetic anomalies thought to be associated with Middle Proterozoic granitic intrusive complexes correlate with the locations of large lakes. Particularly prominent manually mapped LANDSAT lineaments inferred to be the surface expressions of subsurface faults correlate with locations of basement faults manually mapped from magnetic intensity imagery. Five small oil fields which produced oil from equivalents of the Trenton and Black River Groups also occur along these inferred basement faults, implying basement control of the oil traps.

Even though the Precambrian basement may be buried by as much as 500 meters of Paleozoic rock and Pleistocene glacial overburden, significant Precambrian basement control of surface features is implied by the correlations among lineaments mapped from LANDSAT, digital elevation, and potential field imagery.

SURFACE EXPRESSIONS OF SUBSURFACE STRUCTURES IN THE NORTHEASTERN PART OF THE MICHIGAN BASIN

John D. Herman – GeoSpectra Corporation

Study of glacial geology, stream drainage, bedrock topography, and subsurface structure maps of Isabella, Midland, Arenac, Gladwin, Clare, Ogemaw, and Iosco Counties revealed distinct correlations between patterns and types of glacial deposits and subsurface structures. Anticlinal structures associated with the Mt. Pleasant, Buckeye North and South, Hamilton, Deep River, Clayton, Logan, and West Branch oil and gas fields occur along areas where northeast trending glacial moraines are truncated, attenuated or deviated. Furthermore, these anticlinal structures are associated with lacustrine sands and gravels and glacial outwash deposits nearly surrounded by glacial tills or lacustrine sands and clays. All of these anticlinal structures are associated with bedrock topography highs and, stream drainage features are parallel to the trends of the structures. These correlations between subsurface structure, bedrock topography, and surface glacial features indicate that the subsurface structural configuration influenced glacial depositional patterns in detectable and predictable ways.

THE KEWEENAWAN NONESUCH FORMATION OF THE MIDCONTINENT RIFT, NORTHERN MICHIGAN: COPPER-SILVER ORE DEPOSITION AND THERMAL HISTORY

Eileen S. Ho, Jeffrey L. Mauk and Philip A. Meyers – University of Michigan

The unmetamorphosed, Proterozoic sedimentary rocks of the Nonesuch Formation pose intriguing questions with regard to Precambrian biology, petroleum generation, and ore deposition. Our study investigates the nature and timing of geochemical processes involved in ore deposition (i.e. the role of organic matter in copper mineralization) in the Nonesuch Formation within the context of the thermal history of the Lake Superior portion of the Midcontinent Rift.

Stratiform copper deposits are hosted by shales, siltstones, and sandstones in the basal portion of the Upper Keweenawan-age Nonesuch Formation and the uppermost Copper Harbor Conglomerate. These sediments are part of a volcanic-clastic infilling of the Lake Superior segment of the Midcontinent Rift System. The presence of abundant organic matter, including occurrences of migrated petroleum, may have been an important factor in the deposition of ore metals in the Nonesuch and upper Copper Harbor strata.

The classic, main-stage mineralization event involved cupriferous fluids which migrated into the Nonesuch Formation from underlying strata, resulting in the deposition of primarily disseminated chalcocite with some native copper. The stratiform copper deposit is best represented at the White Pine Mine in Ontonogan County, MI. Both regionally and within the mine, ore-grade copper mineralization is confined to specific stratigraphic horizons: the black and dark-gray shales and siltstones containing the highest concentrations of organic matter. This observation implies that geochemical interactions between sedimentary organic matter and hydrothermal fluids caused deposition of the metal ores.

Recent work in the southwest portion of the mine has revealed a second-stage of copper mineralization associated with thrust and tear faulting. Second-stage mineralization is superimposed upon the main-stage mineralization, consisting mainly of native copper and some copper sulfides in high-angle and bedding parallel veins and veinlets. The relationship between structures and second-stage mineralization in the mine suggests that cupriferous fluids were introduced during the thrusting event. Petroleum seeps and occurrences which are also associated with the thrusting event provide further constraints on the timing of and thermal conditions during the tectonic deformation of the Nonesuch Formation.

A MECHANISM AND MODEL FOR THE BIOGENIC ORIGIN OF SEDIMENTARY IRON FORMATIONS

Allan M. Johnson – Michigan Technological University

Research on acid mine drainage and on bioleaching applications for metal recovery processes reveal some interesting facts on some aspects of the biogeochemistry of iron. When assembled properly, these data can be interpreted to form a consistent rational model for the origin of some sedimentary iron formations.

The model invokes sulfur and iron oxidizing bacteria (e.g.: Thiobacillus ferrooxidans and related genera) acting on pyrite and other metal-bearing sulfides. These lithotrophic bacteria extract energy for their sustenance from the oxidation of sulfide minerals. During this process, they produce an acidic environment which is capable of mobilizing the dissolved iron (and other metal ions) at rates of one million fold over non-biogenic systems. The solubilized iron can be easily transported to some sedimentary basin where normal chemical reactions occur to precipitate the iron as relatively insoluble ferric hydroxide compounds. These deposits could well be the precursor to a sedimentary iron formation.

Supporting evidence based on geology, mineralogy, environments of deposition, and geochemistry consistent with this model will be presented.

GROUND-WATER FLOW SYSTEMS AND DISTRIBUTION OF AGRICULTURAL NON-POINT SOURCE CONTAMINANTS IN A GLACIOFLUVIAL FAN AQUIFER

Alan E. Kehew, W. Tomas Straw, Patrick G. Barrese, William K. Steinmann, and Michael C. Kasenow – Western Michigan University

The highly productive Schoolcraft aquifer in southwestern Michigan is a thick body of glacial outwash of which at least the uppermost 100 feet were deposited in a glaciofluvial fan covering a surface area of about 60 square miles. Large capacity wells tap the aquifer and support extensive irrigation of commodity crops including corn, beans, wheat and "snap" beans. This unconfined, sole source aquifer is extensively contaminated with nitrate ranging up to 50 ppm.

More than 30 piezometers, including 10 vertical nests were installed to define stratigraphy and ground-water flow in the aquifer, identify recharge and discharge areas, and determine ground-water quality. Head distributions, water-quality data and tritium levels indicate that flow is subhorizontal in shallow local systems that are recharged by direct infiltration and interact with lakes and wetlands; and virtually horizontal in the deeper regional system that is recharged near the head of the fan. High tritium content in shallow wells versus very low levels in deep wells supports this interpretation.

Configuration of the flow systems limits nitrate and other contaminants to the shallow flow systems. Completion of relatively low-yield water-supply wells near the base of the deeper flow system may provide protection from contamination in the shallow flow systems. The effects of drawdown by high yield irrigation wells on contaminant distributions have yet to be determined.

SOURCES FOR WATER AND SOLUTES IN SUBSURFACE FLUIDS: MICHIGAN BASIN

David T. Long – , Earth's Surface Systems Program, Geological Sciences, Michigan State University, and – Michigan RASA Program, U.S. Geological Survey, Lansing, Michigan and – Timothy P. Wilson, Geology, Kent State University

Inputs from marine and meteoric water and processes, such as water-rock reactions, determine the isotopic and geochemical character or signature of subsurface fluids in sedimentary basins. Models developed for the origin and evolution of these fluids based on interpretations from the isotopic signature are expected to be compatible with models based on the aqueous geochemical signature. This study investigates whether isotopic and geochemical signatures can be linked in determining the origin of subsurface waters in the Michigan basin.

This question is addressed by interpreting the sources of the water molecules and solutes from the study of stable isotopes (del deuterium and del oxygen-18) and aqueous geochemistry, respectively. Data for this study include a basin wide survey of approximately 500 samples collected from wells completed in formations ranging in age from Silurian

to Quaternary. The data were reduced by graphical and statistical analyses and chemical modeling.

The results show that there is a systematic variation in the isotopic and aqueous geochemical signature of the ground water, both vertically and horizontally. Local anomalies in the signature appear to be related to the effects of glaciation. A variety of geochemical facies can be delineated in waters from Pennsylvanian- and Mississippian-age units because these waters are between brines deeper in the basin

and fresh near-surface ground water. Water in bedrock formations at the margins of the basin generally has a lower dissolved-solids concentration than water at the center of the basin. Most water in the basin originated as postglacial, glacial, and interglacial meteoric water, or seawater. Major sources of solutes include meteoric water, seawater, and the dissolution of halite. The geochemical signature has been modified by water-rock interactions and microbiological processes.

The results also show that a major control on the isotopic and aqueous geochemical signatures of the Michigan basin ground water is the mixing of brine and modern meteoric water. Plots of the regressions of del deuterium against Br

and del oxygen-18 against Br also show that the dilute end-member water is modern meteoric water.

On the basis of these results, a relation exists between isotopic and aqueous geochemical signatures for the ground water in the Michigan basin.

GEOLOGIC FACTORS AFFECTING ANTRIM SHALE GAS PRODUCTION II - GEOLOGIC MAPPING AND FRACTURE ANALYSIS

Katherine C. Manger and Stephen J. P. Oliver - ICF Resources Incorporated

Although the Antrim Shale has seen a dramatic increase in drilling

activity over the past two years, little is known about its geology and the geologic controls affecting gas production. As part of the Gas Research Institute's field-based project, we examined geologic factors affecting Antrim gas recovery in southwest Otsego County. Subsurface mapping and fracture analysis based on geophysical log and core data suggested a correlation between Antrim Shale geology and gas and water production. Subsurface mapping of the Lower Antrim identified several structural and isopach trends. Structural mapping identified regional and local highs that possibly influenced the migration and accumulation of gas. The structural highs represent potential sites of structural trapping. Well location relative to these highs may affect the amount of gas produced and gas-water ratios.

Isopach mapping revealed variations in thickness for the shale units making up the Antrim. These variations may be associated with changes in reservoir rock volume and indicative of stratigraphic trapping. Areas with thicker black shale sequences may suggest greater reservoir volume while pinch-outs and other changes in bed thickness may indicate stratigraphic

trapping.

Combined evaluation of the structural and isopach maps highlighted regions with both structural and stratigraphic enhancement. These areas should have the greatest potential for high gas productivity. Comparison of the mapped features to available production data indicates that a correlation exists.

Fracture analysis of cores combined with Formation Microscanner logs and Borehole TV identified a dominant northeast-southwest fracture set with vertical to steep northwest dips. A much weaker conjugate set may also be present in some of the facies. Minor bedding plane fractures occur in the black shales but not in the gray shales. Fracture intensity varies depending on the lithology of the shale. The strong orientation of the principal fracture set suggests that well performance may be affected by well direction.

DEVELOPMENT OF THE PEAVY POND COMPLEX, IRON COUNTY, MICHIGAN

D. J. Matty, K. Huysken, S. D. Stahl, and A. Heft - Department of Geology, Central Michigan University

The Peavy Pond Complex (PPC) is a metamorphosed, composite pluton of Penokean age that intrudes complexly deformed, biotite to sillimanite grade pelitic to quartzose shales and graywackes of the Proterozoic Michigamme Formation (MF) and basic pyroclastics and lavas of the Proterozoic Hemlock Formation (HF). The lithologic succession gabbro-diorite-granodiorite-granite characterizes the complex. In the southern portion of the complex, gabbro and diorite are the dominant lithologies and are commonly associated with HF wallrocks. The more silicic tonalites, granodiorites and granites are restricted to outcrops primarily in the northwestern portion of the complex. Here, the igneous rocks lie in close proximity to those of the MF; these rocks often contain xenoliths of MF and develop locally into migmatites.

