GEOLOGIC FEATURES RELEVANT TO GROUND-WATER FLOW IN THE VICINITY OF THE PADUCAH GASEOUS DIFFUSION PLANT

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INTRODUCTION

Various types of structural geologic features may significantly affect ground-water flow in the vicinity of the Paducah Gaseous Diffusion Plant. Numerous faults, folds, and liquefaction structures have been recognized in western Kentucky and adjacent areas of Illinois, Missouri, and Tennessee. Therefore, the primary goal of this report is to compile information concerning local and regional geologic structures that could significantly affect ground-water flow and the dispersal of water-borne contaminants in the vicinity of the plant. A secondary goal is delineating structures that, if reactivated, could affect the structural stability of buildings in the plant area.

At the onset of this study, a series of deliverables was proposed. These included (1) a bibliography of pertinent geologic and geophysical literature, (2) one or more structural features maps, (3) a basement structure map, (4) a surface fault map, (5) a lineament map, (6) field notes and maps, (7) appropriate remote sensing and geophysical data for future analysis, and (8) recommendations for future studies. Instead of field notes and field maps, we are providing a summary of field investigations. In addition to the listed deliverables, we are adding this final report, which discusses the potential significance of faults, liquefaction features, and lineaments to ground-water flow in the study area.

GEOLOGIC AND GEOPHYSICAL LITERATURE AND DATA COMPILATION

A bibliography of pertinent geologic and geophysical publications was compiled from various sources (Appendix A). Maps showing faults, folds, areas of abundant clastic dikes, earthquake epicenters, and linear features were compiled for the area of the Paducah and Murray 30 x 60 minute quadrangles at a scale of 1:100,000 (Plates 1 and 2). Another map, covering the area of the Paducah West, Metropolis, Joppa, and Heath 7.5-minute quadrangles, showing structural features, clastic dikes, and earthquake epicenters, was compiled at a scale of 1:48,000 (Plate 3). We also produced a 1:100,000-scale basement structure map based on proprietary reflection-seismic data (Plate 4). Base maps used for the plates in this study were produced from digital line graphs supplied by the U.S. Geological Survey. Side-looking airborne radar (SLAR) imagery (Fig. 1) was used in lineament interpretations (Plate 2, Fig. 2). A sparker profile obtained from the U.S. Army Corps of Engineers (Fig. 3) was used in fault interpretation (Plate 3).

BIBLIOGRAPHY

A bibliography of structurally relevant geologic and geophysical publications is presented in Appendix A. These references are basically of two types: those that relate directly to the delineation of geologic structures, liquefaction features, or earthquake epicenters in the area of the plant; and those that aid in the understanding of these phenomena.

Unpublished field notes compiled during the joint U.S. Geological Survey-Kentucky Geological Survey geologic mapping program of the 1960's and 1970's served as an important source of local field data for the Paducah area. Most, but not all, of the mappers' field notes were microfilmed and are on file at the Kentucky Geological Survey. Unfortunately, the quality of the microfilm copies is variable, and in some cases, pages were omitted.

REGIONAL SURFACE STRUCTURAL FEATURES

The structural data shown on Plate 1 come from three basic sources. The majority of the structures shown in the Paducah 30 x 60 minute quadrangle part of the map (northern half of Plate 1) were obtained as digital files from the Illinois State Geological Survey. Compiled as part of the Conterminous United States Mineral Assessment Program (CUSMAP), these files were digitized in 1992 from 1:100,000-scale base maps drawn on Mylar by W.J. Nelson. The primary source of these data was 7.5-minute geologic quadrangle maps (1:24,000 scale) (referenced in Appendix A). Revisions were made to the digital files in 1993, 1994, and 1995 as more 7.5-minute quadrangles were mapped.

Other primary sources of structural information for the Paducah 30 x 60 minute quadrangle were Kogala and others (1981), Nelson (1995), and Nelson and others (1996). Because the work of Nelson (1995) and Nelson and others
STRUCTURE ON TOP OF THE PRECAMBRIAN BASEMENT

The structure on top of the Precambrian basement for the Paducah and Murray 30 x 60 minute quadrangles has been interpreted by Drahovzal, based on proprietary reflection-seismic data available to the Kentucky Geological Survey. The definition of the top of the Precambrian basement is the base of the pre-Knox sequence and the top of the post-Grenville or pre-Grenville surface as defined by Drahovzal (1996, in press). Locations for most of these data are currently proprietary, and only interpreted contour maps may be published or otherwise released. An exception is the published data for a part of the northern half of Plate 4 (Potter and others, 1995). Much of the faulting has been projected downward to the top of the basement, based on surface faulting (Plate 1) and on interpretation of the reflection-seismic data. P-wave, rock-velocity assumptions used in determining depth are: post-Paleozoic rocks—6,000 ft/s, post-Knox Paleozoic rocks—16,500 ft/s, Knox Group—21,400 ft/s, and pre-Knox rocks—18,000 ft/s. Plate 4 is part of a regional basement map being produced as part of a seismotectonic atlas by the U.S. Geological Survey and the Illinois Basin Consortium.

SUMMARY OF FIELD INVESTIGATIONS

Field investigations were not a primary task of this study. However, in order to develop a better understanding of the geology of the Paducah area, we made three trips to the area to observe and search for geologic structures.

