SLAR: Side Looking Airborne Radar

REPORT FY-1985 PROGRAM

GEOPHYSICAL AND REMOTE SENSING STUDIES
OF BEDROCK AQUIFERS IN FRACTURE ZONES

by

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1. INTRODUCTION

Remote sensing techniques were used to study groundwater in fractured bedrock. The remote sensing methods consisted of statewide and regional lineament mapping using primarily Landsat Satellite imagery and SLAR (side look airborne radar). Aerial photography of various types were used for detailed local lineament mapping. Mapping lineaments using these new remote sensing techniques have been shown to be related to bedrock fracture zones, specifically faults and joints and to 80% of known structural features (Greiling, 1981). In addition, remotely sensed lineament mapping has been shown to relate closely to geophysically mapped bedrock lineaments, specifically magnetic and gravity surveys (Gabrielsen and others, 1981).

Three aspects of Rhode Island hydrology related to remotely sensed mapped lineaments were investigated in this present study at three levels: statewide, regional and local:

A. STATEWIDE: The relationship of detailed mapping and inventory of surface hydrogeologic features to these Landsat lineaments on a state-wide basis.

B. REGIONAL: The relationship and mapping of SLAR bedrock lineaments to the major subsurface glacial aquifer systems of southern Rhode Island.

C. LOCAL: The hydrogeologic relationship and remote sensing mapping of bedrock lineaments of the Tiverton area as related to bedrock residential wells and local fuel oil contamination of certain wells.

Geophysical studies concentrated on fractures related to the northeastern extension of the Watch Hill Lineament in South County and North Kingston, Rhode Island. The groundmagnetic map over the URI Turf Farm was completed and
the magnetic modeling concept, demonstrated in the previous report (Frohlich and Fisher, 1985), was used to calculate the dimensions, in particular the width, of buried fracture zones. Geoelectrical depth soundings were conducted to support the magnetic fracture model and to estimate fracture porosities.

These studies were extended to a large area that includes the SODGRAS Farm on the Slocum and Wickford Quadrangles. A residual gravity map was completed and magnetic observations were completed to 90 percent.

Final resources were used to study the site of contaminated bedrock wells in Northeastern Tiverton, R.I. The site was selected with personnel from DEM, who are interested in how fast the observed well contamination can spread through the bedrock aquifer. The geophysical part was restricted to a detailed groundmagnetic survey.

Besides DEM, the R.I. Solid Waste Management Corporation was interested in this study, because of a need for methods to estimate bedrock permeabilities underneath landfill areas in general.

In pursuit of the above research projects the following were also undertaken:

1. John Fisher completed a reconnaissance map survey of the bedrock controlled glacial aquifers in Richmond for the Richmond Town Conservation Commission.

2. Joseph Savarese, graduate student under J. Fisher, was provided with a half-time internship by the RI Department of Environmental Management (DEM) Ground Water Division to work with us on the Tiverton bedrock fracture groundwater project. His thesis proposal on the same topic has been accepted in the
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6. Reinhard Frohlich was invited by the Geological Soc. of Maine to present a paper on "The location of buried fracture zones with geophysical methods ", on March 30, 1986 at Bates Coll. in Lewiston.

7. Reinhard Frohlich was invited to participate in a geophysical pilot study of aquifers in fractured bedrock near Presque Isle, Maine.
2. REMOTE SENSING (JOHN J. FISHER)

2.1 LINEAMENTS AND HYDROGEOLOGY

Lineaments are natural linear or curvilinear features that are usually detectable only on regional aerial photographic mosaics or more recently on different types of remote sensing satellite imagery. Lineaments are considered at times to reflect subsurface control and are common as anomalous trends on magnetic and gravity maps, where there is often a direct relationship between these geophysical lineaments and those mapped from satellite imagery. Lineaments often relate therefore to bedrock fracturing and the hydrogeology of subsurface groundwater.

Relationships between "fracture traces" (lineaments) and groundwater was shown earlier for carbonate rock in humid areas (Lattman and Parizek, 1964). Linear features as related to groundwater distribution in Texas was also later established (Finch and Wright, 1970). Use of earlier Skylab satellite imagery showed a direct relationship between lineaments and groundwater in the Susquehanna River Basin of Pennsylvania (Parizek, 1976). Lineaments mapped using later Landsat satellite imagery indicated a direct relationship between linear hydrologic features and bedrock joint systems in Texas (Finley and Gustavson, 1981).