Bayley (1959) and Dutton (1968) mapped the PPC and surrounding area in considerable detail. Bayley suggested that the mafic rocks of the PPC evolved through fractional crystallization of a parental basaltic magma. He considered the more silicic phases of the complex to have been derived from variable assimilation of the MF by this parent magma. Other

explanations for the development of the complex must be considered, however, inasmuch as Bayley's interpretations were based principally on field and petrographic data. Other mechanisms potentially related to the evolution of the PPC include development of each phase of the PPC as a separate magma, variable mixing of magmas, partial melting of wallrocks, or some combination of these processes with the fractionation- assimilation mechanism suggested by Bayley.

The PPC has potential tectonic significance in that it intrudes rocks considered to represent a passive margin sequence (Larue, 1981; Ueng et al., 1988), a rifted passive margin assemblage (Cambray, 1978), a forearc or backarc basin (VanSchmus, 1976), or a foredeep (Hoffman, 1988; Barovich et al., 1989). Recent studies of the Hemlock volcanics and the associated Kiernan Sills (which lie about 4 km to the north of the PPC) indicate that these rocks are characterized by geochemical signatures similar to MORB. While these data suggest a MOR-like rift-related origin for these units, they could be interpreted to conversely reflect a back-arc origin for the HF and Kiernan Sills (Ueng et al., 1988; Wee, 1989). The spatially associated Badwater (Greenstone) Formation displays geochemical characteristics that suggest an origin closely related to that of the HF and the Kiernan Sills (Cudzillo, 1978; Wee, 1989).

The goals of our study were to determine the processes by which the PPC evolved and to gain insights into the tectonic evolution of this area through geochemical studies of the PPC.

MAJOR ELEMENT VARIATIONS WITHIN THE PPC - Plots of major oxides vs. FeO/(FeO + MgO) for our PPC data relative to that of the MF, the HF, the Kiernan Sills, the Badwater Fm. and the Northern Wisconsin Arc Complex clearly distinguish mafic phases of the PPC from other units largely on the basis of the higher MgO and lower FeO concentrations of the PPC rocks. With increasing differentiation, the mafic PPC phases show relatively strong depletions in FeO, MnO, and MgO and corresponding enrichments in Al2O3, Na2O, K2O, and to some extent in TiO2. These trends suggest that fractionation was dominated by crystallization of ferromagnesian mineral phases rather than by phases such as plagioclase. Similar trends involving FeO, MgO, and Na2O + K2O appear on AFM diagrams; these further indicate the tholeiitic nature of the mafic phases of the PPC. The more silicic phases of the complex tend to converge towards the compositions of the MF rocks indicating possible interaction of the MF in the evolution of the PPC as suggested by Bayley (1958). Generally higher concentrations of K2O, SiO2, and to some extent Na2O in the silicic PPC phases relative to the MF could be interpreted as resulting from assimilation processes, however, the elevated concentrations of these elements could also be explained by partial melting of MF rocks near the minimum within the Q-Ab-Or-H2O system.

TRACE ELEMENT VARIATIONS WITHIN THE PPC - Like the major elements, trace elements provide useful information that allow discrimination between the mafic rocks of the PPC and other mafic rocks of the region. For example, concentrations of Sc and Co are generally lower and concentrations of Ni, Ta, Ba and Sr are generally higher in the PPC rocks than in the HF, Kiernan metagabbros, or Badwater Fm. In the mafic phases of the PPC, compositional trends of decreasing Sc, Cr, Co, and Ni with increasing differentiation are present; such trends are consistent with the removal of phases that preferentially incorporate these elements, perhaps chromite, olivine, pyroxene, or some combination thereof. Mafic samples that are clearly cumulates have been noted in the field and in the lab; chemically, these samples typically are characterized by the most extreme compositions among the mafic samples. Fractionation of oxides, olivine or pyroxene would increase the relative concentrations of Ba and Rb in more differentiated rocks of the complex, consistent with observed trends. The increase of Sr concentration with increasing differentiation supports the assumption of little plagioclase fractionation, since this process would result in a systematic decrease in Sr with increasing differentiation. Limited plagioclase fractionation is also supported by REE data which are characterized by relatively flat, LREE-enriched, profiles and development of only small positive and negative Eu anomalies.

Trace element concentrations of PPC silicic rocks also converge towards the compositions of MF rocks, supporting the hypothesis of MF involvement in the evolution of these rocks. This is discussed further below.

SPIDERGRAMS - To test the validity of the hypothesis that silicic PPC rocks are related by assimilation or partial melting of MF rocks, we constructed spidergrams (modified from Thompson, 1982) normalized to average MF as well as to average MORB.

Among other things, the spidergrams indicate that rocks of the HF are depleted in LILE and enriched in HFSE relative to MF. The PPC diorites and gabbros appear similar in most respects to the HF rocks; major exceptions are the higher concentrations of Sr and the lower concentrations of Th, P, Y, and Yb in the PPC rocks. The lower Th concentrations in particular are noteworthy in that these values may reflect differences in the relative source regions and/or ascent paths of the PPC and the HF. In comparison to average MORB, both the HF and the mafic phases of the PPC are enriched in LILE.

The PPC tonalites, granodiorites and granites cluster around the average MF composition. There is only a small overall variation from unity (and thus from average MF) for the PPC tonalites. This could result from 1) large-scale contamination of gabbroic parental magmas by assimilation of extensive amounts of MF or 2) almost complete melting of MF to form the tonalites; the latter hypothesis is broadly consistent with observed major element data. The elevated concentrations of the LILE, the LREE, as well as Zr and Hf in the PPC granites and granodiorites relative to average MF suggest that partial melting processes rather than assimilation processes were dominantly responsible for the production of these rocks; this is consistent with interpretations regarding the major element compositions of these rocks. When normalized relative to MORB, the silicic phases of the PPC are characterized by large LILE enrichments as well as enrichments of certain HFSE.

TECTONIC DISCRIMINATION - The determination of the tectonic setting of the PPC has some bearing on our understanding of the geologic evolution of this region of the continent. In order to arrive at an understanding of the tectonic setting of the complex, however, it is important that we consider only the most primary magmas associated with the PPC. This is especially important because many of the more silicic phases of the complex have apparently interacted strongly with the associated, mostly arc-derived (see Barovich et al., 1989), MF. We have so far applied only a few of the many available methods of geochemical discrimination diagrams to the PPC rocks to learn more about their original tectonic setting. AFM diagrams indicate a distinct calc-alkaline trend for all rocks of the PPC. When plotted alone, however, the mafic PPC rocks could be interpreted to reflect indistinctly either a calc-alkaline (arc-derived) trend or a tholeiitic (MORB-like) trend.

Plots of CaO/TiO2 vs. TiO2 and of Al2O3/TiO2 vs. TiO2 (Sun and Nesbitt, 1978) suggest the derivation of the PPC from a relatively undepleted mantle source similar to that which produces MORB. More silicic rocks of the complex plot in the same field as the MF.

A MORB-like affinity of the mafic PPC rocks is also indicated by Zr/Y vs. Zr plots (Pearce, 1979; Pearce and Norry, 1979) as well as Zr-Ti-Y (Pearce and Cann, 1973) plots, however some PPC gabbros could be interpreted to be (calc-alkaline)arc-related on the basis of both diagrams. In both diagrams, silicic phases of the PPC plot with rocks of the MF.

A calc-alkaline to low-K tholeiite character of the PPC gabbros is suggested by plots of Zr-Ti-Sr (Pearce and Cann, 1973). Furthermore, a transition from orogenic (calc-alkaline) basalts to more MORB-like tholeiites is suggested for these same gabbros by variations in FeO-MgO-Al2O3 (Pearce et al., 1977).

There exists at this time no unambiguous explanation for the tectonic setting of the Peavy Pond Complex. While it seems clear that the original gabbroic magma was MORB-like, and probably originated in either a MOR-like rift or a back-arc setting, we are unable to distinguish between these environments at this time. There is some evidence suggesting that some of the PPC gabbros may have originated within a volcanic arc. We cannot unilaterally reject such hypotheses due to the relatively close proximity of the northern Wisconsin arc to the PPC. However, at the same time, we believe that the arc-like characteristics of these gabbros are best explained by assimilation of MF or by assimilation of calc-alkaline material at depth. The calc-alkaline arc-like character of the more silicic phases of PPC could also reflect an origin within a volcanic arc environment, however, there appears to be substantial geochemical, petrologic, and petrographic evidence to support the hypothesis that these rocks were derived largely through assimilation or partial melting of the calc-alkaline MF.

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ORGANIC GEOCHEMICAL REASSESSMENT OF PETROLEUM SOURCES AND THERMAL HISTORY IN THE MICHIGAN BASIN

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Paleozoic sedimentary rocks fill the Michigan Basin and provide the sources of the oils produced in this basin. The present geothermal gradient is not high in this shallow sequence, raising questions as to whether Devonian and younger strata are sufficiently thermally mature to have sourced petroleum. The thermal maturities of rock samples from Late Cambrian to Pennsylvanian strata have been determined using the kinetics of apparent transformations of biomarker molecules as an index, augmented by vitrinite reflectance measurements and Rock-Eval pyrolysis data. The amount of sterane isomerization and the degrees of steroid aromatization in biomarkers extracted from these samples permits reconstruction of the geothermal history of the Michigan Basin. Organic matter in Devonian strata from the center of the basin is thermally mature; it is overmature in more deeply buried Ordovician rocks. The thermal history of this basin has evidently been more complex than generally thought, suggesting higher temperatures or lower conduction rates in the past.

SUCCESSFUL APPLICATION OF NEW TECHNOLOGY IN ANTRIM SHALE COMPLETIONS

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The Antrim shale in the Michigan Basin has been a horizon of much interest to operators in recent years. A conventional completion and production technique for the Antrim shale is to fracture stimulate the Antrim, then produce the Antrim shale gas and water naturally through tubing that is placed in the well before or after the stimulation process. Some operators have used artificial lifting techniques to produce the water from Antrim wells. Artificial lifting of water from the Antrim Formation can enhance gas production if sand does not flow back into the well bore during the lifting process.

Sand flowback into tubing and casing may impede the production of a well by plugging the pumps used to lift water from the Antrim formation. This paper explores a way to control sand flowback during production in a well by adding a stream of liquid expoxy resin directly to blending equipment during a sand fracturing treatment. This liquid epoxy resin attaches itself to the sand grains and hardens to form a highly permeable, consolidated fracture bed. This consolidated fracture bed will then prevent sand flowback into a wellbore during flowback and production.

This paper presents techniques for using resin-coated sand to help prevent proppant flowback and describes the results in case histories.