A trip to the Barnes Creek area of southern Illinois (August 14, 1996) served largely to verify some of the observations of Nelson and others (1996) and Kiefer and others (1997). Unquestionably, the McNairy Formation and Mounds Gravel exhibit deformation in the creek bed, but we failed to see many of the structures described by Nelson and others (1996). This may have been because of the dense vegetation on the creek banks and because some of the exposures may have been destroyed by gravel dredging operations in the creek bed. Many more of the structures were observed and verified by earlier work (Kiefer and others, 1997). Kiefer and others (1997) concluded that although there are significant Quaternary and Tertiary structures of tectonic origin in this part of southern Illinois, some of the purported tectonic features are actually slump or original sedimentary structures.

From September 10 through September 13, 1996, Hendricks conducted a preliminary field investigation of selected streams in the Paducah West, Metropolis, and
Heath Quadrangles. Hendricks walked along the north bank of the Ohio River from the barge-loading facility west of Fort Massac State Park near Metropolis upstream to Brookport, Ill. (Plate 3), and noted no structural features or clastic dikes. All outcrops showing the faults documented by Kolata and others (1981, p. 22–24), including where the Rock Creek Fault (?) had been reported exposed, were covered with rip-rap during construction of the barge-loading facility.

The second stream examined for this study was Massac Creek near Metropolis, Ill., which forms the eastern boundary of Fort Massac State Park. Our fault map (Plate 3) indicates that the Rock Creek Fault (?) may cross this stream between U.S. Highway 45 and the confluence of the creek with the Ohio River. The creek flows mainly in alluvium, but some Mounds Gravel and McNairy Formation sands may be present. No unequivocally structural features were noted, but some deformation was present in cut banks in the stream. We have regarded this deformation, however, as probable Quaternary slumping.

The third area examined during this phase of the study was the south bank of the Ohio River, from the boat ramp in downtown Paducah for approximately 2 miles to the west. No geologic structures were noted. The only sediments present along the river bank were Quaternary alluvium. Much of the river bank was covered by concrete and rip-rap.

Little Bayou Creek was examined from the water-monitoring station on Kentucky Highway 358, upstream toward the plant (Plate 3). No structures were noted in the creek bed, which was entirely within Quaternary alluvium. Hendricks exited the creek when he encountered signs indicating radioactivity and PCB contamination.

The final stream examined in the Paducah area was near Reidland, Ky., where Olive (1966b) mapped a clastic dike in the Porters Creek Clay. Numerous excellent exposures of Mounds Gravel are in the stream bed and banks. The clastic dike is located in a steep stream bank approximately 1,000 ft east of Reidland High School. This feature was described by Kiefer and others (1997) as being composed of gray, micaceous sand, nearly vertical in attitude, and up to 3 in. wide. Logging operations in the area in September 1996 had obscured the dike.

We visited areas exhibiting abundant clastic dikes in the Elva and Oak Level Quadrangles (see the northwestern of two red boxes northwest of Benton on Plate 1) on September 19, 1996. Numerous clastic dikes are exposed in the Porters Creek Clay in a creek south of Kentucky Highway 358, west of New Harmony Church in the Elva Quadrangle (Olive, 1963, 1972) (see Figs. 4–7). Olive (1972) reported these structures to be from less than 1 in. to more than 35 ft across, although the larger dikes may actually be sills. The Porters Creek Clay in this area is dark gray and blocky, with a conchoidal fracture. The unit weathers to various shades of medium, olive, and light gray. The lithology of the clastic dikes ranges from medium-gray to medium-dark-gray, very micaceous, medium-grained sandstone (Figs. 4–6) to medium-dark-gray, very micaceous, silty clay (Fig. 7). The dikes range from less than a few in. to several ft in width, and small waterfalls form where the creek crosses the more resistant sandstone dikes. Although many dikes are fairly straight, some bifurcate, and others make right-angle turns (Fig. 6). One sandstone dike in the creek bed and bank is approximately 16 in. across, widens abruptly upward into a sill-like body approximately 8 ft wide and 4 ft high, and then narrows upward into a 1-ft-wide dike at the top of the outcrop. The Porters Creek Clay is partly brecciated adjacent to the sill, and excellent examples of slickensides are present at the sill margins.

We attended the Association of Missouri Geologists Field Conference on September 20 and 21, 1996, in Cape Girardeau, Mo., principally to examine faulted strata of late Quaternary age and associated liquefaction features (Palmer and others, 1996). This trip enabled us to examine recent faulting and liquefaction features in Missouri (Figs. 8–9) in order to better recognize similar phenomena in the plant area.

**DISCUSSION**

**FAULTS**

In the northern part of the Mississippi Embayment, which includes the Jackson Purchase Region of Kentucky, strata of Eocene age and older are largely concealed by continental deposits (Mounds or “Lafayette” Gravel), aluvium, and loess. Outcrops of indurated strata are rare throughout the region, and the Paducah area is no exception. The scarcity of outcrops, the relatively gentle topography with low-gradient streams, the unconsolidated sediments present at the surface, and the density of vegetation in the plant area make field geologic investigation very difficult. Olive (1972) regarded the concentration of mapped faults in certain areas of the Jackson Purchase to be largely a function of the nature of the surficial materials. More faults have been mapped in areas where the Paleozoic-Cretaceous boundary and the boundaries of the Porters Creek Clay are exposed, because these are easily recognized, correlatable horizons. Therefore, many unrecognized faults may be present in the plant area.