Side looking airborne radar (SLAR) was successfully used to locate potential sources of fracture-controlled groundwater in Pre-cambrian crystalline basement rocks of north-central Nigeria (Gelnert and Gardner, 1979). Twenty four of 26 wells drilled
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Side looking airborne radar (SLAR) was successfully used to locate potential sources of fracture-controlled groundwater in Pre-cambrian crystalline basement rocks of north-central Nigeria (Gelnett and Gardner, 1979). Twenty four of 26 wells drilled based on lineament analysis produced to maximum pump capacity. These crystalline Pre-cambrian basement rocks are similar to much of Rhode Island's bedrock.

The tectonic theory for the origin and development of lineaments is that basement regional structural trends, often seen in geophysical maps, are transmitted upward through overlying rocks. Surface expression of these trends are often as linear geologic features or linear geomorphic terrain features, "the lineaments". Lineament studies in New England have not been common. Barosh (1976) showed that various regional geophysical studies (gravity, aeromagnetic and aerosradioactivity) indicated lineament patterns that complemented those mapped by regional satellite imagery but no satellite lineaments were shown for Rhode Island. Satellite imagery mapping indicated only five lineaments ("lines") for Rhode Island in mapping conducted as part of the Preliminary Safety Analysis Report for proposed nuclear power plants at Charlestown, Rhode Island (NEC, 1977). Preliminary Rhode Island satellite imagery mapping (Fisher and Boyle, 1982) indicated a more numerous and complex pattern of lineaments. This pattern in part may be the result of the welding of a minor continent or sub-plate (Avalon), during a plate collision with Africa (Frohlich and Fisher, 1985) as has been predicted from other geologic studies (Mottl et al. and others, 1980).

2.2 REMOTE SENSING METHODOLOGY

2.2.1 MAPPING TECHNIQUES

Three different types of remotely sensed imagery were used for different aspects of the lineament mapping. This was so that the
best imagery would be used for the best purpose depending on the scale of the mapping. Mapping was accomplished at three scales for three different problems:

A. Statewide lineament mapping (Rhode Island—entire state) — surface and subsurface hydrologic features

B. Regional lineament mapping (Southern Rhode Island — Washington County) — subsurface aquifer systems.

C. Local lineament mapping (Tiverton area, Rhode Island) — detailed bedrock fractures, site of fuel oil contamination.

Landsat satellite imagery were used for the statewide lineament mapping, while both Landsat and SLAR (side looking airborne radar) imagery were used primarily for the southern Rhode Island study. High Altitude Photography (HAP) was also used for this regional study. For the local detailed mapping Landsat and SLAR imagery were used to map the major lineaments while low altitude aerial phography was used to map the remaining lineaments. Actual mapping was accomplished by transferring various geologic and geomorphic terrain linear features (lineaments) onto dimensionally stable mylar film using a Bausch and Lomb Zoom Transfer Scope. This scope is an optical anamorphic correcting, copy ("transfer") system that allows enlargement ratios as great as 1:14. This enables direct optical overlay transferring of larger scale imagery of any scale onto smaller scale base maps. Base maps used for this study include A. Quinn's U.S. Geological Survey Map of Rhode Island (Quinn, 1971) at a scale of 1:125,000. This enabled relating lineaments to faults and geologic contacts. In addition, all satellite lineaments were transferred to
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A Landsat satellite color composite print of Rhode Island at the 1:125,000 scale (same as above U.S.G.S. Geologic map) was produced using special flat-field copying lenses by J. Fisher for a previous Water Resources Project (Frohlich and Fisher, 1985).

This facilitated mapping Landsat lineaments, since the largest scale satellite imagery available for NASA is only half that size at the 1:250,000 scale. For the present study similar 1:125,000 scale Rhode Island SLAR imagery photographs were produced, both north and south looking, using the same techniques, together with available 1:100,000 SLAR mosaics.

2.22 SLAR (Side looking Airborne Radar) IMAGERY

Since SLAR (Side Looking Airborne Radar) imagery differs markedly from the more common aerial photography or even Landsat satellite imagery it is necessary to describe those features of SLAR imagery that area applicable to the present hydrogeology and lineament study. In 1980, the U.S. Geological Survey began this SLAR program to evaluate geologic, cartographic and hydrologic application of SLAR imagery (Southworth, 1984) with emphasis on the Appalachian Mountains of West Virginia, (Pohn and others, 1984). In addition to use in geologic analysis the U.S. Geologic
Survey has indicated that SLAR imagery can be useful for petroleum and mineral exploration, land use mapping and groundwater studies (U.S. Geological Survey, 1985). Lineament analysis of SLAR imagery has proved useful in groundwater exploration for wells in igneous fractured bedrock in West Africa (Gelmett and Gardner, 1979) and it is expected that similar fractured bedrock in Rhode Island exhibits similar groundwater hydrology.