THE IMPLICATIONS OF MULTIPLE SCALE HETEROGENEITY FOR REGIONAL HYDRODYNAMIC MODELING OF THE ST. PETER SANDSTONE

Gerilynn R. Moline, Lisa D. Shepherd, and Jean M. Bahr – University of Wisconsin – Madison

A study is currently underway to investigate the occurrence of pressure compartmentation in the St. Peter Sandstone of the Michigan Basin. In particular, we are interested in identifying and characterizing the seals which bound these compartments. Basin-wide pressure-elevation profiles for the St. Peter, Glenwood, and Prairie du Chien formations show pressure discontinuities at similar depths, suggesting that these seals cross-cut stratigraphy and are diagenetic in origin. A preliminary analysis of pressure data obtained from drill stem tests indicates a region of anomalously high heads in the vicinity of Saginaw Bay, and a vertical pressure distribution compiled from Repeat Formation Tester (RFT) data confirms the presence of overpressures in this region. Although the St. Peter is described as a macroscopically homogeneous mature quartz sandstone, core and thin section analyses indicate significant variability in hydraulic parameters at several scales. Pressure buildup curves from RFTs show the presence of alternating zones of high and low permeability ranging from a few feet to a few tens of feet. At the thin section scale, porosity has been observed to vary abruptly from less than 1% to over 20% in zones of apparent diagenetic banding. One of our goals is to construct a regional picture of the permeability and porosity distribution within the St. Peter for use in flow modeling. However, many direct measurements of permeability from in situ well tests and core plug evaluations are treated as proprietary due to active gas exploration within this formation. As an alternative, a multivariate statistical approach is used to discretize the wireline logs into "electrofacies" and to correlate these electrofacies with lithologic descriptions and with hydraulic parameters from core analyses. On the basis of these correlations, the electrofacies associated with very low permeabilities, ie. potential seals, are characterized. These electrofacies characterizations are then used to identify "tight" zones in individual wells and to correlate between wells, providing a picture of the vertical and lateral distribution of potential seal zones throughout the basin.

This research supported by the Gas Research Institute.

RESERVOIR CHARACTERIZATION OF THE ANTRIM SHALE

J. E. Nicol and S. J. P. Oliver – ICF Resources Incorporated

Commercial quantities of gas have been produced from this Devonian-age formation since the 1940's; however, little was known about the reservoir mechanisms controlling gas production. The drilling pace in the Michigan Basin has recently accelerated considerably with more than 500 wells completed in the Antrim Shale in 1989 and almost 700 wells in 1990. The Michigan Basin was ranked third in the nation for new field wildcats in 1989.

This paper presents the results from a detailed investigation into reservoir mechanisms governing gas and water production for the Antrim Shale in the Michigan Basin. Previous investigations (Rushing and Oliver, 1989) indicated long term gas production from this shallow fractured shale to be controlled by fracture properties, desorption characteristics, and drainage area. Since that preliminary investigation, Gas Research Institute's (GRI) field-based research project aimed at improving gas recovery has for the first time collected detailed in-situ reservoir data on the Antrim Shale. These date include permeability from pressure build-up and injection fall-off tests, porosity measured from cores, desorption measurements and natural fracture characterization. The results of GRI's research are presented in this paper.

In addition, a small scale area is simulated with a three dimensional, dual porosity, two phases reservoir mode. This model is used to delineate optimum well spacing and production methods aimed at dewatering the shale and accelerating gas production by allowing free gas to flow to the wellbore and absorbed gas to desorb from the shale matrix. In addition, the different geological settings found the in the Antrim Shale, for example varying natural fracture intensity, are simulated with the model to determine optimum completion and production strategies.

GRI'S ANTRIM SHALE RESEARCH PROJECT

S. J. P. Oliver – ICF Resources Incorporated

The Antrim Shale of the Michigan Basin is estimated to contain up to 76 Tcf of natural gas. Although commercial quantities of gas have been produced from this Devonian-age formation since the 1940s, no comprehensive reservoir engineering studies of the Antrim Shale have been made, and consequently, little is known about the reservoir mechanisms controlling gas production. This lack of knowledge is also due, in part, to the small number of wells completed in the Antrim Shale prior to 1988, and a resulting limited data base for reservoir characterization. However, the drilling pace in the Michigan Basin has recently accelerated considerably, with more than 200 wells completed in the Antrim Shale in 1988 and 500 wells in 1989. The increased drilling effort offers an excellent opportunity to develop a basic reservoir engineering understanding of this important new source of gas reserves. As part of its continuing goal of securing reliable sources of domestic natural gas, the Gas Research Institute (GRI) has recently initiated a concerted study program aimed at defining the production mechanisms and ultimately improving gas recovery from the Antrim Shale.

Advanced technology from R&D in the Antrim Shale has the potential to make the economics of gas production more favorable. Ultimately, a considerable increase in producible reserves of natural gas and hence decreased gas costs can be realized.

The Antrim has been called a "no brainer" by one operator, implying that little if any geologic and geophysical investment is required. One simply drills the wells, completes open hole, applies a standard fracture treatment, drills a disposal well and hooks up the producing wells to a pipeline. It is our feeling that the with the application of "some brains", the Antrim Shale could become an even more attractive natural gas play. Research work by GRI in the Appalachian Basin has shown that field-based research program can have a positive impact. Only with better reservoir data can the full potential of the Antrim Shale be realized, moving it from a perceived marginally economic gas play to a significant source of low-cost natural gas.

THE ROLE OF SHEAR FAULTING IN FLUID FLOW MECHANICS IN THE MICHIGAN BASIN

C. E. Prouty – Department of Geological Sciences, Michigan State University

External simple-shearing stresses applied to the Michigan Basin and environs established a shear model structure characterized by vertical shear faults which extend from the basement complex through essentially the entire geological section, including the Pleistocene Drift. These external stresses on the basement occurred episodically throughout the Paleozoic causing periodic lateral offset along the numerous shear faults. Stresses other than the active extra-basinal forces probably caused the vertical Post-Paleozoic extension of the faults, with perhaps glacial overloading being a strong possible candidate.

The faults have been fluid channelways since development, probably in Late Ordovician time. Effects of this movement along the faults can be demonstrated in at least four circumstances. The first three occurred during rising fluids believed derived from downward flow of waters along the flanks of the frame structures bordering the Michigan Basin and then rising hydrostatically along the shear-fault channelways; the fourth caused by downward movement of concentrated saline solutions.

These four circumstances are:

(1) Rising dolomite solutions that formed porous reservoir rock along the faults and adjacent wallrock, occurring episodically up to about Middle Mississippian time.

(2) Rising hot pore-filling solutions carrying hydrocarbons, sulfide minerals and saddle dolomite, involving rocks up to about Middle Mississippian

age.

(3) Upward flow of water as in (1) above but not charged with mineral solutions, occurring up to the present with the fault traces often observable to LANDSAT imagery at the surface.

(4) Downward-moving solutions along the faults derived from saline waters which dedolomitized dolomite formed earlier according to processes outlined under (1) above.

SATELLITE IMAGE AND GIS-AIDED ANALYSIS OF GLACIAL FEATURES IN THE CENTRAL UPPER PENINSULA, MICHIGAN

Robert S. Regis – Michigan Technological University, Houghton, MI

Satellite imagery and digital elevation model (DEM) data were used to identify glacial features in south-central Marquette and northern Dickinson Counties, of the central Upper Peninsula of Michigan. Combinations of imagery and 3-D perspective views of the terrain afforded the necessary components (large area of coverage and relief) for analysis of regional glacial geomorphic trends. Landsat Thematic Mapper, Landsat MSS, and SLAR remotely sensed images in paper and digital format were used in conjunction with 1:250,000 scale DEM data.

The major moraines of the region identified on the imagery mark the terminal extent of the Greatlakean ice of about 11,800 YBP in the west, and the Marquette ice of 9850 YBP in the east. During Greatlakean time, two separate ice lobes entered the area, one from the northeast (Michigamme lobe) and the other from the east-southeast (Green Bay lobe). Recessional moraines record stillstands or minor advances as the Greatlakean ice receded from the area. A west-to-northwest oriented drumlin field was created by the waning Green Bay lobe. From the satellite perspective, many of these features appear to be a combination of elongate ridges and troughs eroded into earlier till. Flutes and grooves on the surfaces of the drumlinoid features indicate the final direction of ice motion. An interlobate tract of high relief, coarse-grained kame deposits trends east-west at the junction of the two lobes. Outwash plains are readily apparent on the DEM data and form a stairstep pattern on the landscape, decreasing in elevation eastward. As many as five separate levels have been identified. Deposition of fluvial sand and gravel has buried much of the earlier deposits throughout the area. Subsurface data is required for a complete glacial reconstruction, and is being acquired.

Textural and lithologic analyses of sediment samples are underway to discriminate variations in the drift types and temporal relationships between the Michigamme and Green Bay lobes. Preliminary indications show 1) Green Bay lobe deposits are in part, re-worked older drift, containing a suite of clasts resembling Northern Complex and Marquette Synclinorium rocks, 2) an abrupt northward and more gradual westward decrease in percentage of carbonate clasts in the Green Bay lobe drift, and 3) a lack of carbonate clasts in the Michigamme lobe sediments.

BEDROCK TOPOGRAPHY OF THE EASTERN TWO-THIRDS OF MICHIGAN'S NORTHERN PENINSULA

Richard L. Rieck – Western Illinois University, Department of Geography and Department of Geology

A newly-compiled bedrock topography map of the northern peninsula (east of the Ishpeming meridian) is based on nearly 13,000 data points from well logs, outcrops, and soil maps. Although gaps are present, the map reveals a buried, cuesta-form topography in the east. The Niagaran cuesta is the most prominent feature with local relief 300 ft (100 m) but the Black River, Richmond, and Lake Superior Groups also have associated scarps locally 100 ft (30 m) high. "Preglacial" drainage was to the north and northwest off the scarp slopes.

West of the Au Train-Whitefish lowland the cuestas give way to a relatively smooth surface which gently rises northwest to the contact with higher, more rugged crystalline rock. Underlain primarily by the Trenton Group, the lowland channelled ice flow, smoothing the weak rock. Small erosional remnants remain only in the south where flow lines were less confined.

Lake Superior today drains south through the St. Mary's River. Yet, if a "preglacial" drainage connection existed in the study area between the Lake Michigan and Lake Superior basins, it was most likely via a buried valley trending north from St. Martin Bay northeast of St. Ignace. There the thalweg is at about 550 ft (170 m) asl. Breaching several cuestas, the valley trends north past Rudyard to Brimley where its bottom is below 200 ft (60 m) elevation.

STRATIGRAPHIC DIFFERENCES WITHIN THE NEGAUNEE IRON FORMATION: EMPIRE MINE AREA

T. Wentworth Slitor – Cleveland Cliffs, Inc. and Joe Mancuso – Bowling Green University

The stratigraphic subdivisions of the Negaunee Iron Formation in the Empire Mine area differ substantially from the Empire Main Pit area to the south as compared to the Cliffs Drive 1 Pit to the north. The Empire Main Pit area comprises over 3,000 feet of continuous iron formation above the Siamo Formation while in the adjacent Cliffs Drive 1 area only 1,600 feet of iron formation occur between the Siamo Formation and the Tracy Sill. The prominent clastic horizon in the Empire Main Pit does not continue into the Cliffs Drive 1 area. Interbedded metadiabase sills are common in the CD-1 area but only occur on the north and west margins of the Empire Main Pit.

The differences in the stratigraphic section from south to north might be explained by: 1) a complex fault with great displacement such as the Palmer fault, 2) an Archean fault zone which was active during deposition of the iron formation and reactivated during the Penokean Orogeny, or 3) an abrupt change in basin geometry from south to north.

These distinct stratigraphies affect the daily ore blending decisions and mine planning strategies at the Empire Mine. Computer truck dispatching and state-of-the-art computermine planning hardware and software are used effectively in the mining operation to address the the complexities of stratigraphy, mineralogy, and structure of the Negaunee Iron Formation in the Empire vicinity.

EVIDENCE FOR TIDALLY-INFLUENCED DEPOSITION IN THE "BRAZOS SHALE", CENTRAL MICHIGAN BASIN

George L. Smith – Department of Geology and Geophysics, University of Wisconsin – Madison

Sub-millimeterscale (0.1 to 0.5mm), fining-upward, silt-shale laminations are evidence for tidally-influenced deposition in the informally-named "Brazos Shale" of the central Michigan Basin. Silt-shale laminations occur in packages of 8 to 12 layers, which thin upward within each package. Individual laminations and the style and scale of packaging are similar to millimeter-scale tidal laminations documented in Pennsylvanian siliciclastics in Indiana (Kvale and Archer, 1990, Journal of Sedimentary Petrology). "Brazos Shale"-type laminations have not been identified in the coarser, more heavily bioturbated siliciclastics and carbonates of over- and underlying units.