The plant area lies at the southwestern edge of the Fluorspar Area Fault Complex (Treworgy, 1981). As mapped on the surface, the Fluorspar Area Fault Complex trends northeastward through Hardin, Pope, and Massac Counties in Illinois and Crittenden and Livingston Coun-
ties in Kentucky. The Fluorspar Area Fault Complex probably extends for some distance southwestward beneath the Cretaceous and younger sediments that fill the Mississippi Embayment (i.e., into McCracken and adjacent counties in Kentucky). Nelson (1995), Nelson and others (1996), and Keifer and others (1996) have confirmed faulting in the Quaternary and Tertiary rocks of southern Illinois. In addition, the faulting is interpreted to continue downward to the Precambrian basement and possibly deeper (Plate 4). The northeast-trending faults mapped in the plant area (Plates 1 and 3) are probably the surface manifestations of buried Fluorspar Area Fault Complex faults. In all likelihood, the plant area is as intensely faulted as are areas in Pope, Massac, and Hardin Counties, Ill. Furthermore, the number of earthquake epicenters recognized in the area indicates that active faults are present at depth near the plant. The relationship between the faults shown on the Precambrian basement map (Plate 4) and earthquake epicenters is not well understood, and is the subject of continuing research.

Sparker-profile data from the Ohio River (Alpine Geophysical Associates, 1966), available from the U.S. Army Corps of Engineers, reveals an abrupt offset in the profile of a reflector beneath the river at mile marker 948 (Plate 3, Fig. 9). The stratigraphic identification of the reflector is not known, but it may be equivalent to the top of the Mississippian limestone. The offset in the immediate vicinity of mile marker 948 is approximately 100 ft and down to the southeast. The offset on the profile may represent a fault. Overlying horizons show no evidence of offset or faulting, suggesting that Quaternary units have not been affected. The offset may represent a down-to-the-southeast normal fault. Because this potential fault appears to have a similar magnitude of offset as the Barnes Creek and Massac structures farther northeast in Illinois (Nelson and others, 1996) and because it appears to be on trend, it is referred to as the Barnes Creek-Massac Creek Fault Zone(?).

The predominantly northeast-trending faults in the plant area are significant in light of the geometry of the contaminant plumes in the regional gravel aquifer in the plant area. Because faulting, a clastic dike, and lineaments (Plate 2, Fig. 2) in the area all trend northeast, as do the contaminant plumes, local faulting and fracturing may be significantly affecting ground-water migration. Preliminary results from six-fold seismic-reflection studies carried out by Dr. Ron Street of the Department of Geological Sciences at the University of Kentucky (written communication, 1997) confirm faulting at possibly the Clayton-McNairy interval north of the plant. The lineament along the northwest contaminant plume coincides with the southeast seismic-detected fault zone found by Street.

Liquefaction Structures (Clastic Dikes)

Clastic dikes have been mapped in a number of outcrops of the Porters Creek Clay throughout the Jackson Purchase (Olive and McDowell, 1986). For the most part, these features are restricted to the Porters Creek. Although this association may be related to the time of emplacement, it is possible that factors related to the lithology and physical properties of the Porters Creek make it particularly well suited for the emplacement of clastic dikes, and that adjacent strata are not suited.

Demoulin (1996) described Quaternary clastic dikes in Belgium that were prevalent in alluvial sands and silts, but either ended abruptly at the base of overlying gravel beds or penetrated them, at a reduced angle, for only short distances. Only the major dikes crossed the gravel beds without significantly changing dip, but no gravel beds thicker than 15 cm were traversed by dikes.

The Porters Creek Clay is particularly well suited for the emplacement of clastic dikes because it is predominantly a fairly brittle clay that overlies sandy, liquefaction-prone sediments of the Clayton and McNairy Formations. The Porters Creek itself also contains sandy layers that may liquefy during earthquakes and be intruded into overlying material. Furthermore, the Mounds Gravel and reworked Mounds Gravel may possess liquefaction-inhibiting properties similar to the gravels in Belgium described by Demoulin (1996). This may help explain why no true clastic dikes have been recognized in the Mounds, reworked Mounds, or other overlying sediments in the Paducah area (we have determined that suspected clastic dikes in Quaternary reworked Mounds gravels were not intruded, but rather are erosional features over which the gravels were subsequently deposited).

Only two clastic dikes were mapped in the area of the Paducah West, Metropolis, Joppa, and Heath 7.5-minute quadrangles during the U.S Geological Survey-Kentucky Geological Survey mapping program (Finch, 1966; Olive, 1966a) (Plate 3). The dike mapped in the Paducah West Quadrangle is composed of reddish-brown sand intruded into the Porters Creek Clay; the dike is vertical and trends approximately N85°W (Lambert, unpublished USGS field notes). The dike mapped in the Heath Quadrangle in the bed of Bayou Creek by Olive (1966a) was reported to be from 3 to 4 in. in width, trending N70°W (Olive, unpublished USGS field notes). The Heath Quadrangle dike is at an angle of about 35° to the lineaments mapped in the area of the plant (Fig. 2).