SLAR is an electronic image-producing system whose name indicates that the radar beam is transmitted at an angle to the surface but perpendicular to the aircraft or spacecraft acquiring the data (Fig. 2.1). It is thus similar in principal to the side-scanning sonar used in oceanographic work which operates in a different frequency in a different manner. Airborne SLAR also differs from spaceborne radar, called synthetic-aperture radar (SAR) which requires spacecraft motion to imitate a larger antenna but at greater heights (Elachi and Granger, 1982). Seasat radar imagery and space shuttle imaging radar (SIR) were both SAR systems. In a comparison study in Virginia (Moore and Sheehan, 1981), the Seasat data appeared to have poorer resolution than Landsat images because of radar image speckle. The result, in the case of SLAR, is an obliquely apparently "illuminated" view of the terrain which can pick out subtle surface features, such as folds and faults (Banks, 1975). In addition, it appears that certain lineaments are also emphasized. It is actually a radar signal or pulse which is transmitted from the aircraft and reflected from the terrain which is the apparent "illumination" (Fig. 1).
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Greater reflectivity can be indicated as greater "illumination". The azimuth is the direction of flight while the range refers to the "lock" direction of the radar pulse. A factor of interpretation is the change of shadow length across this look direction from the near (less shadow) to far (greater shadow) range.

SLAR products are available as image strips of the flight line and as mosaics of several flight lines and in a very few special cases as computer compatible tapes (not New England). Positive transparencies are considered superior to photographic paper for analysis and that form was ordered for the present project. SLAR imagery was acquired by the U.S. Geological Survey using a digital high resolution synthetic aperture SAR-1 radar system at flight altitude of 33,000 feet. Look direction was east, average depression angle was 22 degrees and date flown was May 25, 1984. Black and white near and far range paper print mosaics (1:100,000) and black and white film strip positives (1:250,000) were used. A combination of SLAR imagery and aerial photography has been found best for geologic analysis (Galnett, 1975) and that technique was used for the detailed Rhode Island contamination study (see aerial photographs below).

2.23 LANDSAT SATELLITE IMAGERY

The special aspects of Landsat satellite imagery that applies to this study has been discussed in an earlier Water Resources Report (Frohlich and Fisher, 1985). Both false color composite and individual multi-spectral bands (Bands 4, 5, 6, and 7) were available from that study as positive transparencies for May 5, 1976. For the present study, the most recent imagery from Landsat 5 on January 18, 1985 was acquired. To complement the early summer imagery of the previous study, winter imagery was specially
requested and prepared for this study at special handling additional cost. It has been shown (Caran and others, 1982) that winter imagery, when the angle of solar elevation is least, emphasizes low-relief topographic features. Rhode Island lineaments have been found to be of low relief topography in several cases. In addition, the imagery was snow and cloud free and with a minimum of foliage. Most satellite imagery used for land-use or vegetation mapping are from summer months and the foliage can obscure the subtle topographic and geologic features necessary for lineament and other hydrogeologic features necessary for lineament and other hydrogeologic analysis.

In addition to acquiring winter season imagery, newly available spectral bands of the thermatic mapper system were acquired. These included the mid-infrared reflectance (Band 5 - TM) as well as Band 1 (Blue-Green) and False Color Composites (Bands 2,3,4). The thematic mapper (TM) in addition to an extended spectral sensitivity has twice the resolution (40m vs 80m) of the earlier and still available multi-spectral sensor (MSS).

2.24 AERIAL PHOTOGRAPHY

Aerial Photography has been considered the standard for remote sensing for detailed geologic studies for several decades and has been shown to still be the best medium for detailed geologic mapping in association with SLAR radar imagery (Gelnett, 1975). For the present study three different types of aerial photography were used, each chosen for a specific purpose:

A. - Large scale recent aerial photography April, 9, 1985: Black and white contact print paper prints, 9 inches by 9 inches were ordered for the Tiverton aspect of the study from Aerial Data Reduction Inc., Pensauken, NJ. Detailed lineament mapping on these photographs were necessary to supplement those mapped from Landsat satellite and SLAR imagery. The greater resolution of
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B. Early Archival Aerial Photography:
In order to map lineaments before commercial and residential development in the Tiverton area, the earliest aerial photographs of the area (January 26, 1939) were acquired from the National Archives of the Library of Congress, Washington. These 9 inch by 9 inch black and white contact print paper photographs at an original scale of 1:24,000 were also ordered as enlargements to a scale of 1:5,000 to match the recent photography.