The "Brazos Shale" is a laminated shaly dolomitic siltstone of Early to Middle Ordovician age. The "Brazos" is the uppermost member of the Prairie du Chien Group and is overlain by the St. Peter Sandstone. The "Brazos" lithofacies, which reaches a maximum thickness of about 70 m, is areally restricted to central portions of the Michigan Basin, where it is easily identified in cores, cuttings, and logs by its dark, laminated appearance and high gamma signature.

The laminated, relatively unbioturbated and unfossiliferous nature of "Brazos" siltstones suggests deposition in a non-marine or marginal marine setting. Tidal laminations indicate "Brazos" deposition in a marginal marine setting such as an estuary, not in an isolated brackish or hypersaline lagoon. Portions of modern estuaries contain similar, tidally laminated, weakly bioturbated sediments. If "Brazos" deposition was tidally-influenced, tidal currents may have been an important sedimentary agent throughout Prairie du Chien and St. Peter deposition. Thus,

the epeiric sea had good connections to the open ocean, and was not an isolated, tideless body of water.

Research supported by the Gas Research Institute.

HYDRAULIC FRACTURE TREATMENT ANALYSIS IN THE ANTRIM SHALE

M. B. Smith – NSI Technologies

Gas production from the Devonian Antrim Shale of the Michigan Basin has been the target of an active drilling play in north-central Michigan. The

shallow Antrim produces modest amounts of gas (25 to 400 Mcf/D) and water (25 to 150 BW/D) after conventional fracturing with nitrogen foam. The typical treatment consists of 60,000 pounds of 20/40 sand and 32,000 gallons of foam.

As part of their effort to increase natural gas recovery and accelerate its production, the Gas Research Institute (GRI) has been working with several Michigan Basin operators to design optimal stimulations for the Antrim Shale. This collaboration has included pre-and post-fracture buildup tests, as well as the collection and analysis of fracture treatment pressure data.

Pressure data collected from several Antrim wells in Otsego County indicate that in some areas the typical Antrim fracturing treatment may not be achieving its potential. Bottomhole treatment pressures are sufficient to trigger a change in fracture geometry, possibly to a less efficient, horizontal fracture. Proppant is concentrated near the fracture tip, reducing conductivity in the main vertical fracture and near the wellbore.

Preliminary analysis of the data suggests that at least two types of fracturing behavior can occur. In low permeability settings, initial treatment pressure is high and possibly no vertical fracture is initiated; in higher permeability settings, the onset of this pressure appears to be delayed. Based on interpretations of this data, modified fracture treatments were designed to improved fracture conductivity and prevent inefficient fracture geometry.

INDUCTIVE ELECTROSTATIC GRADIOMETRY EXPLAINS KEWEENAWAN NATIVE COPPER PLUMBING SYSTEM

Jim Trow – Department of Geological Sciences Michigan State University

Dowsing is really inductive electrostatic gradiometry (IESG). L-shaped welding rods and Y-shaped wooden rods rapidly and inexpensively detect positive and negative self-potential (SP) anomalies inductively, rather than conductively (as with porous pots, reels of wire, and a voltmeter). The quantity measured is dv/dx (the first derivative of SP voltage with respect to horizontal distance), and therefore the dowser's "peaks" occur on both flanks of the ore rather than directly above it. One caution: a blind zone occurs where one traverses approximately 45 degrees to the strike of a vein. The "sensors" are in the dowser's head, and the "meter" consists of the dowser's body, limbs, and the rods. Sensitivity is inversely proportional to the "meter's" capacitance. Only static electricity is being measured, therefore the method is blind commodity wise, extravagant claims by dowsers notwithstanding. Physics experiments confirm the electrical mechanism. An Ontario copper-silver mine serves as a detailed example where ore is identified as negative SP anomalies, and the fault down which migrated cold oxidizing water of the convective hydrothermal cell is identified as a positive anomaly. Gibbs free-energy calculations involving oxygen activity as the unknown yield a mineral-formation sequence which mimics observed mineral zoning.

The above findings, applied to the native copper lodes of Michigan, explain the Keweenawan plumbing system. As expected, the native copper lodes yield negative SP anomalies. The Keweenawan fault yields the largest positive SP anomaly I have ever encountered, suggesting that this surprisingly relatively unmineralized fault in a hydrothermal area may have served as the master conduit for the downward migration of cold oxidizing water (from the Jacobsville Sandstone), which oxidized the sulfur of the hydrothermal solutions to produce native copper instead of the more typical hydrothermal chalcopyrite, bornite, etc., in this hydrothermal convective cell. The Keweenaw fault as a supplier of oxygenated downward-circulating water supplies the sole lack (sufficient water) of Walter Stanley White's superb theory for the formation of these ores.

VIEWING A HYDROFRAC IN THE ANTRIM SHALE WITH SHEAR WAVE VSPs

Roger Turpening and Carol Caravana – Earth Resources Laboratory, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology

The VSP method was used in an oil shale project in the thumb of Michigan. The Department of Energy (DOE) supported the Dow Chemical Co. in a four-year field experiment aimed at the extraction of energy from the Antrim shale. Much experience had been gained by Dow Chemical personnel in the early 1970s with this shale, and only in situ processes were deemed economically viable. Furthermore, the success of in situ energy extraction methods was known to depend on the success of the fracturing methods. Therefore, the DOE-funded work in the late 1970s was concerned with a study of three different fracturing techniques.

In order to study fracturing techniques, one must have some way of viewing the fractures and/or fracture volume. Many techniques are available to measure the communication between wells, such as air flow or the movement and detection of rare chemical compounds. These were used by Dow personnel on this project. However, investigators required a technique that could view the entire volume of fractured rock or the entire extent of a hydrofrac. The VSP technique was used with the variation that data were collected before and after each fracturing attempt was made. Furthermore, both compressional and shear wave VSPs were acquired. Thus, this is the first use of before and after shear wave VSPs. Although compressional VSPs were obtained, the significant signal variations were seen in the shear waves in the hydrofrac viewing experiment.

GEOCHEMICAL ANALYSIS OF THE MIDDLE TO LATE ORDOVICIAN STRATA IN THE MICHIGAN BASIN

R. Vandrey, P. Drzewiecki, P. Brown, C. Johnson, A. Simo, G. Smith, and J. W. Valley – University of Wisconsin-Madison

Different dolomite generations were identified by petrography and cathodoluminescence from core samples and cuttings of the Ordovician Prairie du Chien Group (PDC), St. Peter Sandstone, and Glenwood Formation in the Michigan Basin. These dolomites were analyzed for 18O, 13C, 87Sr/86Sr, fluid inclusions, and concentrations of Sr and Fe.

Each formation has a characteristic range of 13C and 18O values. Dolomitic packstones/grainstones and boundstones in the PDC have a higher average 18O value than the other formations and a wide range of 13C values. The overlying St. Peter dolomite cements exhibit a wide range of 18O values. The Glenwood, including the transitional facies with the underlying St. Peter, has more restricted 13C values than the other units and a relatively small range in 18O. The dolomite cements in the transitional facies maintain similar average 13C values with those in the sands of the St. Peter.

Values for 87Sr/86Sr ratio, and Sr and Fe concentrations are also used in the distinguishing types of dolomite cements in the St. Peter and Glenwood. In the St. Peter, 87Sr/86Sr ratios average 0.70877, Sr concentrations range from 21-52 ppm, and Fe concentrations range from 9,190-14, 160 ppm. In the Glenwood, two dolomite generations associated with secondary fracturing, a late porefilling baroque dolomite and the early dolomicritic matrix, were analyzed from cores located 20 km apart. The 87Sr/86Sr ratios for the baroque dolomites range from 0.70836-0.70852 compared to 0.70921-0.70946 for the dolomicrites (seawater values ranged from 0.7080-0.7085 during this time). Both fracture cements and matrix dolomites have similar, low Sr concentrations (39-58 ppm) with slightly lower concentrations occurring in the fractures. Fe

concentrations are several thousand ppm (12,794-36,469), with significant variations between cores (up to 20,000 ppm) and slight enrichment of the fracture-filling baroque dolomite over the micritic matrix (2,000-3,000 ppm).

Fluid inclusions were analyzed from dolomites in the transition facies and found to have similar homogenization temperatures (120° to 170° C) to those in the detrital quartz grains and overgrowths. Fluid inclusion salinities in the dolomites could not be determined, but are low (five % equivalent wt. % NaCl) in the quartz grains and cement. While

fluid inclusions are abundant in the detrital quartz grains, they are extremely scarce in the quartz overgrowths that occlude porosity.

These preliminary results are part of an ongoing project to characterize dolomite cements and their relationship to reservoir seals and pressure anomalies in the Prairie du Chien Gr., St. Peter Ss., and Glenwood Fm. in the Michigan Basin

Research supported by the Gas Research Institute.

HYDRAULIC CONDUCTIVITIES OF PENNSYLVANIAN AND MISSISSIPPIAN SANDSTONES FROM THE MICHIGAN BASIN AND THEIR RELATION TO MINERALOGY AND BOREHOLE GEOPHYSICAL-LOG RESPONSES

D. B. Westjohn – U.S. Geological Survey

Hydraulic conductivities of the principal sandstone aquifers of the Michigan basin were measured to determine the effect of mineral constituents on hydraulic conductivity and to relate hydraulic conductivity to borehole geophysical-log data.

Laboratory-measured vertical hydraulic conductivities of 36 sandstone samples from the Pennsylvanian Saginaw Formation range from 10-9 to 10-2 cm/s (centimeters per second). This range of hydraulic conductivity exceeds the range commonly reported for sandstones. Measured vertical hydraulic conductivities of 17 samples from the Mississippian Marshall Sandstone range from 10-9 to 10-4 cm/s; the range in horizontal hydraulic conductivities of 16 side-wall cores from this formation is similar.

Aquifer tests of the Marshall Sandstone were conducted in five boreholes with double packers to isolate selected intervals. In the areas tested, this aquifer is 150 to 180 meters below land surface and contains water with dissolved-solids concentrations that range from 472 to 98,700 milligrams per liter. Hydraulic conductivities determined from aquifer tests range from 10-5 to 10-4. cm/s. These values are approximately the same as the highest hydraulic conductivities measured in the laboratory, indicating that values determined by means of aquifer tests reflect the hydraulic conductivity of the sandstone matrix.

Differences in matrix-controlled hydraulic conductivities of Mississippian and Pennsylvanian sandstones are primarily a function of cement type and degree of cementation. Low hydraulic conductivities were measured in samples cemented by kaolinite, chlorite, and illite; these minerals are authigenic phases that partly fill pores and pore throats. Sandstones that are cemented by layer silicates also undergo a reduction in hydraulic conductivity as confining stress increases. Laboratory-applied confining stresses of 69 to 2,000 kilopascals reduced hydraulic conductivity by three orders in magnitude for some specimens. Sandstones cemented with quartz and/or carbonate have consistently higher hydraulic conductivities

than sandstones cemented by layer silicates and do not undergo significant reductions of hydraulic conductivity with increased confining stress.