The areas of abundant clastic dikes in the Oak Level Quadrangle (Olive and Davis, 1968) and the Elva Quadrangle (Olive, 1963) (see northwestern of two red boxes just northwest of Benton on Plate 1) were described in detail by Olive and Davis in unpublished USGS field notes.
notes. A rose diagram was prepared for this study using the orientations of all dikes described on the Elva, Oak Level, Paducah West, and Heath geologic quadrangle maps (288 individual measurements) (Fig. 10). The many measurements make these data particularly significant. The primary trend among the clastic dikes is northeastward, and the secondary trend is northwestward (normal to the primary trend). The coincidence of the primary trend of the clastic dikes and the direction of faulting in the plant area probably reflects that the faults and dikes formed under similar stress conditions.

If a sufficient number of clastic dikes are present in the vicinity of the plant, they may exert a significant control on ground-water flow in the area. However, because the Porters Creek Clay is not well exposed in the Paducah area, the density of these features cannot be accurately assessed.

LINEAMENTS

As part of this initial study, photographic and digital imagery available to the Kentucky Geological Survey was assessed for use in the project, particularly as a means of suggesting areas of potential faulting and extensive fracturing (i.e., lineament studies). Only data in KGS files and some data easily obtainable from the Illinois State Geological Survey were considered. Most of the data available at KGS consisted of 1:1,000,000- and 1:500,000-scale Landsat satellite imagery for the Paducah area. Because of the small scale, this imagery was only very generally examined, and was not considered appropriate for lineament studies. Because of the lack of funding for remotely sensed data in this project, other potentially available, but expensive products were not considered for purchase.

A SLAR image mosaic for the Paducah area was made available for study by the Illinois State Geological Survey. The mosaic includes the Paducah 30 x 60 minute area covered by the conventional U.S. Geological Survey map and is at a scale of 1:250,000. The image was produced by the SAR system and is west-looking, X-band, near-range synthetic-aperture radar data printed as a photographic mosaic by the U.S. Geological Survey. The imagery was produced by Aero Service Division, Western Geophysical Company of America, from data flown during November 1984 at 30,000 ft above mean sea level. Part of the mosaic used in the analysis is shown here as Figure 1 and represents the area in the vicinity of the plant and to its east and north.

The study area was examined for lineaments that might represent faults or fractures important to understanding the ground-water flow system of the area. This examination was made using the unenhanced photographic version of the data. The examination was made by eye, looking at low angles along approximate northeast and southwest directions on the photograph. Linear features were drawn by fine-point pen on a Mylar overlay and transferred to a 1:250,000-scale base map using landmarks such as the configuration of the Ohio River as registration points.

This procedure revealed many northeast-oriented lineaments, some of which correspond to mapped faults, but all of which are parallel or subparallel to the structural grain of the area (compare Plates 1 and 2). The lineaments in the vicinity of the plant site were transferred onto a larger scale map (Fig. 2). The placement of the lineaments on Figure 2 is not highly accurate, however, because of the vast difference in scale between the lineaments interpreted on the 1:250,000-scale mosaic and the roughly 1:45,000-scale of Figure 2. More accurate lineament mapping is beyond the scope of this study.

The results of this preliminary lineament study, however, are encouraging. Several lineaments have been interpreted in the vicinity of the plant that are oriented N45°E. All of the lineaments are subparallel to the two northeast-oriented Tc99 and TCE ground-water pollution plumes shown on Figure 2. The lineaments form an angle of about 35° with the clastic dike mapped by Olive (1966a–b).

One of the prominent northeast-oriented lineaments is closely coincident with the northwest contaminant plume and is centered on a major fault zone interpreted by Ron Street of the UK Department of Geological Sciences (written communication, 1997) from a six-fold seismic-reflection profile run along a part of State Highway 385 northeast of the plant site. The lineament extends southwest of the plant site, as well as northwest to the Ohio River. It is unknown north of the river. The lineament is subparallel to a short road segment, but extends to the southwest and northeast beyond the extent of the road. Another fault zone detected by Street to the northeast along the road does not correspond to a lineament detected in this study.

These results suggest that further lineament studies with higher resolution, larger scale, remotely sensed data could be a fruitful avenue for future research.

CONCLUSIONS

In all likelihood, the plant area is traversed by the Fluorspar Area Fault Complex, and is therefore underlain by a series of northeast-trending faults. These structures are predominantly obscured by Cretaceous and younger sediments of the Mississippi Embayment, but a few northeast-trending structures have been mapped in the Paducah area (Plate 3). The number of modern-day earthquakes reported in the area indicates that these structures remain
active and therefore constitute a possible threat to foundation stability.

The two linear, northeast-trending, contaminant plumes in the regional gravel aquifer beneath the plant closely parallel the strikes of the faults and lineaments mapped in the area. Furthermore, fault zones identified on seismic-reflection profiles (Street, written communication, 1997) are coincident with the lineaments and the contaminant plumes. This strongly suggest that the northeast-oriented fault zones are controlling ground-water flow in the region and the distribution of the contaminants.

