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GEOLOGIC MAPPING - A NATIONAL ISSUE

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The strength of any nation is based, in a large part, on its mineral wealth and water resources. These valuable assets are dependent upon geologic mapping for their discovery, evaluation, and adequate development. In addition, the prudent use of these resources involves the proper disposal of waste products that may be harmful to man's continued existence on our planet. In its basic, most fundamental form, geologic mapping involves the gathering of information about the distribution of rocks and rock materials at the surface of the earth and plotting this information on maps. All segments of society, including federal agencies, state and local governments, private industry, academia, and the general public, benefit, either directly or indirectly, from the use of geologic maps.

Since President Kennedy's pledge to place a person on the moon, our nation has witnessed a decline in activities related to characterizing in graphic form the nature of the rocks at the surface of the earth in favor of "black-box" research to collect vast amounts of data on things that have limited impact on the immediate problems that directly affect mankind. Although mapping the dark side of the moon may be of great scientific interest, it has little impact on protecting the essentials of life such as water and air. Nor does it provide important information concerning the location and development of mineral resources for the present and near future. Not only did government abandon support for fundamental geological data gathering, but also our universities began emphasizing "high-tech" research methods while phasing out courses in geologic mapping which would provide needed basic information. Now that an overcrowded earth is rapidly destroying its water supply and trying to hide evidence of a throw-away society by burying everything from PCB's to diapers, our need to know about the nature and distribution of rock materials at and near the earth's surface has become much more critical. How do we reverse the trend? Who will teach the students to collect, interpret, and compile geologic data and produce geologic maps? How can government reverse its ever-increasing trend toward "high science"?

Currently the combined capabilities of state, federal, and academic groups to provide mapping are not sufficient to meet the present need of our country, not to mention future needs, which will be greatly increased. A focused nationwide effort with dedicated dollars in the federal budget is required if the nation's needs are to be met as we enter the 21st century.

A 1987 report prepared by a committee of the National Academy of Sciences clearly recognized the importance of a national geologic mapping program to meet the needs of today's society. The committee stated that those persons and agencies responsible for geologic mapping should take the necessary steps to ensure that adequate geologic information is made available. Further, the committee found that although geologic mapping is carried out in support of other national programs such as wilderness studies, the siting of high-level nuclear waste repositories, federal land management, and earthquake- and volcanic-hazard studies, no separate national geologic mapping program exists in the federal government.

Geologic mapping is both a national issue and a state issue; therefore, it must be addressed at both the federal and state levels. Many states, through their state geological surveys, currently have ongoing geologic mapping programs. However, past progress has been very slow, and these programs will not provide in a timely manner the maps that our nation needs. Therefore, a concentrated effort by the federal government in cooperation with the various states must be made to provide the geologic maps that are needed to satisfy our country's ever-increasing demands for information about our natural resources and environmental concerns.

Geologic maps are the principal sources of geologic information needed for the resolution of nearly all basic and applied earth-science research and decision-making problems. In addition to providing fundamental geologic information, geologic maps indicate mineral-resource potential and serve as a guide to most of the human interactions with the earth. They are used to determine the distribution and availability of energy and mineral resources, the locations and characteristics of natural hazards, the occurrence and availability of water resources, and the availability and limitations of land and water for various uses. Applications include screening and site characterization for toxic and nuclear waste-disposal sites, earthquake-hazard reduction studies, landslide-hazard assessments, volcanic-hazard reduction, siting of critical facilities, evaluation of excessive coastal erosion, and basic earth-science research. While it is commonly recognized that geologic maps are indispensable in the modern search for fuels, mineral deposits (including strategic minerals), and ground-water supplies, it is not well known that geologic maps provide much of the basic data needed for planning many types of engineering construction projects, such as dam and reservoir sites, highways, railroads, pipelines, foundations for buildings, bridges, and industrial plants, location of construction materials, and avoiding construction sites rendered hazardous because of landslides, unstable foundations, and similar earth-rock related problems.