C. High Altitude Aerial Photography:
In addition, National High Altitude Photography (NHAP) was acquired of the area west of Narragansett Bay as 9 inches by 9 inches color film transparencies at a scale of 1:100,000. The advantage of NHAP imagery is that it is available as both color infrared imagery and natural aerial ektachrome color. The resolution of this imagery lies between Landsat satellite-SLAR imagery and aerial photography.

2.3 HYDROGEOLOGY OF RHODE ISLAND LINEAMENTS

2.31 LINEAMENT HYDROLOGY

It is now believed that lineaments are the surface expression of deep-seated basement rock fractures often propagated upward through overlying consolidated rock and even unconsolidated geologic materials, such as sediments and glacial material (Goy, 1972). While there is yet no agreement on the exact mechanism for the origin of lineaments, some workers (Geln and Garner, 1979) consider that they are initially tensional fractures extending to great depths. These lineaments mapped fractures are not necessarily normal faults nor do the scale and length reflect joints directly.
Regional tensional lineaments however would have associated open joints which would strongly influence the overall fracture controlled surface and subsurface hydrogeology. Various surface geomorphologic terrain drainage features would develop (Fig. 2.2) influenced by these dominant joint sets as would be the ground water reservoir capacity especially of the normally low porosity and low permeability crystalline rocks.

2.32 SURFACE LINEAMENT HYDROLOGY

Regional lineaments in the Arctic coastal plain on Landsat satellite imagery has been found to be related to surface hydrological features such as lakes and their orientations (Fischer and Latham, 1973). The lineaments were alignments of small lakes, distortions in the shorelines of large lakes, linear areas between groups of lakes and curvilinear alignments of small lakes. Geological and geophysical studies show that these lineaments are features of the underlying geologic structure. Surface drainage hydrogeology patterns have also been shown related to underlying structures. Drainage patterns as mapped on Landsat imagery in five areas of North America (Saunders and Thomas, 1973) were related to the fracture patterns. In some cases, fracture patterns formed lineaments that extended up to a hundred miles. Analysis of Landsat imagery in Texas (Finley and Gustavson, 1981) indicate linear hydrogeologic surface features including stream channels, stream valleys and aligned lake depressions which form lineaments which relate to joints mapped in the field and regional structural trends. Since there were few faults in the area, joints were the structural geologic control. Joints provide paths along which surface drainage will develop preferentially and joint intersections provide sites for downward percolation of water.
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2.33 SUBSURFACE LINEAMENT HYDROGEOLGY

Zones of enhanced hydraulic conductivity have been shown to be associated with large scale structural "mega-lineaments" as mapped from Landsat imagery in the karst plateau region of Kentucky (George, 1984). Lineaments mapped as related to surface hydrologic karst features such as sinkholes (Allison, 1980) were shown to be also directly related to fractures and fracture intersections in the bedrock. Relationship of lineaments to subsurface hydrogeology is indicated from a recent detailed unpublished study (Heller, 1980) in West Virginia. Bedrock wells with a high yield-to-depth ratio were found in areas of high photolineament density. Although these were limestone rocks and secondary karst permeability is a factor, the high lineament density also indicates a higher fracture density which would allow increased development of secondary karst porosity and permeability. This would lead to an increase in yield from the bedrock wells. In Rhode Island, there was little glacial erosion since the continental glacial was mainly melting in southern Rhode Island. Therefore, the bedrock fracture zones, even in crystalline rocks, beneath the surface lowland hydrological features are probably highly weathered, that is pre-glacially weathered in time, and thus highly porous and permeable.

2.34 RHODE ISLAND LINEAMENT HYDROGEOLGY

Relationship of mapped Landsat satellite lineaments (Boyle, 1980) to surface hydrogeologic features were determined for the entire state (Fig. 2.3). These features were established from analysis of lineaments plotted on thirty 1:24,000 topographic maps as well as aerial mosaics, HAP (high altitude photography) and individual aerial photographs as available. Six linear hydrogeologic features are probably related to subsurface bedrock fractures.
such as primarily joints and secondarily faults as diagrammed schematically in Fig. 2.2. The following classification, in order of importance, of surface hydrologic features was developed:

1. **ALIGNED DRAINAGE**: relatively short, straight drainage channel reaches commonly connecting at right angles. Stream segments were included only if they form a sequence of linear channels along a lineament.

2. **LINEAR STREAM SEGMENTS**: long, linear reaches of a stream either in a narrow valley or a wide floodplain lowland. Again several linear stream segments were necessary in a series along a mapped linear lineament.