Although only two clastic dikes have been mapped in the area of the Paducah West, Metropolis, Joppa, and Heath 7.5-minute quadrangles, these features are abundant in areas south of Paducah. The dikes are predominantly restricted to the Porters Creek Clay, principally because the lithology of the Porters Creek and the underlying units is conducive to their formation. Perhaps dikes are not found in the Mounds Gravel or the reworked Mounds Gravel because such gravel deposits inhibit the upward migration of liquefied sediment.

Analysis of the orientations of 288 clastic dikes exposed in the Paducah West, Heath, Oak Level, and Elva 7.5-minute quadrangles indicates the presence of two major dike trends, including a primary northeast trend and a secondary northwest trend (Fig. 10). If a sufficient number of clastic dikes are present in the vicinity of the plant, it is possible that these structures exert a significant control on ground-water flow in the area. Because clastic dikes are predominantly or wholly restricted to the Porters Creek Clay, and because the Porters Creek is not well exposed in the Paducah area, the density of these features cannot be accurately determined.

**RECOMMENDATIONS**

This study has revealed a number of interesting facts, but the subsurface structure of the plant area remains largely unknown. Future studies of the area should be comprehensive, and incorporate detailed field work, seismic investigations, and analysis of aerial photographs and satellite imagery.

Field reconnaissance, although difficult in the area of the Mississippi Embayment, may add to the understanding of the nature, distribution, and timing of the structural deformation and liquefaction phenomena in the area. It may also suggest areas for further investigations with other tools, such as reflection-seismic profiling and trenching. Reflection-seismic investigation, if executed using the proper acquisition parameters, will help delineate local faults that may affect the migration of ground-water contaminants in the area, or, if reactivated, pose a threat to the structural stability of the plant.

Analysis of aerial photographs and satellite imagery may help delineate local and regional structures in the plant area and provide a relatively inexpensive tool to highlight areas for further investigations. Any analysis of aerial photographs should include the examination of historic photographs from the late 1930’s, which are now housed in the National Archives. Because these photographs predate the construction of the Kentucky Ordnance Works and the Paducah Gaseous Diffusion Plant, many features may be visible on the historic photographs that are obscured on modern photographs. Of particular importance is the search for sand blows, which can delineate hydrogeologically significant clastic dike trends. In addition, it is important that the transmissivity ranges of clastic dikes in the subsurface be investigated.

Many of the recommendations discussed above are part of a preproposal submitted to the U.S. Department of Energy through Dr. Lyle Sendlein of the Federal Facilities Oversight Unit: Environmental Remediation of the Kentucky Water Resources Research Institute on September 26, 1996, entitled “Geologic Features Relevant to Ground-Water Flow in the Vicinity of the Paducah Gaseous Diffusion Plant: Geologic Field Reconnaissance and Reflection-Seismic Data Collection.” Such a study would be the next step in achieving the overall goal of defining any geologic structure in the vicinity of the plant that could significantly alter ground-water flow and affect the dispersal of associated water-borne contaminants or that could affect current or future foundation stability of the facility and nearby supporting facilities.

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APPENDIX A:
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APPENDIX B

PHOTOINTERPRETATION OF SIDE-LOOKING AIRBORNE RADAR OF THE PADUCAH QUADRANGLE FOR FrACTURE TRACES AND LINEAMENTS

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KGS Disclaimer: This report has been edited only for grammar and style. It has not been through a thorough review process, and the data and conclusions are therefore presented “as is.”

ABSTRACT

Linear drainage patterns are often formed in response to geologic structures, such as faulting and prominent fractures in unglaciated southern Illinois, southeastern Missouri, and northern Kentucky. Thirty-seven percent of the lineaments identified on side-looking airborne radar (SLAR) imagery were coincident with known structures. Imagery of confirmed structures was used for extrapolating known features and interpreting structures where detailed mapping is incomplete. Seven criteria were used to identify lineaments.

Criteria for distinguishing lineaments were:
1. Linear and curvilinear drainage
2. Drainage pattern
3. Wide valleys with linear segments and escarpments
4. Wide mouth at confluence of streams
5. Orientation of drainage
6. Topographic expression of structure
7. Prominent changes in imagery texture or tone not attributable to shadowing or mosaicking.

A total of 266 lineaments were identified on the U.S. Geological Survey 1:250,000 SLAR mosaic. Thirty-three (12 percent) of the traces were coincident with known structures. Thirty-nine (15 percent) of the lineaments were coincident with known structures and extended. One hundred seventy-five (66 percent) were probable traces not coincident with known structures. One syncline could be matched with drainage indications on the SLAR imagery, but two other known synclines could not be identified.
BACKGROUND AND STUDY AREA

The purpose of this study is to extend mapped folds and faults and the unmapped joints and fractures in the Paducah 1 X 2 degree quadrangle as part of a Conterminous United States Mineral Assessment Program (CUSMAP) with the U.S. Geological Survey. The Paducah Quadrangle covers southern Illinois and parts of southeastern Missouri, northwestern Kentucky, and a small area of southwestern Indiana. Detailed geology of part of the quadrangle is mapped at 1:24,000 scale.

Fluorite and other minerals have been mined or occur in fractures and faults in the area covered by the Paducah Quadrangle. Extraction of coal and other economic resources occurring in the region can be adversely affected by unknown geologic structures. Ground control problems in mines have been related to lineaments identified on satellite imagery (Moebs and Sames, 1988; Peters and others, 1988). Furthermore, the region lies to the north of the Mississippi Embayment and the New Madrid Seismic Zone. Consequently there is interest in extrapolating structural geology information to areas not geologically mapped in detail at 1:24,000 scale.