As documented by the 1988 National Academy of Sciences report on geologic mapping, direct users include such diverse groups as private industry, federal, state, and local governments, universities, and the general public. That report clearly attached a high level of importance to geoscience maps in the future. Federal users that benefit from, and are at least in part involved in, preparing geologic maps include the Department of the Interior (U.S. Geological Survey, Bureau of Mines, Bureau of Land Management, Minerals Management Service, Bureau of Reclamation, and Office of Surface Mining), Department of Energy, Environmental Protection Agency, Department of Agriculture, Department of Defense, Department of Commerce, Department of Transportation, Nuclear Regulatory Commission, and the Federal Emergency Management Agency.

Kentucky and Puerto Rico have been completely mapped at a scale of 1:24,000. Kentucky, Connecticut, and Puerto Rico were all mapped as a part of cooperative projects with the U.S. Geological Survey. The Kentucky project required 18 years to complete, and cost approximately $22 million. Estimated benefits from that project have exceeded the costs many times over. The value of petroleum, coal, fluorspar, limestone, and clay deposits discovered during the mapping project exceeded the mapping costs by tens of millions of dollars, and the maps continue to be indispensable tools in the search for much-needed fossil fuels, and other mineral resources. Likewise, much use of the maps is being made in the area of land-use planning, particularly for earthquake preparedness activities in the highly faulted areas of central and western Kentucky (New Madrid area).

Conversely, the lack of adequate geologic information has led to economic and personal disasters due to the improper location and design of such structures as dams, roads, and waste-disposal facilities. The failure of just one large reservoir dam has the potential for great loss of human life and the destruction of millions of dollars in property. Likewise, the cost in tax dollars and human health relative to the improper disposal of toxic wastes resulting in the need for a Superfund site cleanup demonstrates the necessity of knowing in detail the nature of the earth, information that is provided by geologic maps.

In view of the obvious benefits that can be derived from geologic maps, what is the status of geologic mapping in the United States today? Most geologic mapping is conducted by the USGS and the various state geological surveys. According to a report issued in 1987 by the National Academy of Sciences, mapping by the USGS is very much on the decline. For example, the USGS mapped approximately 400,000 square miles in the 1960s, 250,000 square miles in the 1970s, and 120,000 square miles during the 1980s. Furthermore, data indicate that geologic mapping by state surveys is also on the decline. Many older geologic maps, once considered adequate, are now out of date and need revisions in order to meet modern standards. Combined geologic mapping by the USGS, the various state geological surveys, and others is not sufficient to meet the needs vital to the national security, environmental protection, and energy requirements of our country.

Although it is a demonstrated fact that our nation would benefit greatly from a comprehensive geologic mapping program, many factors have contributed to the declining production of such maps. Tight budgets in conjunction with ever-increasing costs are major factors. Moreover, we in the geological sciences have turned our attention to other areas of endeavor that are considered by some of our colleagues to be more sophisticated, or which are more rewarding monetarily, such as geochemistry, geophysics, oceanography, or lunar geology. In addition, the promotion and reward system in our federal and state geological surveys is oriented toward success in the "high sciences," thereby discouraging geologists from becoming involved in basic geologic mapping. This situation is in sharp contrast with that in some other nations such as the Soviet Union and Canada. Field geologists in the Soviet Union are highly regarded and rewarded for their efforts, and the economic and environmental benefits of geologic maps have long been appreciated in Canada. The Soviet Union has placed such emphasis on large-scale geologic mapping that the entire country will have complete coverage by the mid-1990s. In contrast, the United States is considered one of the most poorly mapped nations in the free world, with less than 30 percent of the country mapped at a scale of 1:50,000 or larger. Clearly, geologic mapping must be given much higher priority in the United States.