3. **ALIGNED LAKES**: lakes or ponds of differing shapes but forming a linear series of three or more along a mapped lineament, some lakes maybe also elongated.

4. **ELONGATED LAKES**: lakes or ponds of distinctly linear shape with the linearity aligned in the direction of a mapped lineament.

5. **SWAMPS OR WETLANDS**: wetland terrain as indicated on the topographic maps by the marsh symbol. Considered to be standing water beneath grass or shrub vegetation. A minimum of three or more wetlands and swamps were included which fell along a mapped lineament trend.

6. **LINEAR LOWLANDS**: long, linear valleys, lowlands or negative terrain. Always in these lowlands would be examples of the above linear hydrogeologic features. Those lowlands were included which fell along a mapped lineament trend.
such as primarily joints and secondarily faults as diagrammed schematically in Fig. 2.2. The following classification, in order of importance, of surface hydrologic features was developed:

1. ALIGNED DRAINAGE: relatively short, straight drainage channel reaches commonly connecting at right angles. Stream segments were included only if they form a sequence of linear channels along a lineament.

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An inventory of these hydrogeologic surface features as related to the lineaments (Fig. 2.3) also indicates the percent of these features along the lineament by Roman number I-IV:

I - 100 to 90 percent of the lineament follows or closely parallels this hydrogeologic features.

II - 90 to 50 percent of the lineament follows or closely parallels this hydrogeologic features.

III - 50 to 10 percent of the lineament follows or closely parallels this hydrogeologic feature.

IV - 10 to 0 percent of the lineaments follows or closely parallels this hydrogeologic feature.

As tabulated from Table 2A and 2B, there are 136 mapped Landsat satellite imagery lineaments with 446 mapped hydrologic linear features. The greatest number of lineament associated hydrogeologic features are those of linear valleys and lowlands which represent 30 percent. Although many of these lowlands are the result of selective fluvial erosion along fractured bedrock joint systems, the larger, more extensive lineament valleys probably have developed along a normal fault system, tensional in nature.

Interestingly, the second most common lineament associated hydrogeologic feature are swamps and wetlands at 24 percent. These swamps are often associated with the above linear valleys and it is probably daming by glacial deposits that developed these particular swamps. Elongated lakes make up 15 percent of the features and they are usually in the lowlands in the glacial material and appear to be indirectly bedrock fracture control but at depth. Aligned drainage features at 13 percent are more likely to be bedrock
controlled while aligned lakes at 10 percent are usually located in glacial material and bedrock fracture control would be at depth. Straight stream segments make up less than 10 percent of the hydrogeologic features and this is due to extensive glacial material in most large valleys which allows the stream to meander on the surface.

As discussed in the previous report (Frohlich and Fisher, 1985) some of these major lineaments pass through significant hydrogeological features through the state. The longest lineament (21 miles) lying wholly in Rhode Island (lineament #26, Fig. 2.3) passes through the east, dam, end of the Scituate Reservoir along streams and ponds and then to the Central Landfill site and Almy Reservoir in Johnson. In southern Rhode Island a parallel set of four lineaments (numbers 21, 64, 135, 136) pass through the Great Swamp on the west and extend to Narrow River on the east. In fact, along Narrow River is another lineament which trends north-south, paralleling other north-south lineaments in southern Rhode Island. This is not meant as an extensive description of all the satellite lineament hydrogeologic features listed on Table 1A and Fig 2.3 but just a representative sampling.

2.4 SOUTHERN RHODE ISLAND AQUIFERS AND MEGA-LINEAMENTS

2.41 MEGA-LINEAMENTS OF SOUTHERN RHODE ISLAND

Numerous northeast-southwest parallel trending lineaments were mapped (Frohlich and Fisher, 1985) for southern Rhode Island using Landsat satellite imagery (see Fig. 2.3). However SLAR (side looking airborne radar) imagery lineament mapping for this study revealed the existence of another lineament system. This system trends primarily northwest-southeast and is not apparent on Landsat imagery but only the SLAR imagery. The reason that these lineaments are not apparent on Landsat imagery is that the Landsat imagery is
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In a geologic fracture mapping remote sensing study of the western overthrust belt in Montana (Moore and Shoehan, 1981) an area of northwestern trending faults were investigated. Because this trend also parallels the solar azimuth of the Landsat system, faults were not obvious. The only way to overcome this limitation in geologic terrain or fracture pattern mapping is to use another imaging system. In this case of the above Montana study SLAR imagery was used to indicate these solar-azimuth trending faults. Since SLAR aircraft can fly any azimuth but usually will fly either north-south or east-west, the look direction will then be either east-west or north-south (Fig. 2.1) and illuminated these northwest-southeast trends. For Rhode Island, recent SLAR has an east look direction.