Measured hydraulic conductivities also can be related to geophysical data recorded on borehole-resistivity logs. Geophysical logs that measure resistivities at different horizontal distances away from the borehole into the formation (shallow, intermediate, and deep) show differences in resistivity where borehole-fluid has displaced native formation fluid. Fluid-invasion profiles are recorded on electrical-resistivity logs only for sandstones that have hydraulic conductivities greater than 10-5 cm/s. Resistivity logs from hydrocarbon-exploration boreholes are available for many areas of the Michigan basin, and fluid-invasion profiles indicated on these logs provide a means of estimating hydraulic conductivities of bedrock aquifers.

ECONOMIC POTENTIAL AND GEOLOGICAL RELATIONSHIPS IN THE GRANITOIDS OF THE NORTHERN COMPLEX, MICHIGAN

Richard T. Wilkin and Theodore J. Bornhorst – Department of Geological Engineering, Geology and Geophysics, Michigan Technological University

Geologic mapping at a scale of 1:24000 of Archean granitoids in the eastern portion of the northern complex, Upper Michigan, has revealed a diverse geologic history and the existence of structurally controlled zones which may have potential for gold. This report is based on mapping by Gair and Thaden (1968), and Puffett (1974), and more recently by Wilkin *et al.* (in preparation). The granitoids are dominantly tonalitic to granodioritic in composition with minor quartz monzonite and rarely granite, based on modal classification. Major and trace element and rare-earth-element (REE) patterns indicate that these rocks are typical of Archean TTG assemblages (trondhjemite- tonalite- granodiorite). Gneissic diorite may represent a cratonic segment which predates volcanism of the Marquette-Ishpeming greenstone belt. The tonalitic suite is intrusive into the Marquette- Ishpeming greenstone belt and foliations are consistent between the mafic volcanic and plutonic sequences. In the Negaunee NW quadrangle a late- to post- kinematic hornblendite- diorite suite is intrusive into the tonalite.

Sulfide mineralization and alteration of the granitoids is confined to structural zones. Silicification is common in some zones with quartz veins up to 10 meters thick. Chlorite-epidote alteration and hematite as coatings on fracture surfaces is associated with the silicification. Pyrite, up to several percent, is the main sulfide mineral. Chalcopyrite and sphalerite are rarely present. In some pyrite-rich zones silicification is less prominent. The pyritic granitoids are usually weathered to an orange-brown limonite which is readily visible in outcrop. Gold determinations by INAA/fire assay have yielded gold concentrations from background levels to 70 ppb with one highly anomalous sample of 800 ppb. These zones suggest that the granitoids warrant additional work with regard to economic potential.

This project was partially funded by grants from the Michigan Geological Survey, COGEOMAP program of the U.S. Geological Survey and the Minerals Institute Program of the U.S. Bureau of Mines.

TERRAIN CHARACTERISTICS IN THE GRAND RAPIDS AREA PRIOR TO LATE WISCONSINAN GLACIATION

Harold A. Winters – Michigan State University and Richard L. Rieck – Western Illinois University.

Outcrops of glacially buried Pleistocene organic deposits are rare

in Michigan but water well logs reveal the presence of carbonaceous deposits within drift at more than 400 places in the Southern Peninsula. Although some of these appear as isolated occurrences, most are concentrated to varying degrees in several areas and all are believed to represent evidence for buried Pleistocene paleosurfaces. One group in and around Grand Rapids is especially interesting 1) because it contains about 100 relatively closely spaced sites and 2) because four pertinent 14C dates for recovered samples suggest that some, if not all, of the carbonaceous material formed in association with a paleosurface that existed there during the Mid-Wisconsinan.

In combination with the four 14C dates the 1) subsurface altitude, 2) Quaternary stratigraphy, and 3) relative location of the glacially buried organic deposits provide a basis for recognizing aspects of two adjacent but very different Mid-Wisconsinan terrains in the subsurface; one to the west being relatively flat with all the attributes of a lacustrine plain, the other a rugged eastern region with morainal characteristics. Furthermore, the present topography directly reflects the two pre-existing and markedly different surfaces. Our research indicates that similar relationships also exist in several other Southern Peninsula tracts.

These findings indicate that certain areas of the Michigan landscape are palimpsest; that is, rather than being wholly a product of final deglaciation, they directly reflect the topography of one or more ancestral terrains.

DIAGENESIS OF THE MARSHALL SANDSTONE

S. K. Young, J. A. Eluskie, D. F. Sibley, – Department of Geological Sciences, Michigan State University and D. B. Westjohn U.S. Geological Survey

Diagenesis of the Marshall Sandstone included mechanical and chemical compaction. During diagenesis, quartz, calcite, ferroan dolomite, ankerite, feldspar, kaolinite, and pyrite precipitated; feldspar dissolved. Feldspar dissolution, which generated secondary porosity, is probably the source of authigenic kaolinite. Carbonate cementation was the most effective mechanism of porosity reduction. Del oxygen-18 values range from +3 to -8 per mil and del carbon-13 values range from -2 to -13 per mil for carbonate cements. The iron to magnesium plus calcium ratios in these cements range from 0.03 to 0.28.

Carbonate cements in sandstones sampled from six boreholes can be distinguished on the basis of isotopic and chemical compositions. Water from these boreholes also has distinguishable chemical compositions. Distributions of authigenic phases and dissolution features as well as major-element and stable-isotopic compositions of carbonate cements in the Marshall Sandstone indicate that these rocks have not chemically equilibrated with present pore water. The diagenesis of the Marshall Sandstone represents the end result of interactions in a previous hydrochemical system.

ASBSTRACTS of POSTERS by AUTHOR

MINERAL DEPOSITS OF THE MIDCONTINENT RIFT, LAKE SUPERIOR REGION, U.S. AND CANADA

William F. Cannon and Teresa A. McGervey U.S. Geological Survey

About 450 mineral deposits are known in middle Proterozoic rocks of the Midcontinent Rift system in Michigan, Wisconsin, Minnesota, and Ontario. The location, character, and geologic setting of these deposits provide clues for further exploration of the rift, both where exposed in the Lake Superior region and for the nearly 2000 km-long extension of the rift in the Precambrian basement beneath Paleozoic cover in the midcontinent region. The 1:500,000 scale map presented here, and in press in the USGS MF-map series, shows the location, size classification, and geologic type for these deposits on a geologic base map.

The principal mineral produced from the rift has been copper from native copper deposits hosted in basalt flows and interflow sedimentary rocks, and from shale-hosted chalcocite-native copper deposits in lacustrine shales. Lesser copper production has been from sulfide veins in basalt and from breccia pipes. Silver has been produced from epithermal veins in Ontario, which also host polymetallic deposits of lead, zinc, copper, barite and fluorite.

Very large resources of copper-nickel-cobalt mineralization are proven in the Duluth complex and other rift-related mafic intrusive bodies. Lesser, but potentially significant known resources include uranium in pitchblende veins, uranium and rare earth elements in alkalic rocks, copper sulfide (chalcocite) deposits in volcanic rocks, titanium and vanadium in mafic intrusive rocks, and platinum group elements in mafic intrusive rocks.

All of the deposits and resources have been discovered in about 15% of the strike length of the rift – that portion which is reasonably well exposed in the Lake Superior region. The subsurface extensions of the rift in the midcontinent region, well known from geophysical studies and a limited number of basement-penetrating wells, constitutes a major exploration frontier. If the buried portions of the rift are as prolifically mineralized as the exposed portions, several thousand mineral deposits should be present at the Precambrian surface beneath Paleozoic cover rocks.

STREAM CHANNEL AQUIFER SERVES AS A SOURCE OF GROUND WATER FOR MARQUETTE STATE FISH HATCHERY, MARQUETTE MICHIGAN

Frank Chenier – MichiganDepartment of Natural Resources, Geological Survey Division

A series of high capacity water wells were constructed within a buried stream channel aquifer that lies below Marquette State Fish Hatchery. The wells serve as a reliable source for a large volume of relatively warm, constant temperature ground water needed for hatching fish eggs and raising small fish.

Attempts to obtain large supplies of ground water in the vicinity of the hatchery were unsuccessful for many years. Test wells drilled in the recent past discovered a narrow channel aquifer, probably not more than two hundred feet wide, capable of producing several hundred gallons of water per minute per well. The completed wells show the aquifer to be strongly artesian with static water levels up to 15 feet above the ground surface and natural flows in excess of 60 gallons per minute per well.

Michigan Geological Survey Division personnel oversaw the design, construction, and development of five supply wells completed in the channel aquifer, which lies at depths between 120 and 160 feet below surface. The deposit, which consists of stratified sand and gravel layers, appears to lie within a buried bedrock valley that leads up to the Sands Plain aquifer to the southwest - the apparent source of recharge.

Two supplemental wells were recently completed to prove the availability of additional ground water needed for the proposed hatchery expansion scheduled to take place next year. Total combined production will be in excess of 1300 gallons per minute from the five wells. A sixth well will serve as a backup to the primary production wells.

THE STATEWIDE GROUNDWATER DATA BASE

David W. Forstat – Michigan Department of Natural Resources, Geological Survey Division

Michigan's interest in developing a statewide groundwater data base was emphasized in September, 1984 by the Governor's Cabinet Council. The proposed data base system, which is beyond the development stage and is now a full fledged operation, provides managers with geology, hydrogeology,

quality and quantity information. This will assist managers in predicting environmental impacts on potential contamination sites, solving existing groundwater use conflicts, characterizing contamination incidences, planning for cleanup, and making risk analyses associated with developing strategies and plans for contamination prevention. Links also exist between the Statewide Groundwater Data Base (SGDB) and the Michigan Resource Information System (MIRIS) at the state level.

The data gathered by the SGDB starts by accurately verifying the location of water wells. Water well records are located by using county specific data and resources such as tax parcel information, aerial photographs, subdivision maps, plat maps, and actual field verification where necessary. When the water well location is verified, it is then plotted on a USGS topographic map, and labeled according to a pre-specified numbering system. Next, the verified locations are digitized using software called C-MAP. Data automation of the water well records occurs next using software developed by SGDB called WELLKEY. There is absolutely no interpretation of the water well record, it is entered as is. The data base reflects just a computerized version of the actual water well record. Included in the data automation is a separate file with all of the geologic information within a specific location of a water well. This data is later used extensively by the data base to create such final products as geological cross sections, clay thickness maps, bedrock topography maps, drift thickness maps, water table evelvation contour maps, and other client specific products. In some cases a chemical data base is created for an area of concern so that chemical iso-concentration contour maps can be created.

Data from county agencies is included in the data base by SGDB personnel who provide training in the verification and automation process in exchange for final data.

THE CHAMPION MINE, MARQUETTE COUNTY, MICHIGAN: GEOCHEMISTRY OF SELECTED MINERALS

Adam W. Heft and David J. Matty – Department of Geology, Central Michigan University

The Champion Mine, in western Marquette County, Michigan, was an active iron mine from 1868 to 1910 and from 1949 until its closing in 1967. During this time, over 7 x 10^6 tons of iron ore were produced from this deposit, which consists predominantly of jaspilitic iron formation that grades locally into irregular bodies of specular hematite and/or magnetite. In addition to the iron ore that is characteristic of this deposit, other potentially economic minerals have been found; these include minerals and ores of barium, bismuth, copper, fluorine, lithium, manganese, molybdenum, titanium, and tungsten, as well as native gold. Metamorphic minerals associated with the deposit indicate that conditions equivalent to staurolite grade were reached locally in the vicinity of the deposit.