Both the USGS and the various state geological surveys have legal mandates to conduct geologic mapping. The USGS was established in 1879 by an Act of Congress, and charged with the responsibility for "classification of the public lands, and examination of the geological structure, mineral resources, and products of the national domain." Much work has been accomplished to satisfy this Congressional mandate, but much more is still critically needed, especially now when our requirements for basic geologic information are the greatest in the history of our country.

A focused nationwide effort with dedicated dollars in the federal budget is required now to address the issue of geologic mapping. The program should be managed by the federal government, and the mapping should be done in cooperation with the states, utilizing qualified state and federal geologists in appropriate partnership. A crisis is upon our nation relative to energy, minerals, water supplies, and waste disposal, and it is a crisis that persons in authority must address without delay. A National Geologic Mapping Program will require a significant amount of funding over an extended period of time; however, the alternative to an organized program such as this is to continue to respond to individual crises on an emergency basis. This method of dealing with the situation could cause irreversible damage to the national security and the environment at costs far greater than would be required to map our country in an orderly fashion.

A National Geologic Mapping Program is being promoted by the 51 members (50 states and Puerto Rico) of the Association of American State Geologists in cooperation with the USGS. An implementation plan has been developed which provides a mechanism for direct involvement of the federal survey and state geological surveys, and would involve the nation's colleges and universities. The plan calls for a systematic mapping of the United States at a functional map scale that will satisfy the many needs that are so pressing today, and which will be even more critical in the future. The program would be financed through a Congressional appropriation mandated for this purpose and matched by the participating states.

This program is desperately needed in our country, and it is one that every person in every walk of life will benefit from. It is also a program that geologists and engineers can support regardless of their personal pursuits, whether private enterprise, government, or education. It is not a question of affordability. We cannot afford not to do it. Our future and the future of our children and grandchildren depend upon it.

Dr. Haney is State Geologist of Kentucky and as 1989-90 President of the Association of American State Geologists led AASG's effort to develop the National Geologic Mapping Program.

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THE ROLE OF THE MISSISSIPPI OFFICE OF GEOLOGY IN MINERAL RESOURCES DEVELOPMENT

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The practice of geology has always had a practical bent. Long ago, the Pharaohs of ancient Egypt depended on "geologists" to find and quarry stone suitable for construction of the pyramids and carving into large statues. William Smith, who made the first geologic maps in England in 1815, was a canal-builder who used his knowledge of rock layers and their fossils in his work. Today, our technological society is increasingly dependent upon a tremendous variety of high-tech metals and ceramics, plastics derived from petroleum, and artificial mineral crystals. But the basic infrastructure of our society is built upon the more mundane but vital industrial minerals. These include such materials as rock for riprap and construction, clay for common bricks and coated paper, gravel for road-building, and chalk for cement manufacture. An industrial mineral is defined by the American Geological Institute's *Glossary of Geology* as "any rock, mineral, or other naturally occurring substance of economic value, exclusive of metallic ores, mineral fuels, and gemstones."

Mississippi has an abundance of basic mineral resources of the types that form the foundation of modern society. Production of industrial minerals contributes more than $100 million annually to Mississippi's economy. The Office of Geology, since its creation as the Mississippi Geological Survey in 1850, has always had as its basic charge the responsibility for mapping and publishing reports about the state's mineral resources. The following list of economic minerals and publications that address them, while far from exhaustive, should serve to illustrate the types of mineral resources that have been studied. Some are mined today; others have potential for economic utilization. The list is made up mostly of industrial minerals, but mineral fuels have been added. Lignite was mined to a small extent early in this century and has potential use as fuel for electrical generation. Bituminous coal in northeastern Mississippi could produce coalbed methane or in the future be deep-mined. Oil and natural gas are included here because of their significance in the state's economy, having contributed billions of dollars.