Large scale mega-lineaments were mapped using SLAR imagery in southern Rhode Island (Fig. 2.4). These lineaments trend northwest-southeast and form a parallel system extending 6 to 10 miles across Washington County from the
Connecticut border almost to the west shore of Narragansett Bay. Separation between the lineaments is only 1 to 2 miles. A second lesser northeasterly trend occurs in the eastern half of Washington County. Some of these, trending NNE by SSW, are equally long but more widely separated. A third trend is more ENE by WSW. While it occurs in both North and South Kingstown nearer the Bay it may be related to the trend of the Watch Hill fault in the Westerly area (Frohlich and Fisher, 1985). There are a few long NS widely spaced lineaments in the western half of Washington County. This NS trend parallels the similar trend of the Lake Char Fault, just west of the Rhode Island border in Connecticut. About 40 percent of this mega-lineament system was mapped from Landsat imagery and 60 percent from SLAR imagery.

Regional fracture patterns appear to be the explanation of this lineament pattern. One of the major northwest-southeast trending lineaments follows the trend of the mapped Hope Valley shear zone (Gromet and O'Hara, 1985). In general, the west part of southern Rhode Island exhibits a northwest-southeast trending pattern. While for the eastern half of southern Rhode Island, the lineament pattern exhibits a northeast-southwest trend. Dividing these two regions is a distinctive set of north-south trending lineaments. According to the Bedrock Geologic Map of Rhode Island (Quinn, 1971) this lineament trend divides the Ten Rod granite gneiss on the east from the Scituate granite gneiss on the west. Differences in structure including fracture patterns of the two large rock bodies probably account for the different lineament pattern trends. The northeast-southwest lineament trend in the east has previously been related to fracture systems relating to a rifting of Narragansett Basin (Frohlich and Fisher, 1985). An unusual step-like pattern of the aquifer near the junction of Richmond, Exeter and Hopkinton (A, Fig. 2.5) suggest a series
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2.42 RHODE ISLAND AQUIFERS AND MEGA-LINEAMENTS

Realization that the major aquifers of southern Rhode Island was related to satellite lineaments patterns was while constructing a general location map of the glacial aquifers for the Richmond Town Conservation Commission (Fisher, 1986). The aquifers of southern Rhode Island are important present and potential water supply systems and since they are subsurface it would be useful to develop a model to predict their geologic patterns. The hydrogeology of these aquifers is principally river valleys underlain by sand and gravel of glaciofluvial origin with adjacent till covered bedrock hills 200-500 feet above sea level (Gontier, et al, 1974). Significant to the mega-lineament pattern of these aquifers are these deep buried bedrock valleys (Fig. 2.5). Although not always apparent on the surface, these bedrock valleys exist throughout the coastal zone of New England. Along the coastal region of Connecticut, Rhode Island, Massachusetts, New Hampshire and Maine these glacially filled buried bedrock valleys are the most important aquifers. Hydrogeologic development of these valleys is related to fluctuations of sea level (Upson and Spencer, 1964) with the valleys eroded subaerially during a period of lower sea level. This relatively lower sea level was perhaps the result of the readvance of ice of Late Wisconsinan time or earlier. The water necessary to develop this additional ice had to come from the oceans and thus lower its level. However, during this time, the subaerial fluvial erosion drainage patterns were guided by pre-existing fracture patterns in the bedrock.
Relationship of bedrock fractures in valley development is seen in a hydrogeologic study in West Virginia (Wyrick and Borcher, 1981). Fracture systems affected both the occurrence and movement of groundwater in a typical Appalachian valley. These stress-relief fracture systems underlying the valleys constituted the most transmissive part of the regional aquifer and further affect surface water hydrology. Although this fracture system is in sedimentary rock it indicates that erosion of bedrock is related to fracture systems located in valley situations. Recently, E-an Zen, U.S. Geological Survey geologist mentioned that he felt that almost all valleys in the Appalachians were underlain by a greater number of fractures than the adjacent hill tops (Talk, Washington Geological Society, Winter, 1986).

Drainage courses in the Northern Coast Ranges were mapped as large scale lineament systems using both Landsat and SLAR imagery (Gelnott, 1974). The lineament pattern was related to both local faulting as well as a regional conjugate shear or fracture pattern resulting from a triple plate junction at Cape Mendocins. Thus there is the possibility that a conjugate shear fracture pattern or other tectonic stress system influenced the early drainage pattern in southern Rhode Island. Minor lineament patterns may be related however to joint systems as in Norway (Greiling, 1981) where most of the Landsat mapped lineaments represent normal joints. However, in Norway, it was suggested that glacial erosion the joint system was accentuated, a possibility also for the small streams in Rhode Island.