Structural geology of many parts of the region is known from evidence gathered during field reconnaissance and mapping (Baxter and Potter, 1963; Baxter and Desborough, 1965; Baxter and others, 1965; Nelson and Lumm, 1986a–c). However, indications of geologic structure such as faults and fracture zones may be covered or offset and may not be exhibited at the surface (Sabins, 1978; Collins, 1990). Sources of information such as photointerpretation can be used to extrapolate field data or to construct a preliminary map based upon geomorphic evidence such as lineaments, drainage patterns, and other landscape elements. Interpretation in this study was confined to the unglaciated part of the Paducah Quadrangle.

A lineament is defined as a mappable simple or composite linear feature of a surface, whose parts are aligned in a straight or slightly curving relationship, and which differs distinctly from the patterns of adjacent features and presumably reflects a subsurface phenomenon (O’Leary and others, 1976).

Lineaments may be tonal or topographic. Topographic lineaments can be escarpments, valley walls, or more commonly stream segments. Alignments can be in a single watershed or in contiguous watersheds.

Heather and others (1991) were unable to find 1- to 20-m-wide mineralized fractures in Ontario on satellite imagery, airborne radar, or aerial photography; however, the radar imagery provided the most data on the regional deformation zone which contains the gold ore. Sabins (1978), citing an example in Ethiopia, called lineaments observed on LANDSAT imagery but not observed on 1:250,000-scale imagery “zones of weakness in the crust” where surface displacement has not occurred. Observation of lineaments on one scale of imagery but not another occurs in comparison of the interpretations by Kisvarsanyi and Martin (1977) and McHaffie (1983) with interpretations of 1:250,000-scale SLAR imagery by this author.

METHODS AND MATERIALS

Aero Service Division, Western Geophysical Company of America, under contract to the U.S. Geological Survey, collected synthetic aperture radar (SAR) in November 1984 in north–south west-looking flightlines over the Paducah Quadrangle (1:250,000 scale) of southern Illinois, southeastern Missouri, northern Kentucky, and southwestern Indiana. The X-band, side-looking SAR transmitted and received horizontally polarized (HH) signals. Imagery was collected from an altitude of 30,000 feet. Resolution of the original imagery is calculated to be 10 m. The mosaic is prepared from near-range imagery with a depression angle between 14 to 27 degrees.

Interpretation was made manually using positive image transparency (no digital data is available for this quadrangle), transparent compilation of geologic structure (Nelson, 1990), and USGS topographic quadrangle at 1:250,000 scale. The SLAR imagery was overlain with Nelson’s geologic structures map in order to discern whether and how faulting was related to drainage features. Extrapolation made on the basis of drainage characteristics associated with the known faults is discussed in detail below.

The advantage of using imagery and overlays for this project is the capability to roam and view large section[s] of the imagery synoptically rather than be confined to the rather small field of view of a monitor. This was particularly advantageous in comparing topographic expression of drainage in areas which did not adjoin. Repeated use of the imagery transparency for production of diazo copies distorted the image; consequently, there are problems in positional accuracy. Diazo copies of imagery made at different contrasts and colors enhanced copies used in interpretation.

Season of imagery, the eastern illumination angle of the SLAR, and enhancement of the imagery by lighting influenced interpretation. Illusions recognized in interpretation include SLAR look direction, arcuate and circular lineaments not in contiguous drainage basins, very long lineaments not in contiguous drainage basins, and poorly manifested lineaments suggested by an absence of lines drawn on a portion of a map.

IMAGERY INTERPRETATION
Systematic interpretation of imagery is a function of (1) relating physical phenomena to patterns and spectra on SLAR imagery, (2) relating the imagery patterns and spectra to known features of interest on the ground, then (3) extrapolating features having similar patterns and spectra on the imagery to adjacent or nearby areas. Extrapolation is based upon the patterns of tone, texture, shape, contrast, and context of features on the imagery.

**Relating Physical Phenomena to Imagery Patterns and Spectra (Brightness)**

Radar backscatter energy from natural materials is most influenced by topography and is modified by surface roughness (wavelength and depression angle of the radar system) and complex dielectric constant (moisture). Placid water acts as a natural specular reflector which has virtually no backscatter; consequently, it appears dark on the imagery. Moist ground reflects more energy than dry ground. Metallic objects such as bridges and brain bins reflect highly (Sabins, 1978).

Topography, moisture, and surface roughness account for the predominant changes in backscatter patterns of natural features. Because of the considerable foliage at the time of overflight, interpretation is complicated. Except for obvious field patterns and speckle, tonal variation on the imagery was considered [an] indication of topographic relief—i.e., bright areas faced the east, dark areas faced the west (shadows).

**Relating Imagery Patterns to Ground Features**

Valleys are an indication of weak, fractured rock. Bauer (1987) tested rock cores for strength, finding rock 60 m beneath preglacial valleys was up to 26 percent weaker than rock from the same depth away from the valley. His tests also showed that rock strength (acoustic wave velocities, slaking, and compressive strength) is reduced from shallow to deep parts of a valley. Consequently, deep, well-developed valleys suggest profound fracturing in response to stresses such as caused by displacement along a fault.