With few exceptions, there is a paucity of information concerning the chemistry of minerals associated with the Champion deposit. Lane and others (1891) studied the mineral chemistry of chloritoids found at Champion. Mandarino (1950) described several of the minerals found in the Champion area that are associated with the deposit but did not report any chemical analyses. Babcock (1966) reported that more than 70 distinct mineral species occur in the rocks at Champion but his study centered primarily around the manganese-bearing silicate phases associated with the deposit. In a later work, Babcock (1974) reported additional information of the manganese-rich iron minerals of Champion. Babcock's studies were based largely on the results of X-ray diffraction studies and unit cell determinations or on semiquantitative X-ray fluorescence studies of bulk mineral separates. While these methods provide useful information concerning the structure and the general chemistry of minerals, they often fail to yield substantial information about the minor chemical components present in mineral phases. Furthermore, these methods provide little, if any, information concerning inter and especially intragranular homogeneity in mineral phases.

This study represents an initial attempt to broaden the available database of the chemistry of minerals associated with the Champion deposit. Many of the minerals analyzed in this study were reported originally by Mandarino (1950) and later by Babcock (1966; 1974). While the mine workings at Champion are no longer accessible, rocks composing the remaining piles of tailings provide numerous examples of the diverse mineralogy of the deposit. Samples collected from the tailings piles were studied initially in hand sample. Representative samples were selected for further analysis on the basis of the hand specimen study results. Polished thin sections were prepared from the selected samples and analyzed optically using standard petrographic techniques. Areas of special mineralogical interest identified through the course of the optical studies were noted for later microanalytical study. Microanalytical results of minerals identified through optical studies were obtained using a Tracor-Northern TN-5500-II Energy-Dispersive X-ray analyzer (EDS) attached to an AMRAY 1200 Scanning Electron Microscope. The resultant analytical data were generated using standardless semiquantitative analytical software. Raw data was corrected using the Phi-Rho-Z correction method. Elements commonly sought included: Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Mn, Fe, Ni, and Cu. Charge-balanced stoichiometric formulas of minerals were calculated from the analytical results. Inasmuch as all data presented herein reflect the analytical methods used, we consider these data to be preliminary; more detailed studies utilizing quantitative electron microprobe analysis are underway. This study represents the results of an undergraduate senior thesis by Heft completed as part of requirements of the Geology curriculum at Central Michigan University.

The results of this study indicate that the majority of analyzed minerals are enriched in iron whenever this is mineralogically possible. Many nonsilicate as well as silicate phases were analyzed. Nonsilicate phases include minerals belonging to the carbonate, halide, oxide, phosphate, and sulfide groups. Analyzed silicate phases include aluminosilicates, chloritoid, garnet, staurolite, tourmaline, talc, chlorite, biotite, muscovite, orthoclase, and quartz.

Carbonate minerals identified optically and analyzed by EDS include calcite that ranges in composition from almost pure $CaCO_3$ to grains that contain appreciable amounts of MgO (to ≈20% dolomite) as well as small amounts (< 2%) of the siderite and rhodochrosite components. Certain grains may be interpreted to contain a significant amount of the kutnahorite ($Ca\,Mn\,(CO_3)_2$) component, but the end member phase identified by Babcock (1966) was not identified in this study. We did obtain an analysis of pure siderite.

Certain spectra that we recorded could be interpreted as nothing other than mixtures of halite and sylvite. These phases were most commonly associated with magnetite grains and as the samples were in contact with no salt-bearing solutions during sample preparation, we infer that these phases are naturally-occurring grains within the Champion deposit. The analytical data is somewhat ambiguous, however, in that the small size of these grains (0.5 microns or less) hinders optical observation and precludes accurate EDS analysis; edge effects resulting from the electron beam interaction with adjacent phases add to the problem of interpretation. Nonetheless, the presence of Na and K halides at Champion may be an important clue in deciphering the chemistry of the ore-forming fluids of this deposit.

Several oxide minerals were analyzed and include magnetite, hematite, ilmenite, and rutile. Of these, hematite, ilmenite, and rutile are present as essentially pure end-member phases, i.e: Fe_2O_3, $FeTiO_3$ and TiO_2. Magnetite compositions, on the other hand, vary widely in composition. Most of this variation takes the form of variations in Ti vs. Fe. As a result, magnetites range in composition from Mt100 Usp0 to Mt 31.8 Usp 68.2 ; the strongly titanian magnetites may reflect edge effects with adjacent rutile. Other variations are less severe, with Mg, Al and Si being the most variable; Mg and Al vary with substitution of the spinel component ($MgAl_2O_4$) into the magnetite structure while Si varies most probably as a function of edge effects with adjacent silicates. There is considerable intergranular as well as intersample variability of magnetite compositions in the samples studied; intragranular variations are minor. Jacobsite ($MnFe_3 + 2\,O_4$), reported by Babcock (1974) was not identified in this study, although this phase could be present in small amounts as a component within the magnetite solid solution.

In one sample, three different phosphates were analyzed. These included pure apatite, a separate grain of apatite that contained more than 1% europium, and another individual grain of monazite, the rare-earth-rich variety of apatite. These were the only phosphates located and analyzed in this study.

Sulfides present within the rocks of Champion that were analyzed include molybdenite and pyrite. Both phases were almost always close to the ideal stoichiometric composition.

Of the silicate minerals identified and analyzed in this study, several show little compositional variation while others range considerably in composition. The aluminosilicates are one such group that are characterized by minor compositional changes. Babcock (1966) reported the occurrence of both andalusite and kyanite at Champion. While EDS analysis does not allow us to discriminate between polymorphs of a given phase, we did note the presence of kyanite in our samples when we observed them petrographically; we did not optically identify andalusite. Analysis of these phases indicates substitution of ferric iron (range from 1.6% to 4.4% Fe_2O_3) for Al as well as the presence of small amounts of Mg (.2% to 1.2% MgO) . Stoichiometrically, however, the large amounts of Al and Si within these minerals almost always results in an Al:Si ratio that closely approximates 2:1.

Chloritoid was very common in the rocks we studied, and is commonly associated with quartz, muscovite, biotite, and garnet. Generally, the analytical results agree (to within a few percent) to those reported by Lane and others (1891). Substitution of Mn and Mg for Fe in chloritoid produces most of the chemical variability of this sample. No consistent trends in the substitution of these elements was noted, however, there does exist a strong intersample variability in the composition of chloritoid. Intrasample intergranular heterogeneity also exists but is not as strongly evident as the variation between samples.

Garnet was analyzed extensively by Babcock (1966) who noted that apparently four distinct species of garnet occur at Champion. The compositional differences noted by Babcock (1966) are predominantly related to variations in Mn, Fe, and Al in garnet. We analyzed more than 20 different garnets in 10 samples. Our results indicate that while garnets do vary in composition, the majority fall within 15 mole percent of the almandine end member ($Fe_3 Al_2 Si_3 O_{12}$). We were unable to locate any Mn-rich garnets with appreciable amounts of spessartine (maximum concentration = 6.5% Sp) or calderite substitution. On the other hand, a few garnets with appreciable magnesium substitution were analyzed. The most magnesian garnet contained more than 25% of the pyrope component.

Staurolites present at Champion are typically iron-rich and characterized by low concentrations of MgO. Most staurolites are relatively homogeneous between samples as well as within samples.

Tourmaline is present at Champion and is generally found as small black crystals within quartz, forming a layer between hematite and quartz, or as massive concentrations of small black grains. Optically, many of the tourmalines were noted to be zoned. Tourmaline compositions vary widely; a range of compositions from near dravite to near schorl appears to be present; the associated range of Fe/Mg in these phases is approximately 2.6 to 29.5.

Sheet silicates analyzed in this study include iron-rich talc (composition approximately Fe_5 Mg (Fe^{3+}, Al, $Si)_8$ O_{20} $(OH)_4$), biotite that ranges from near the iron-rich annite end-member to more intermediate Fe-Mg biotites, and essentially pure muscovite that may contain small amounts of iron.

We also believe that we have identified iron-rich chlorite. Pending further analyses of this particular sample, this is the first documentation of chlorite at Champion. This phase may form as a result of either retrograde metamorphism or, more probably, as an alteration product of a related mineral.

Other silicates present at Champion include orthoclase, which contains minor, but unspectacular, substitutions of Na and Ca, and quartz.

Acknowledgments

This project was supported in part by NSF-CSIP Grant # 8750320 and by a grant from Apple Computers, Inc.

LOG CORRELATIONS OF THE PRE-GLENWOOD SECTION FROM THE MICHIGAN BASIN TO THE ILLINOIS BASIN

J. J. Jessmore, R. J. DeHaas, & R. V. Brady – Michigan Petroleum Geologists Inc.

The Foster Formation is not found southwest of the Michigan Basin. However, all of the St. Peter and pre-Foster Formations can be traced into the Illinois Basin. The lower Franconian is correlated to the Ironton Formation in Indiana. The Franconian, Ironton, and Galesville are collectively called the Davis Formation in Illinois. There is a strong facies relationship between tne upper Mt. Simon and the lower Eau Claire from the Michigan Basin to the Illinois Basin.

Thickness wise, most formations are of relatively uniform thickness from southwestern Michigan to northeastern Illinois. However, the St. Peter, Umlor, Trempealeau and the basal sand member of the Eau Claire Formation show considerable thickening into the Illinois Basin.

NORTHERN LITHOSTRATIGRAPHIC BLOCK OF THE ARCHEAN MARQUETTE-ISHPEMING GREENSTONE BELT, MICHIGAN

Rodney C. Johnson, Theodore J. Bornhorst and Richard T. Wilkin – Department of Geological Engineering, Geology, and Geophysics, Michigan Technological University

The northern lithostratigraphic block of the Marquette-Ishpeming greenstone belt is dominated by tholeiitic pillow basalt flows of the Lighthouse Point Basalt, with an estimated minimum stratigraphic thickness of 7,100 m. This formation contains four informal interflow units. Near the base is the Nash Creek glomerophyric basalt unit. Near the middle of the formation is the Reany Lake pyroclastic unit, an ash to lapilli-ash pyroclastic deposit characterized by disseminated base metal sulfides. Directly above this unit is the Fire Center iron-formation unit, a chert-magnetite iron formation. Near the top of the formation is the Hills Lake pyroclastic unit, a lapilli-tuff breccia to lapilli-ash tuff. The stratified units are intruded by sill-like bodies of gabbro that are chemicaly similar to the basalts. These rocks were subjected to recumbent folding which was accompanied by emplacement of tonalites that bound the greenstone belt. The tonalites metamorphosed the adjacent basalt to amphibolite grade. The first deformational event was followed by isoclinal to open folding about east-west axes. Porphyritic rhyolite dikes and granodiorite were emplaced during this deformational event.

Gold mineralization is interpreted as associated with the second deformational

event. It occurs in sheared, carbonate-altered, and quartz-veined rocks. Brecciated margins of rhyolite dikes are common hosts of anomalous gold. Pargenetically later, base metal and silver mineralization occurs in quartz-carbonate veins within brecciated fault zones and may not be Archean in age.

This project was partially funded by grants from the Michigan Geological Survey, COGEOMAP program of the U. S. Geological Survey and the Minerals Institute Program of the U. S. Bureau of Mines.

STRATIGRAPHY OF THE NEGAUNEE IRON FORMATION, EASTERN MARQUETTE RANGE, MICHIGAN

Joe Mancuso and Jeff Stephen Bowling Green State University with Bill Kangas and Went Slitor Cleveland Cliffs Inc.