Agricultural lime, used on cropland to correct acidity and promote plant growth:
Bulletins 13 (published in 1916) and 46 (1942); Information Series 77-1 (1977)

Bauxite, an ore of aluminum:
Bulletins 19 (1923) and 97 (1963)

Bentonite, a swelling clay used in drilling mud and as a clarifier of vegetable oils:
Bulletins 22 (1928), 22a (1934), 29 (1935), and 102 (1964)

Bleaching clays, used for clarifying oils and fats:
Bulletin 29 (1935)

Building stone, used in construction and for ornamental facings:
Bulletin 26 (1935)

Cement and Portland cement materials:
Bulletin 1 (1907)

Clays, perhaps Mississippi's most underutilized natural resource, used primarily in brick and tile manufacture:
Bulletins 2 (1907), 4 (1908), 6 (1909), 86 (1959), and 112 (1970)

Chalk, marl, and limestone, used for such purposes as agricultural lime, cement manufacture, and riprap:
Bulletins 1 (1907), 13 (1916), 46 (1942), 62 (1945), 86 (1959), and 112 (1970); Information Series 77-1 (1977)

Coal, a fuel and a potential source for coalbed methane:
Bulletin 86 (1959); Report of Investigations 1 (1989); Open File Reports 2 (1979) and 3 (1980)

Geothermal energy sources, a potential energy supply:
Open File Report 1 (1978)

Glauconite, used as an absorbent, filtering agent, and agricultural fertilizer:
Bulletins 86 (1959) and 112 (1970)

Gravel, see Sand and gravel

Heavy minerals, an assortment of minerals sometimes concentrated in sands, with a variety of uses (ilmenite, one of the so-called heavies, is imported into Mississippi from Australia for use in paint pigments):
Bulletin 93 (1962)

Iron ore of potential commercial quantity and quality is present in northern and north-central Mississippi:
Bulletins 10 (1913), 73 (1951), 74 (1952), and 101 (1963)

Kaolin and kaolinitic clay, used in the manufacture of

chinaware and high-quality paper:
Bulletins 19 (1923) and 97 (1963)

Light-weight aggregate, clays suitable for the manufacture of:
Bulletins 61 (1945) and 103 (1964)

Lignite, used for fuel and as a chemical feedstock:
Bulletin 3 (1907); Information Series 74-1 (1976)

Limestone, see Chalk, marl, and limestone

Oil and natural gas, used for fuel and as chemical feedstock:
Bulletins 15 (1919), 21 (1928), 36 (1937), 79 (1954), 85 (1958), 96 (1962), 97 (1963), 109 (1968), and 119 (1974); Reports of Investigations 1 (1989) and 2 (1991); Cross Sections 1-5 (1969-1978); Chart of Producing Formations (1981)

Rock wool, for insulating material:
Bulletin 62 (1945)

Salt has not yet been deep-mined in Mississippi, but two of the dozens of piercement salt domes have been solution-mined for storage of petroleum products in cavities:
Bulletins 86 (1959) and 112 (1970)

Sand and gravel, used in construction industries:
Bulletins 9 (1911), 16 (1920), 86 (1959), and 112 (1970)

Sandstone, used as a building stone:
Bulletin 26 (1935)

Uranium, used for fuel:
Bulletins 86 (1959) and 112 (1970)

In addition to the reports listed, each of the 40 county geologic bulletins that have been prepared emphasize the economic minerals of that county. Also, the Economic Minerals Map published in 1983 provides a state-wide overview of these resources on one sheet. The quarterly journal *Mississippi Geology*, published since 1980, has contained articles about gravel, coal, lignite, sulfur, and oil and gas exploration.

Mineral resources are found as a result of surface geologic mapping. The Mississippi Office of Geology conducts such mapping and makes the results of its research available through its publications. Geologic mapping of Yazoo County in 1938 turned up structural anomalies that led to the discovery of Tinsley Field, a giant oil field. Mapping of Warren County led to the establishment of a cement plant some years ago. County bulletins around the state have been useful to private industry in the utilization of brick clay, specialty clays, and limestone.