It is apparent that the pre-glacial or late glacial fluvial streams eroded valleys into the bedrock following one or more different fracture systems in southern Rhode Island (Fig. 2.5). During retreat of the last continental glacier, these valleys were filled with glaciofluvial sands and gravels which are highly permeable and porous (Gonthier et al, 1974). The
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It is apparent that the pre-glacial or late glacial fluvial streams eroded valleys into the bedrock following one or more different fracture systems in southern Rhode Island (Fig. 2.5). During retreat of the last continental glacier, these valleys were filled with glaciolfluvial sands and gravels which are highly permeable and porous (Gonthier et al, 1974). The greatest thickness of these aquifer deposits also occur in these buried valleys (Allen et al, 1966). There can also be seen a difference in the pattern of western aquifers of the lower Pawcatuck River basin which trends northwest-southeast, with a secondary intersecting north-south trend. In contrast, the eastern aquifers of the upper Pawcatuck River basin trend northeast-southwest, with a secondary northwest-southeast trend. As mentioned earlier, these are areas of two different rock types of different ages (Ten Rod granite gneiss to the east and Scituate granite gneiss to the west) so it could be expected that each was subjected to different tectonic stresses. From a hydrogeologic aspect, it is expected that the maximum ground water yield would be found at the intersection of the lineaments with supplemental water from increased bedrock fractures in these intersection areas. In addition, the pattern of the buried valleys and the associated aquifers to the south beneath the Charlestown recessional moraine can be predicted based on the regular patterns developed to the north.
2.5 FIGURE CAPTIONS CHAPTER 2

Fig.2.1: Features of side looking airborne radar (SLAR) available for Rhode Island as related to hydrogeologic lineament mapping. Flight direction (azimuth) is in a north-south direction and the transmitted radar pulse is in an eastward looking direction (range). Reflected radar pulses from topographic surfaces "illuminate" the terrain.

Fig.2.2: Relationship of Rhode Island hydrogeologic lineament "trace" features as related to bedrock fractures. Hydrogeologic features include: elongated lakes, aligned lakes, linear swamps, aligned drainage, straight streams and linear lowlands. Bedrock fractures would be joints, sheeting and faulting and zones of fracture concentration and intersection.

Fig.2.3: Distribution of Rhode Island hydrogeologic features related to Landsat satellite lineaments. Of 136 mapped lineaments with 446 mapped hydrogeologic features as follows: linear valleys or lowlands 30%, swamps and wetlands 24%, elongated lakes 15%, aligned lakes 10%, and straight stream segments 8%. The largest lineament (21 miles) passes through the Scituate Reservoir (#26).

Fig.2.4: Distribution of SLAR mapped lineaments of southern Rhode Island (Washington County). Western Washington Co. lineaments trend primarily in a northwest to southeast trend. Eastern Washington Co. has two lineament sets, one trends NNE by SSW and the other trends ENE by WSW. This latter trend connects with the Watch Hill Fault trend in southwestern Rhode Island.
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SLAR: Side Looking Airborne Radar

John J. Fisher
1986

FIGURE 2.1
SLAR: SLAR: Side Looking Airborne Radar

John J. Fisher
1986

FIGURE 2.1

Lineament Hydrology:
Aligned Drainage
Straight Streams
Linear Lowlands

Lineament Trace Features to Bedrock Fractures

John J. Fisher
1986

FIGURE 2.2
HYDROGEOLOGY of LANDSAT SATELLITE LINEAMENTS
Rhode Island

NOTE: See Inventory Table for Percent and Type of Hydrogeologic Features.

John J. Fisher
Steven T. Boyle
University of R.I.

Percent Hydrogeologic Terrain Features Related to Landsat Lineaments

<table>
<thead>
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John J. Fisher
Steven T. Boyle
University of R.I.

LINEAMENTS OF SOUTHERN RHODE ISLAND

John J. Fisher
Andrew Ross
1986

(lineaments mapped from Landsat Thematic Mapper and North, South and East look SLAR.)
FRACTURE LINEAMENTS AND AQUIFERS
Southern Rhode Island

John J. Fisher
1986

Legend

Aquifer Outwash
Charlestown Moraine Outwash
Fracture Lineaments

FIGURE 2.5
### Table 2a

Percent Hydrological Terrain Features Related to LandSat Lineaments

| Alluvial Plain | Eolian Sand | Alluvial Terraces | Alluvial Terrace | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plain | Alluvial Plane...
# TABLE 2B

**TOTAL**

Percent Hydrogeologic Terrain Features

Related to Landsat Lineaments

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3. GEOPHYSICAL STUDIES (Rainhard K. Frohlich)

Besides the magnetic studies in Northeastern Tiverton, geophysical studies concentrated along the northeastern extension of the Watch Hill Lineament on the Quadrangles of Kingston, Slocum and Wickford (see Fig.3-1).