INTRODUCTION The stratigraphic subdivisions of the Negaunee iron formation in the Empire Mine areas (Secs. 19 & 20) differ substantially from the iron formation in the CD 1 Pit area (Sec. 18) and to the north in Sec. 5, 6, 7, & 8. The Empire Mine area, which comprises over 3000' of continuous iron formation above the Siamo Formation, is informally subdivided into 5 units based on mineralogy, texture, and metallurgy. The Empire Pit is confined to the silicate, carbonate, and clastic units which occupy an 1100' interval (1000' to 2100') above the Siamo contact. The iron formation in the CD 1 Pit area and to the north is less than 1600' thick between the Siamo Formation and the Summit Mountain sill. It is subdivided into 7 informal units. The CD 1 Pit is located in the coarse magnetite unit (unit III) which occupies a 300' interval from 780' to 1080' above the Siamo Formation

COARSE CLASTIC INTERBEDS The Empire mine section includes a 400' zone of iron formation and interbedded coarse clastic sediments (greywackes or arkoses) immediately above the Siamo Formation and a 250–300' zone of coarse clastic sediments and iron formation in the clastic horizon which occupies the interval from approximately 1700' to 2000' above the Siamo Formation. The iron formation in the CD 1 Pit area and north contains no coarse clastic sediments.

DIABASE SILLS In the CD 1 Pit area the Tracy Sill (250' thick) and the Summit Mountain Sill (500' thick) intrude into the lower 1600' of iron formation. No metadiabase sills intrude the 3000' of iron formation in the Empire Mine area.

STRUCTURE AND OXIDATION The Empire Mine sequence strikes NS to N. 40° E. and dips 30°– 45° NW;. It is offset by a number of WNW faults with less than 100' of displacement. Very little oxidation is associated with the faults. The iron formation in the CD 1 pit area strikes NS and dips 30°– 35° W. It is cut by EW and NW faults with less than a few hundred feet displacement. Very little oxidation is apparent. North of the CD 1 Pit in sections 5, 6, 7, and 8 the iron formation strikes N. 35°– 40° W. and dips 20°– 50° SW. Numerous major EW and NW faults with displacements of over 1000' transect the iron formation. The iron formation is completely oxidized to hematite and limonite and, in places, leached of silica.

CORRELATION Similarities between the Empire and CD 1 sections are few but include the following:

1. The carbonate unit in the Empire Mine is very similar in mineralogy, texture, and metallurgy to the coarse magnetite unit (unit III) of the CD 1 Pit area; however, they differ in thickness and position above the Siamo Formation.

2. In the Empire Mine a distinct marker zone of iron formation containing blue riebeckite is found in the upper 150 feet of the carbonate unit. Riebeckite was recently observed at the top of the coarse magnetite unit in the CD 1 Pit.

3. Zones up to 50' thick of wavy–bedded iron formation with magnetite rich granules occur in unit VI approximately 100' above the coarse magnetite unit in the CD 1 Pit area. Stratigraphically this corresponds closely to the position of the clastic horizon which occurs just above the carbonate unit at the Empire Mine.

4. Several thin lenses (less than 2") composed of sand size quartz grains and stilpnomelane occur in the upper undifferentiated unit at the Empire Mine and in unit VI in the CD 1 Pit area.

CONCLUSIONS The Empire mine section and the CD 1 Pit section appear to converge at 14600' south between DDH holes 47 and 50 approximately 1200' north of the boundary between secs. 18 and 29. Their relationship is not evident; however it cannot be considered a simple fault because there is no obvious displacement or oxidation only a change in stratigraphy and thickness. The differences in the stratigraphic section from south to north might be explained by: 1) a complex fault with great displacement such as the Palmer fault, 2) an Archean fault zone which was active during deposition of the iron formation and reactivated during the Penokean Orogeny, or 3) an abrupt change in basin geometry from south to north.

IS THE PORCUPINE MOUNTAINS AREA A KEWEENAWAN CENTRAL VOLCANO?

S. W. Nicholson, K. J. Schulz, W. F. Cannon, and L.G. Woodruff – U.S. Geological Survey

Although magmatism related to the Midcontinent rift system is mostly basaltic composition, intermediate and felsic rocks comprise about 10 to 15% of the volcanic section in the Lake Superior region. Locally, intermediate and felsic rocks dominate the volcanic suite, as they do, for example, in the Porcupine Mountains area of northern Michigan. The Porcupine Mountains area is anomalous in the Midcontinent rift system not only because of its abundance of felsic rocks but also because of the coincidence of two geophysical anomalies — a gravity low and a magnetic low — superimposed on a broader magnetic high (Fig. 1). In addition, the abundant rhyolite and intermediate rocks form a partial ring of topographic highlands making up the structurally complex and apparently folded felsic volcanic pile. For clarity, the entire area underlain by the elliptical broad magnetic high (and the corresponding topographic highlands) will be called the Porcupine Mountains volcanic center. Within this volcanic center, the Porcupine Peak forms the western highlands, and the hills around the Bergland firetower make up the southeastern highlands (Fig. 1). Earlier workers suggested that this area is a remnant of an Icelandic-style central volcanic complex (White, 1972; Green, 1977; Kopydlowski, 1983), but evidence supporting this suggestion has been largely undocumented. To evaluate this hypothesis, mapping, geochemical, isotopic, and geophysical studies were recently undertaken in the Porcupine Mountains area.

For comparison, central volcanoes in Iceland typically exhibit several characteristic features. In the active Icelandic rift zone, central volcanoes are characterized by tholeiitic basalts and intermediate and felsic rocks. These units define low-relief shield volcanoes a few hundred meters high or clusters of low hills interspersed with basaltic shields, which are centered on large fissure swarms. In some, but not all of the central volcanoes, a central caldera may develop. Not all Icelandic central volcanoes produce rhyolite complexes, but intermediate rocks are always present. Walker (1963) described a Tertiary volcanic center about 35 km wide that reached a maximum of about 2 km high. The central volcanoes are interpreted to overlie shallow episodically filled magma chambers characterized by high- level intrusions and localized hydrothermal alteration.

Preliminary results of mapping and geophysical studies indicate many similarities between Icelandic central volcanoes and the inferred Porcupine Mountains volcanic center. For instance, the Porcupine Mountains center formed at the edge of an active rift zone and is about 30 to 40 km wide, comparable in size to Icelandic central volcanoes. Earlier workers recognized that an accumulation of felsic and intermediate rocks, called the unnamed formation," formed a lens-shaped body underlain by the northwest-dipping basalts of the Portage Lake Volcanics (Fig. 1). The "unnamed formation" is more than 2 km thick at its thickest but thins away from the Porcupine Mountains area. The thickness of the overlying Copper Harbor Conglomerate decreases substantially over the "unnamed formation".

Recent mapping has shown that much rhyolite in the southern highlands occurs as subvolcanic bodies that intrude flows of intermediate composition. These rhyolites are commonly porphyritic, containing both quartz and feldspar phenocrysts. Near the top of the "unnamed formation" in the southern highlands, an extrusive rhyolite body contains mostly small feldspar phenocrysts. In contrast, most rhyolite bodies in the northern highlands are extrusive flows. However, these rhyolites are typically massive aphyric flows or they may contain only sparse feldspar +/- quartz phenocrysts. Understanding the chemical relationships among the rhyolite bodies in the "unnamed formation" awaits the results of detailed geochemical studies.

Gravity modeling across the Porcupine Mountains volcanic center requires the presence of a felsic stock to account for the low gravity anomaly beneath the volcanic center (Klasner and Jones, 1989). A felsic stock also is consistent with the coincident low magnetic anomaly (King, 1987). The geophysical inference of a felsic stock lying beneath the volcanic center supports the comparison with the Icelandic model of a central volcano overlying a shallow magma chamber.

Numerous faults and apparent folding complicate structural interpretation in this area. For example, in the northern highlands (in the Porcupine Mountains State Wilderness Area), a change in the dip of volcanic units from south to north led Hubbard (1975) to propose an anticline. However, detailed mapping indicates that some individual stratigraphic units cannot be traced across the proposed fold. An alternative model for the structure of the northern highlands is that different rhyolite bodies may represent individual small (1–3 km wide) flow–dome complexes, some with carapace breccias still intact, and possibly localized along a major caldera–bounding fault. Similar flow–dome complexes have been documented in the Torfajokull volcanic complex in Iceland (Macdonald et al., 1990). Thus, we suggest that the elliptical area of highlands and the coincident geophysical anomalies reflect the original shape of the volcanic shield, although it has been somewhat modified by post–rift compressional deformation.

The Porcupine Mountains volcanic center appears to share many similarities with Icelandic–style central volcanoes, but a more complete understanding of the area will require careful interpretation of structures along nearby seismic reflection profiles, detailed correlation of stratigraphic units and structural analysis within the center, and careful analysis of chemical, isotopic and volcanological data.

ABANDONED MINE LANDS COAL RECLAMATION PROGRAM

Carol Skillings – Michigan Department of Natural Resources, Geological Survey Division

Although Michigan does not have any active coal mining operations, coal mining did occur in the past. Coal was first discovered in Michigan in 1835 in Jackson County while digging the foundations for a mill and from that discovery several small surface coal mines were opened in that area of the state. In 1861, coal was discovered while sinking the shaft for a new salt mine in Bay City. The coal seam was approximately four feet thick and of better quality than any coal being mined elsewhere in the state. This discovery led to the first commercial venture in 1897 and was the start of Michigan's coal mining industry.

Michigan had continuous coal mining from 1897 to 1952, when the last underground coal mine closed (the Swan Creek Mine), outside of St. Charles, Saginaw County. In 1974-75, there was a small surface coal mine in operation just outside of Lansing in Williamston, Ingham County. There are records of over 165 different coal mines in the thirteen counties from the Saginaw Bay Area to the City of Jackson. Over 100 of the 165 coal mines in the state were located in the Saginaw Bay Area.

The Geological Survey Division (GSD) has participated in the Abandoned Mine Land (AML) Coal Reclamation Program since 1981 and has received grants and cooperative agreements from U.S. Department of the Interior, Office of Surface Mining Reclamation and Enforcement to correct health, welfare and safety problems left behind by abandoned coal mines. Since 1981, the GSD has directed the expenditure of over $1.8 million on the AML Coal Reclamation Program, with direct corrective measures completed on 12 different abandoned coal mines.

GEOLOGICAL SURVEY DIVISION'S GEOLOGICAL CORE AND SAMPLE REPOSITORY, MARQUETTE, MICHIGAN

William T. Swenor and, Milton A. Gere, Jr. – Michigan Department of Natural Resources, Geological Survey Division

The Michigan DNR's Geological Survey Division (GSD) maintains the Geological Core and Sample Repository at Marquette, Michigan. This "Rock Library" facility consists of two buildings, one 40 x 100 feet and the other one 40 x 80 feet in size. A small office and an examination room are located on one end of the larger building.

The Repository's collection of core and samples currently represents 28 of the 83 counties in the state; however, the majority of the materials are from the western one-half of the Upper Peninsula. Thus, Precambrian aged rocks are more represented than the Paleozoic aged materials. In late 1990, the collection consisted of core and cuttings from 839 drill holes representing about 267,000 feet - over 50 miles - of drilling.Core

and cuttings are submitted to the Repository from a number of sources: 1) As a partial requirement of fulfilling state metallic and non-metallic mineral leases; 2) From various state sponsored projects; 3) Through company donations of single holes on up to large collections; 4) From other government agencies, for example, the U.S. Bureau of Mines gave the GSD their large collection of Michigan core when they closed their Minneapolis Repository.