The Office of Geology (formerly the Mississippi Geological Survey) has been collecting and publishing information about the geology and mineral resources of Mississippi since 1850. For assistance with inquiries about mineral resources, or to obtain a free copy of the List of Publications, contact the Mississippi Office of Geology at

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CRETACEOUS WATER-ROCK REACTIONS AT THE JACKSON DOME, MISSISSIPPI: GEOCHEMICAL MODELING WITH THE COMPUTER PROGRAM SOLMINEQ.88

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INTRODUCTION

The Jackson Dome lies directly below Jackson, Mississippi, and is cored by a Late Cretaceous plutonic and volcanic igneous complex (Harrelson, 1981; McKibben, 1988; Saunders and Harrelson, 1991). The igneous rocks of the Jackson Dome were intruded through Lower Cretaceous formations that currently contain metal-rich hypersaline Na-Ca-Cl formation waters. Igneous rocks have generally experienced extensive hydrothermal alteration (Monroe and Toler, 1937; Saunders, 1991), which Saunders (1991) interpreted to be the result of water-rock reactions involving formation brines and the cooling intrusions. This interpretation was based on alteration mineralogy, geologic relationships, trace element geochemistry, fluid inclusion analyses, and light-stable isotope data. In addition, Saunders (1991) documented the presence of Cu-Pb-Zn sulfides in hydrothermal veinlets within the altered igneous rocks, and proposed that the metals were largely contributed by brines as well. If these conclusions are correct, then it suggests that the Jackson Dome, and other buried igneous intrusions of the Gulf Coast region, could host significant metallic mineral deposits. Previously, basin brines have been invoked as the source of subeconomic concentrations of lead and zinc (e.g., Kyle and Price, 1986) and strontium (Saunders, 1988; Saunders et al., 1988) within salt dome caprocks in the Gulf Coast.

This study was designed to test the possibility that basin brines were the fluids that altered the igneous rocks of the Jackson Dome by using the new computer program SOLMINEQ.88, which has the capability of modeling water-rock reactions at relatively high temperature and pressure (Kharaka et al., 1988). Results add further support to the idea that basin brines were the altering fluid, and by inference, were the source of the hydrothermal metallic mineralization.

GEOLOGIC SETTING

The reefal Gas Rock on the Jackson Dome has been the site of significant natural gas and minor crude oil production since the 1930's, and more than 200 wells have been drilled into the structure. Cuttings and a limited amount of core were available for study from six wells that penetrated igneous rocks of the Jackson Dome. Igneous rocks encountered comprise stocks, sills, and possibly laccoliths (Saunders and Harrelson, 1991), with only one well intersecting the main intrusive body. The Jackson Dome was a positive topographic feature during the Cretaceous and probably was a volcanic island for a considerable length of time (Harrelson, 1981; McKibben, 1988). However, what has been preserved by deposition of younger sediments appears to consist mainly of subvolcanic intrusions (Saunders and Harrelson, 1991). K-Ar age dating on whole-rock samples and biotite separates indicates an age of 79-69 million years for shallow igneous activity of the Jackson Dome (Saunders and Harrelson, 1991).

The igneous rocks fall into two general types: 1) phonolites, and 2) mafic alkalic rocks (Saunders and Harrelson, 1991). Phonolite of the Jackson Dome typically consists of phenocrysts of sanidine and nepheline in a fine-grained groundmass of similar composition. Mafic alkalic rocks contain variable amounts of nepheline, clinopyroxene (aegerine, aegerine-augite, or titanaugite), biotite (phlogopite), magnetite, garnet, and sphene. The latter rocks are best classified as ijolite, melteigite, nephelinite, and jacupirangite based on their relative mineral abundances. Whole-rock chemical analyses indicate that the rocks are nepheline-normative, are silica deficient, with SiO_2 as low as 26.7 wt. %, are enriched in titanium (TiO_2 as high as 8%) and alkalis, with Na_2O+K_2O typically exceeding 14%. Igneous rocks of the Jackson Dome are mineralogically and geochemically very similar to the Cretaceous Magnet Cove carbonatite complex of central Arkansas, leading Saunders and Harrelson (1991) to propose that the Jackson Dome may be a carbonatite complex as well.