Topography and drainage patterns are indications of ancient stresses and structural geology events. Parvis (1949, 1950), Thornbury (1969), and Gudilin (1973) inferred geologic structure, soil, and rock types from drainage patterns. Black (1989) defined lineaments on the basis of parallel alignments of surface structures, linear trends of geophysical data, drainage patterns controlled by structure, and geomorphic and vegetation contrasts observed on aerial photography and SLAR imagery. Black noted that lineaments related to ancestral basement blocks in Kentucky are expressed at the surface by faults and folds. However, indications of geologic structure such as faults and fracture zones may be covered or offset may not be exhibited at the surface (Sabins, 1978; Collins, 1990). Consequently, SLAR lineaments apparently unrelated to surface phenomena may be related to deep, ancient structures.

**Extrapolating Feature Patterns on the Imagery to Adjacent Areas**

Lineaments were used in this study to extend previously mapped faults into areas where geology has not been mapped in detail on the ground, and to indicate areas of jointing a fracturing of rock. The value of lineaments was recognized by Brock (1972), as quoted in O’Leary and others (1976):

In ignoring lineaments until faulting is proved, one is denying oneself a vast potential source of information concerning fundamental crustal patterns which would remain grossly incomplete without the help of lineaments.

Distinct linear features, drainage, escarpments, etc. (lineaments) not shown on field maps but observed on the SLAR imagery are shown as dashed lines. A few linear features which were less well manifested on this imagery were noted as dotted lines. Several field-mapped faults and structural features were not observed on the SAR/SLAR imagery. Features found and mapped underground, or buried beneath glacial drift, are not visible on the surface.

Features in the vicinity of Hicks Dome are too numerous to be drawn at small (1:250,000) scale; consequently, only prominent features are shown. Escarpments in Kentucky near Lake Barkley and Kentucky Lake have steep scarps with gentle cuestas, reminiscent of dipping rock rather than faulting. Dipping rock can be inferred from escarpments with asymmetrical slopes (prominent in Illinois and Kentucky), fine parallel drainage on a dip slope, and change in lithology observed by texture, tone, and drainage patterns and density, such as in southwestern Illinois and southeastern Missouri.

Owing to the north–south flightlines and eastern illumination, some east–west-trending features were subdued or not seen in interpretation. Agricultural field patterns particularly obscured drainage patterns in Missouri.

Imagery interpretation of lineaments was based upon certain evidence or “rules”:

1. Linear and curvilinear drainage
   
   (a) Continuous linear drainage segment in single drainage basin suggests faulting, prominent jointing at the surface.
   
   (b) Numerous segments that align across adjacent drainage basins suggest ancient faults obscured by subsequent geologic developments.
Offset drainage where streams in contiguous drainage basins are diverted from their course suggests faulting at the surface.

Contiguous curvilinear drainage on outside of meander, accompanied by diversion of river drainage, suggests landslide (gullies parallel to scarp indicate additional stress relief).

Contiguous curvilinear drainage on outside of meander, accompanied by diversion of river drainage, suggests landslide (gullies parallel to scarp indicate additional stress relief).

Parallel drainage pattern suggests strike valleys of inclined, alternately hard and soft rock.

Fine, parallel drainage pattern suggests dip direction of homogenous rock unit.

Rectilinear or offset drainage pattern indicates fault or fracture traces.

Annular, radial drainage pattern suggests dome or basin composed of both relatively erodible and resistant rock.

Wide, linear valley suggests fault system with wide fracture/fault zone, deep or profound (tectonic) tensile stress, or recurring displacement or fracture.

Wide valley with escarpments suggests multiple fractures or fault zone (e.g., graben).

Tributary with a wide mouth and isolated hills suggests a relief point for intersecting faults or fractures or point of stress relief.

Annular and radial drainage pattern suggests a basin or dome; deviation from expected orientation indicates minor flexures and displacements.

Orthogonal drainage pattern suggests drainage developed along fractures that relieve compressive stress occurring from direction bisecting the large angle.

Parallel drainage pattern suggests strike-, dip-, or fault-controlled drainage development.

Abrupt offset or gap in an escarpment/outcrop pattern suggests relatively recent faulting along offset.

Prominent escarpments with contiguous aligned faceted slopes, hogbacks, and cuestas suggests recent faulting with significant displacement.

Alignment of preserved topographic prominences suggests ancient fault scarp or remnant structurally controlled erosion surface.

Change in drainage density and pattern suggests a change in lithology. Gross changes in lithology are observable by changes in land use/cover, drainage pattern, and density, tone, and texture. Limestone-sandstone juxtapositions in southwestern Illinois and southeastern Missouri are particularly noticeable.

A total of 266 lineaments were identified on the U.S. Geological Survey 1:250,000 SLAR mosaic. Thirty-three (12 percent) of the traces were coincident with known structures. Thirty-nine (15 percent) of the lineaments were coincident with known structures and extended. One hundred seventy-five (66 percent) were probable traces not coincident with known structures. Nineteen (7 percent) were weakly manifested lineaments not coincident with known structures. One syncline could be matched with drainage indications on the SLAR imagery, but two other known synclines could not be identified.