The facility is open for visitors to study the core and cuttings, by appointment on weekdays between 8 a.m. and 4:30 p.m., Eastern Time. Some sampling can be arranged on a case-by-case basis. Copies of data derived from the study of the collection are to be made part of the public record for future users. For information or an appointment, call Bill Swenor or Milt Gere at 906-228-6561.

County	Holes	County	Holes
Alger	3	Lenawee	2
Baraga	29	Livingston	2
Bay	1	Mackinac	2
Calhoun	1	Marquette	85
Chippewa	3	Menominee	31
Delta	9	Missaukee	1
Dickinson	228	Monroe	10
Gogebic	131	Ontonagon	16
Houghton	2	Osceola	4
Ingham	12	Oscoda	1
Iron	246	Otsego	2
Isabella	3	Sanilac	4
Jackson	7	Schoolcraft	2
Kalkaska	1	Tuscola	1
TOTALS		28	839

The contents of the Repository continue to expand. A GSD Open-File Report, OFR 91-1, containing the inventory of cores and samples available for study may be obtained from the GSD offices in Lansing for a nominal charge.

Additionally, the GSD maintains well logs and selected well cuttings for oil and gas wells in Lansing. Water well records are also kept in Lansing by the GSD. Call 517-334-6907 for information. Upper Peninsula, Region I, water well records and selected water well cuttings are kept by the GSD at the DNR's District 3 office near Escanaba. Call Frank Chenier at 906-786-2351 for more information.

Counties and the number of drill holes represented by core or cuttings in the GSD Geological Core and Sample Repository, Marquette, are listed in the table above.

THE SAUBLE ANOMALY, WESTERN LAKE COUNTY, MICHIGAN: A REASSESSMENT

M. A. Waters, J. L. Crocco, A. Heft, K. T. Huysken, and S. D. Stahl – Department of Geology, Central Michigan University,

Regional magnetic and gravity maps of the southern peninsula of Michigan show a nearly circular positive magnetic and gravity anomaly in western Lake County. Because it is conterminous with the Sauble oil field, it is referred to as the Sauble anomaly. The half-width of the disturbance is roughly 4.5 miles (7.25 km). The most recent published analysis of the disturbance is that of Meyer (1963), in which the residual anomalies are shown to have an amplitude of 1,130 gammas and 22 mGals for magnetics and gravity, respectively. Meyer performed ground magnetic and gravity surveys and concluded that the anomaly in its entirety was the result of a basic plug, probably Keweenawan in age, within the basement. He interpreted the juxtaposition of the petroleum field and the anomaly as fortuitous.

A weakness in the interpretation of the gravity is that it ignores the contribution of anomalous masses within the lower section of the sedimentary column. Specifically, there is up to 200 feet (61 m) of uplift beneath the unconformable lower bound of the Antrim Shale (Kirkham, 1932; Newcombe, 1933). In this work are presented the preliminary results of an attempt to:

1. Determine the basement contribution from a combined gravity and ground magnetic survey;

2. Filter out this contribution to the gravity anomaly, thereby leaving a residual anomaly caused by anomalous masses within the sedimentary pile;

3. Constrain the geometry of the sedimentary anomalous masses through a very fine gravity grid;

4. Speculate on the structure and tectonics that produced the pre-Antrim uplift.

The data were collected and analyzed as part of the geology curriculum at Central Michigan University including a senior thesis by Waters.

The instrument utilized for the ground magnetic surveys was an EDA Omni IV Tie-Line magnetometer and simultaneous gradiometer. It has a sensitivity of +0.02 gamma, statistical resolution of 0.01 gamma, and an absolute accuracy of +1.00 gamma under normal operating conditions. Initially a gradient profile across the center of the anomaly was performed to evaluate the depth to the source, and the very low gradient indicated that Meyer's (1963) conclusion of a basement charge was correct. Subsequently

profiles along roads across the disturbance with a sampling interval of 0.2 mile (322 meters) were performed. Data were not collected at sites where erroneous readings (due, for example, to north trending fences, power lines, etc.) were probable. Several readings were taken at each site to establish the accuracy of the readings, and data were recorded only when the instrument-calculated error was less than 0.20 gamma. Daily base stations were visited at two hour intervals, and daily transects were tied to a single site that was sampled at the beginning and end of each field day.

The instrument used for the gravity profiles was a Worden Master gravimeter, that has an accuracy of 0.01 mGals. The gravity grid evaluated at this time consists of measurements along all roads that cross the anomaly at a spacing of 0.125 mile (201 meters); readings were also recorded at all locations where elevations are known (for example at bench marks and intersections). Elevations for all sites were determined using two altimeters on a day with minimum air pressure gradient across the anomaly and corrected for temporal variations in air pressure by utilizing base stations. Three or more (depending upon the range) readings were taken and averaged at each site to avoid discrepancies due to microseisms, and the machine was corrected for temporal drift by:

1. Looping back two sites and remeasuring;

2. Daily base stations that were recorded at two to three hour intervals;

3. A base station that was sampled at the beginning and end of each day.

The preliminary results of the project can be summarized as follows:

1. We agree that Meyer's (1963) model of the source of the magnetic anomaly as a vertical, cylindrical basic Precambrian (probably Keweenawan) intrusion wholly within the basement and unconformably overlain by Paleozoic rocks and with a magnetic inclination 75° to 000°.

2. We feel that, while much of the gravity anomaly is due to this same igneous body, the anomaly produced by the offset

of sedimentary layers creating a succession of smaller anomalous masses can be recognized.

Therefore, there is a strong probability that the disturbance in the potential field and the Sauble field are related. Our working model is that the uplift beneath the basal Antrim unconformity represents a positive flower or tulip structure at the western terminus of a fault of strike-slip offset. Such a model fits within available local well data and regional isopach maps and is potentially verifiable through two different methods we intend to pursue:

1. Petrographic analysis of carbonates from cores in the Sauble area to determine if calcite crystals exhibit features indicative of shear stress, and if so quantifying finite strain ellipsoids; and

2. Completing the gravity grid to the extent of coverage to the level of 0.125 x 0.125 mile (201 x 201 meter) boxes in order to determine edge effects within the lower Paleozoic rocks and thereby determine the geometry defined by the sequence of anomalous masses.

Acknowledgments:

This work was conducted using equipment acquired with the support of NSF-ILI #USE-9051763, NSF-ILI #USE-8950573, and a grant from Apple Computers, Incorporated.

BEDROCK GEOLOGY OF THE NEGAUNEE NW QUADRANGLE, MARQUETTE COUNTY, MICHIGAN

Richard T. Wilkin, Rodney C. Johnson and Theodore J. Bornhorst – Department of Geological Engineering, Geology and Geophysics, Michigan Technological University

The bedrock of the Negaunee NW quadrangle is Precambrian, from Archean to late Proterozoic. Geologic mapping in this quadrangle, made possible by grants from the Michigan Geological Survey and the COGEOMAP program of the U. S. Geological Survey, was completed during the summer of 1990. It represents the first new quadrangle map in western upper Michigan in over 10 years and provides a foundation for future geologic work including exploration for mineral resources.

Archean rocks predominate in the Negaunee NW quadrangle. The volcanic succession of the Marquette-Ishpeming greenstone belt crops out in the southern half of the quadrangle and granitoid rocks which intrude the greenstone belt compose the majority of the northern half. The volcanic succession is composed of the Lighthouse Point Basalt and two thin informal members, Reany Lake pyroclastic and Fire Center Mine iron-formation units (Johnson and Bornhorst, in press). These rocks are intruded by Archean gabbro sill-like bodies which along with the volcanic rocks are metamorphosed from greenschist to amphibolite facies. Archean tonalite to granodiorite intruded the volcanic section during a major deformation event and compose the majority of the northern half of the quadrangle. During a second deformation event rhyolite dikes cut the volcanic section. A massive hornblendite- diorite suite intrudes the foliated tonalite to granodiorites. Locally pegmatite and aplite are abundant as are dikes of a lithologically distinct red, biotite granite. Gneissic diorite along the northern border of the quadrangle is interpreted as representing pre-volcanic basement. Economic geology is discussed by Wilkin and Bornhorst (1990, this volume) and Johnson and Bornhorst (in press).

Early Proterozoic diabase dikes cut all of the Archean rock units. These have been metamorphosed to greenschist facies. In the southwest portion of the quadrangle there is an area of thin bedded slate and siltstone which is correlated with the Michigamme Formation of Early Proterozoic age. Relatively unaltered, east-west to northwest trending Keweenawan (Middle Proterozoic) diabase dikes are common within the quadrangle. The youngest bedrock within the quadrangle is in the northeast corner and is represented by several outcrops of shallow dipping sandstone, correlated as Jacobsville Sandstone.

POSTERS without ABSTRACTS by AUTHOR

GRI - ITS MISSION AND GOALS

Hill, D. and Scheper, R.J., – GRI

MICHIGAN ANTRIM TRACKING SYSTEM – MATS

Roberts, P.A., – ICF Resources Incorporated

LITHOSTRATIGRAPHY OF THE ANTRIM SHALE

Manger, Katherine C., – ICF Resources Incorporated, and Vessell, Richard K., – David K. Davies & Associates

ANTRIM SHALE CORE AND LOG ANALYSES

Olszewski, Adam, – ResTech

RESERVOIR MODELLING - A COMPLEX TASK

Nicol, John, and Oliver, S.J.P., – ICF Resources Incorporated

PARAGENETIC SEQUENCE AND TEXTURES OF AUTHIGENIC MINERALS IN PENNSYLVANIAN AND MISSISSIPPIAN SANDSTONES FROM THE MICHIGAN BASIN

Westjohn, D. B. – U.S. Geological Survey, Sibley, D. F. – Michigan State University and, Eluskie, J. A. – Michigan State University

SCHEDULE OF ACTIVITIES

Wednesday

Poster Setup	3:00-6:00 p.m.	Big Ten A Room
Posters	6:00-8:00 p.m.	Big Ten A Room
Ice Breaker	6:00-8:00 p.m.	Big Ten A Room
Registration	6:00-8:00 p.m.	Conference Registration Desk

Thursday

Breakfast	6:30-7:30 a.m.	Red Cedar Room B, for Thursday Speakers
Registration	7:00-8:30 a.m.	Conference Registration Desk ???
Morning Coffee	7:00-10:30 a.m.	Centennial Room
Slide Review	7:30-5:00	Room 108, preparation for Speakers
Presentations	8:00-4:45 p.m.	Auditorium and Big 10 A Room
Lunch	11:45-2:00 p.m.	On your own
Afternoon Coffee	2:00-4:00 p.m.	Centennial Room
Posters	5:00-7:00 p.m.	Big Ten A Room
Cash Bar	6:00-7:00 p.m.	Big Ten A Room
Banquet	7:00-10:00 p.m.	Big Ten A Room, speaker Robert L. Bates

Friday

Breakfast	6:30-7:30 a.m.	Red Cedar Room B, for Friday Speakers
Morning Coffee	7:00-10:30 a.m.	Centennial Room
Lunch	11:45-2:00 p.m.	On your own
Presentations	8:00-4:15 p.m.	Auditorium and Big 10 A Room
Afternoon Coffee	2:00-4:00 p.m.	Centennial Room

General

Parking is available next to the Kellogg Center for $3.00 all day.
Parking is free for hotel guests, with a pass from the front desk.
A coat check is available in the hotel lobby.
Hotel cafeteria and lounge are located on the lower level.
State Room Restaurant is located on the first floor.
Harrison Roadhouse restaurant is within walking distance.
Downtown East Lansing is one mile from the Kellogg Center.

Kellogg Center

First Floor Plan