Intense hydrothermal alteration resulted in significant mineralogic and chemical changes in the primary igneous

TABLE 1.

SUMMARY OF ALTERATION AND VEIN MINERALOGY

Primary Mineral ....alters to.....	Typical Alteration Minerals
titanaugite, aegerine-augite	chlorite, carbonate, smectite, anatase
alkali feldspar	carbonate, analcite, sericite, smectite
nepheline	carbonate, analcite
sphene (titanite)	calcite, anatase, sulfides
titaniferrous magnetite	pyrite, hematite, goethite, anatase
phlogopite ($\pm$biotite)	generally not altered
apatite	not altered

Vein Minerals	Abundance
calcite	major
dolomite	major
pyrite	major
albite	common
siderite	common
quartz	common
adularia	common
base-metal sulfides	common
epidote	rare
anatase	rare

rocks (Saunders, 1991). Clinopyroxenes, garnet, sphene, alkali feldspars, and feldspathoids typically have been replaced by the secondary minerals calcite, dolomite, chlorite, smectite, analcite, anatase, and pyrite, whereas primary phlogopite, biotite, and apatite were largely unaffected by alteration (Table 1). Whole rock analyses indicate that CaO, CO_2, and H_2O increased as a consequence of alteration, whereas Na_2O+K_2O and possibly MgO decreased relative to unaltered samples. In addition, veinlets up to 1 cm wide containing hydrothermal minerals are present in altered samples and consist of two types: 1) calcite, pyrite $\pm$dolomite $\pm$siderite $\pm$albite $\pm$adularia $\pm$epidote; and 2) quartz, adularia, pyrite $\pm$siderite (Table 1). Adularia, the hydrothermal potassium feldspar, is a common alteration phase in volcanic geothermal environments and a common mineral in volcanic-hosted epithermal gold deposits (e.g., Saunders, 1990). In addition, sphalerite (ZnS), chalcopyrite ($CuFeS_2$), galena (PbS), and bornite (Cu_5FeS_4) are minor constituents in veinlets, or are present as disseminations in altered samples (Saunders, 1991).

DISCUSSION AND GEOCHEMICAL MODELING

Present day oil field brines from Lower Cretaceous formations in central Mississippi are typically hypersaline, with total dissolved solids (TDS) greater than 200,000 mg/l, and locally contain >100 mg/l Pb+Zn (Carpenter et al., 1974; Kharaka et al., 1987; Saunders and Swann, 1990). Because of their composition, Mississippi oil field brines have been widely cited as possible analogs to the ore-forming solutions that formed Mississippi Valley-type lead and zinc deposits throughout the mid-continent region of North America (e.g., Sverjensky, 1984). The exact time at which these brines attained their elevated metal contents is not known precisely, but probably they had done so by the time the igneous rocks of the Jackson Dome were intruded. For example, Nunn and Sassen (1986) have modeled thermal aspects of the developing Mississippi Salt Dome Basin using sedimentation rates, and have calculated that the base of the Cretaceous section reached a temperature of 100°C at about 100 million years

TABLE 2.

CHEMICAL ANALYSIS OF BRINE SAMPLE 84-MS-11[1], REEDY CREEK FIELD, MISSISSIPPI

Na	61,700	Fe	465
K	990	Mn	212
Mg	3,050	Pb	20
Ca	48,600	Zn	243
Sr	1,920	Al	0.37
Ba	60	Cd	0.99
SiO_2	27.8	Cu	0.021
Cl	198,000		
Br	2,020		
SO_4	64		
TDS	316,000		
pH	4.93		

[1]Data from Kharaka et al. (1987)

Note: All values for dissolved species are reported in mg/l.

ago. This temperature approximates the temperature of present-day brines in Cretaceous formations within the basin (maximum= 130°C). Because increased metal content generally correlates with higher temperatures and salinities in present-day brines (Carpenter et al., 1974; Kharaka et al., 1987; Saunders and Swann, 1990), it seems reasonable to assume that Cretaceous formation waters would have attained significant metal contents by 100 million years ago. Therefore, igneous rocks of the Jackson Dome with a maximum age of about 80 million years would have been intruded at least 20 million years after the Lower Cretaceous formations attained elevated temperatures and presumably metal contents.