Interpretation of lineaments from SLAR imagery can be performed systematically by (1) relating physical phenomena to patterns and spectra on SLAR imagery, (2) relating the imagery patterns and spectra to known features of interest on the ground, then (3) extrapolating features having similar patterns and spectra on the imagery to adjacent or nearby areas. Seven criteria for distinguishing lineaments were based upon drainage characteristics and topography.

Twenty-seven percent of the lineaments identified on side-looking airborne radar (SLAR) imagery of the Paducah Quadrangle were entirely or partially coincident with known structures. Fifteen percent of all lineaments were extrapolations of previously mapped faults.

Don Lumm suggested comparison of the lineaments with mapped streams. Allan Kover, Alden Warren, and John Jones, U.S. Geological Survey, provided helpful sugges-
tions regarding acquisition and interpretation of the SLAR imagery.

REFERENCES


Figure 1. Part of a side-looking airborne radar (SLAR) image in the vicinity of the Paducah Gaseous Diffusion Plant. From the U.S. Geological Survey.
Figure 2. Lineaments in the vicinity of the Paducah Gaseous Diffusion Plant. Circled line represents the clastic dike. The two short, northwest-oriented lines along Kentucky Highway 385 represent fault zones defined by Ron Street. Base map modified from U.S. Department of Energy map, “Water Policy and Groundwater Contamination Areas.”
Figure 3. Sparker profile obtained on the Ohio River for the U.S. Army Corps of Engineers. Mile markers show the position and horizontal scale. Note the abrupt offset in the dashed reflector at mile marker 948, which may represent the Barnes Creek-Massac Creek Fault Zone.
Figure 4. Clastic dike composed of resistant sandstone in the Porters Creek Clay, Elva Quadrangle, Kentucky. Shovel for scale.
Figure 5. Clastic dike composed of resistant sandstone in the Porters Creek Clay, Elva Quadrangle, Kentucky. Shovel for scale.
Figure 6. Clastic dike composed of resistant sandstone in the Porters Creek Clay. Note that the dike makes a right-angle turn near the shovel blade. Elva Quadrangle, Kentucky.
Figure 7. Clastic dike composed of medium-dark-gray, micaceous, silty clay in the Porters Creek Clay, Elva Quadrangle, Kentucky.
Figure 8. Clastic dike composed of light-gray sand in Quaternary alluvium, Dudley Main Ditch, Missouri. Lens cap for scale is 52 mm in diameter.
Figure 9. Faulted loess in the Old Quarry Trench, Scott County, Mo.
Figure 10. Rose diagram of the clastic dikes described on the Elva, Oak Level, Paducah West, and Heath geologic quadrangle maps (Olive, 1963, 1966a; Finch, 1966; Olive and Davis, 1968).

<table>
<thead>
<tr>
<th>Combined Dike Data</th>
<th>Statistics</th>
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<tbody>
<tr>
<td>N = 288</td>
<td>Vector Mean = 66.8</td>
</tr>
<tr>
<td>Cumulative Length = 0.0</td>
<td>Conf. Angle = 39.56</td>
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<tr>
<td>Class Interval = 10 degrees</td>
<td>R Magnitude = 0.116</td>
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<td>Maximum Percentage = 9.4</td>
<td>Rayleigh = 0.0211</td>
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<tr>
<td>Mean Percentage = 5.56</td>
<td>Standard Deviation = 1.98</td>
</tr>
</tbody>
</table>
Regional linear features are from McHaffie, P.H., 1983, Linear features map of Kentucky—Sheet 1, Paducah Quadrangle: Kentucky Geological Survey, ser. 11, Open-File Report, 4 p., 1 plate, scale 1:250,000. Linear features in the vicinity of the plant were mapped by Drahovzal from 1:250,000-scale side-looking airborne radar (SLAR) imagery.
Fault and dike data are from three sources: (1) 1:24,000-scale structure maps hand-drawn on Mylar by Nelson, W.J., Denny, B.F., Devera, J.A., Follmer, L.R., Masters, J.M., and Sexton, J., 1996, Quaternary faulting in the New Madrid Seismic Zone in southernmost Illinois: Final technical report to the U.S. Geological Survey under the National Earthquake Hazards Reduction Program, award no. 1434-95-G-2525, 41 p.; (2) U.S. Geological Survey geologic quadrangle maps (Finch, W.I., 1966, Geologic map of the Paducah West and part of the Metropolis Quadrangles, Kentucky-Illinois: U.S. Geological Survey Geologic Quadrangle Map GQ-557; Finch, W.I., 1967, Geologic map of part of the Joppa Quadrangle, McCracken County, Kentucky: U.S. Geological Survey Geologic Quadrangle Map GQ-652; and Olive, W.W., 1966, Geologic map of the Heath Quadrangle, McCracken and Ballard Counties, Kentucky: U.S. Geological Survey Geologic Quadrangle Map GQ-561); and (3) interpretations by Drahovzal and Hendricks, including those based on sparker data acquired on the Ohio River for the U.S. Army Corps of Engineers. Faults shown here are in addition to the regional faults shown on Plate 1. Earthquake epicenters were obtained via the Internet from the U.S. Geological Survey–National Earthquake Information Center Earthquake Data Base System; the information is complete and accurate as of August 1996.