The computer program SOLMINEQ.88 (Kharaka et al., 1988) was used to model some possible water-rock reaction paths during hydrothermal alteration at the Jackson Dome. SOLMINEQ.88 is an equilibrium solution model that has an extensive thermodynamic base with the capacity to extrapolate this data to temperatures up to 350°C and 1 kilobar pressure. A series of mass balance equations are solved by an iterative procedure, which allows the user to both characterize a solution at a particular temperature and pressure, and to model water-rock reactions. For example, when a water analysis is input, the concentration and activity of dissolved species (including ion pairs and complexes) is calculated at the desired temperature, and saturation indices (SI's) are calculated for a series of minerals. The SI, which is the log of the ion activity product divided by the solubility constant for a given mineral at a particular temperature (SI=log IAP/K_{sp}), indicates whether it is theoretically possible for a solution to precipitate (SI>0) or dissolve a mineral (SI<0). SOLMINEQ.88 can also be used to model the change in solution chemistry brought on by changes in the solution temperature or pressure, mixing of additional solutions, addition or loss of gasses, or by dissolving or precipitating a specified mineral (Kharaka et al., 1988).

Initially, SOLMINEQ.88 was used to calculate the saturation states of some selected minerals for the Kharaka et al. (1987) sample 84-MS-11 using their estimated reservoir pH of 4.93. Sample 84-MS-11 (Table 2) is representative of metal-rich oil field brines in central Mississippi; it is from the Rodessa Formation in the Reedy Creek oil field, and has a TDS of 316,000 mg/l and >300 mg/l Pb+Zn (Kharaka et al., 1987). Under reservoir conditions, this solution is saturated with respect to adularia, albite, analcite, clays, quartz, and dolomite, and slightly undersaturated with respect to calcite (Table 3). If magmas or cooling intrusions of the Jackson Dome penetrated the formations containing this or similar brines, two principal physicochemical consequences would have occurred: the brine would have been heated and would have equilibrated with aquifer minerals at the elevated temperature. A temperature of 250°C, which corresponds to observed fluid inclusion homogenization temperatures in hydrothermal minerals (Saunders, in prep.) and probably represents a minimum value for a magma-heated solution in close proximity to the dome, was chosen to model the

TABLE 3.

SATURATION STATES OF SELECTED MINERALS IN A REPRESENTATIVE MISSISSIPPI OIL FIELD BRINE AT ELEVATED TEMPERATURES

Mineral	Reservoir Cond. T=102°C, pH=4.93	Heat to 250°C pH=4.62	Equil. w/ K-smect. T=250°C, pH=5.76	Equil. w/ Ca-smect. T=250°C, pH=5.60
Adularia	0.35	-8.16	0.61	-0.10
Albite	1.51	-6.33	2.42	1.73
Analcite	1.72	-5.07	2.38	1.79
Anhydrite	-0.66	0.02	0.02	0.02
Calcite	-0.20	-1.08	0.40	0.22
Celestite	-0.83	-0.04	-0.10	-0.10
Chlorite	-5.74	-5.03	17.67	15.32
Dolomite	0.83	1.23	3.82	4.16
Illite	3.93	-13.19	1.19	0.10
Kaolinite	2.61	-8.74	1.31	0.62
Nepheline	-1.06	-5.83	0.35	-0.16
Phlogopite	-0.84	-1.37	14.21	12.57
Quartz	0.16	-0.99	0.30	0.20
Ca-smectite	3.63	-12.84	0.99	0.00
K-smectite	3.02	-13.84	0.00	-1.00

Note: Modeling based on analysis 84-MS-11 of Kharaka et al. (1987). Values reported are Saturation Indices (SI), where SI= log (IAP/K_{sp}); IAP= ion activity product, K_{sp}= solubility product at the specified temperature. Positive values of SI indicate supersaturation, whereas negative values indicate undersaturation.

solution chemical evolution (Table 3). Upon heating, the pH drops to 4.62 due to the increased dissociation of water, and of the minerals considered, only dolomite and anhydrite are saturated. This solution was then used to equilibrate with possible formation minerals. For example, allowing the heated solution to equilibrate with potassium or calcium smectites causes the solution to become generally saturated with respect to quartz, albite, adularia, analcite, dolomite, calcite, illite, kaolinite, chlorite, and phlogopite (Table 3). Equilibration with illite (not shown in Table 3) yields results similar to the smectites, and equilibration with quartz or calcite *after* equilibration with one of the clays causes only minor shifts in the saturation states for the minerals listed.

Although this modeling is very simplistic, it does allow a qualitative evaluation of possible chemical trends expected as a consequence of heating a typical central Mississippi basin brine within the host formation. Interaction of the heated brine with the igneous rocks would add additional uncertainties to the modeling, and so it was not attempted. However, there is a reasonably good correlation between hydrothermal alteration and vein minerals observed in the Jackson Dome (Table 1) and the minerals that are apparently saturated in the heated brine (Table 3). In addition, the large positive SI for phlogopite (SI>12) after the solution was equilibrated with the smectites is consistent with the fact that phlogopite remained unaffected by hydrothermal alteration. No attempt was made to quantitatively model sulfide mineral solubilities because of the uncertainties involving the reduced sulfur content of the brine. Kharaka et al. (1987) suggested that galena and sphalerite control the solubility of Pb and Zn, and if they were present in the aquifers, would lead to even greater metal solubilities at the higher temperature used in the modeling. Addition of igneous sources of reduced sulfur to the heated brine would lead to sulfide precipitation in a manner similar to that outlined by Kharaka et al. (1987) for brine mixing under reservoir conditions. Sulfur isotope data from sulfides from the Jackson Dome (Saunders, in prep.) indicate that magmatic sources of sulfur caused hydrothermal sulfides to precipitate from the metal-rich, but sulfide deficient, altering and mineralizing fluids.

CONCLUSIONS

Chemical modeling using the computer program SOLMINEQ.88 indicates that the hydrothermal and alteration minerals, including dolomite, calcite, chlorite, analcite, quartz, albite, and adularia, are supersaturated in a representative Mississippi oil field brine at 250°C after equilibration with common aquifer minerals. In addition, the primary igneous mineral phlogopite is also supersaturated in the chemical modeling, which is consistent with the lack of hydrothermal alteration it exhibits. Results of the chemical modeling support previous conclusions based on other lines of evidence that indicate:

1) Late Cretaceous igneous rocks were intruded through Lower Cretaceous formations containing metal-rich formation waters;
2) Large thermal gradients initiated the development of a convective hydrothermal circulation system that caused formation brines to move into the cooling igneous rocks, resulting in hydrothermal alteration and mineralization;
3) Metals from the formation brines were deposited as sulfide minerals in hydrothermal veinlets and disseminations as they encountered magmatic sources of reduced sulfur.

The available data indicate that conditions were favorable for the deposition of significant quantities of metals in the Jackson Dome during the Cretaceous. The burial of the igneous rocks of the Jackson Dome by at least 900 m of sediments probably precludes exploration and exploitation of this possible resource based on the present day economic considerations. However, results from the Jackson Dome indicate that other more shallow intrusions in the Gulf Coast may have some economic potential, as might other intrusions in other sedimentary basins.

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