3.1 MAGNETIC STUDIES OVER THE URI TURF FARM

Airborne- and groundmagnetic surveys are frequently used to locate and trace structural elements, including faults and folds. Large-scale tectonic units show magnetic anomaly patterns that can be traced over several hundreds of miles (Higgins and Zietz, 1983). Less known is the direct relationship between faults and fractures and their magnetic signatures. Magnetic anomaly patterns can be interrupted and offset across shear faults (Schwab and Frohlich, 1976), as it is most likely the case northeast of the contaminated well site in Northeastern Tiverton (see chapter 4.4). Henkel and Guzman (1977) correlated fracture zones with trends of subdued magnetic anomalies. The partial extinction of magnetic anomalies is caused by a decrease of the magnetic susceptibility within the fracture zone. Thin section analysis suggests an oxidation of magnetite to hematite, named "martitization", which is a process believed to originate from solutions that circulate within the fractures. Frohlich (1982) showed that this concept, if applied to a uniformly magnetized sheet, can produce elongate magnetic lows over a nonlinear magnetic gap that represents a "martitized" fracture zone. In the following magnetic models are compared with the magnetic anomaly map over the URI Turf Farm to determine the width of the fracture zone.

The magnetic anomaly map over the URI Turf Farm was further expanded and completed. This location is ideally suited for geophysical surface studies, as the bedrock is covered by glacial outwash, which presents an almost level
surface. Fig. 3-2 shows the extended magnetic anomaly map. Magnetic stations were established on a two-dimensional grid at station intervals of 100 ft. Each station reading presents the average of three adjacent readings obtained with a proton precession magnetometer, model Geometrics G816 and G856. Observations were rejected if the three adjacent readings differed substantially from each other (>30 nT). Steel fences, landfill (northeastern part), pipes and railroad tracks prevented a further expansion of this map.

The magnetic anomaly map with 20 nT contour intervals shows three northeast trending relative magnetic lows, characterized by hatchured contours. The northwestern anomaly low A is parallel to the railroad tracks (see Fig.3-3), which may have influenced the magnetic anomaly pattern. The southeastern anomaly low C shows some irregularities, possibly caused by some man made structures along the road. The anomaly low B in the center shows the most regular anomaly pattern and was reproduced with a magnetic model.

Profile A' - A in Fig.3-4 shows a center anomaly of -80 nT. It is compared with two model anomalies with a computer program described in Appendix A. The width of the fracture zone is between 90 and 120 m. The relatively small magnetic susceptibility of 0.0004 emu is an average value observed on outcrop samples further south (Frohlich, 1982). The amplitude of the magnetic low is strongly dependent on the magnetic susceptibility and the inverse to the depth of the magnetic layer. The value of 15 m is in agreement with wells that penetrated the glacial deposits. Variations to the depth of the bottom of the sheet (=500 m) have a relatively small influence on the amplitude of the anomaly. Further changes of the model anomaly with changes in the model parameters are shown in Appendix A. It is important to note that this relatively simple geological model concept is based on induced magnetization only which is the major component of granite magnetization.
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3.2 GEOELECTRICAL STUDIES

3.21 INTERPRETATION OF DEPTH SOUNDINGS BASED ON HORIZONTAL LAYERING

In the absence of bedrock outcrops at the URI Turf Farm the interpretation concept for magnetic lows was confirmed with geoelectrical depth soundings. Should magnetic lows indicate bedrock fractures, one would expect low bedrock resistivities over magnetic lows and high bedrock resistivities over magnetic highs. Three geoelectrical depth soundings after Schlumberger were conducted parallel to the northeastern trend of the anomalies (see Fig. 3-3). The first depth sounding, VES#1 (Vertical Electrical Sounding), is parallel to the railroad tracks over anomaly low A; the second sounding VES#2 was located over a magnetic high; and the third sounding VES#3 is over the magnetic low B. As the base lines, the spread of the current electrodes, is parallel to the magnetic anomaly trend, lateral inhomogeneities in resistivity, caused by the fractures, are optimally suppressed.

The depth soundings were interpreted by comparison with multilayer model curves derived from a horizontally layered resistivity depth model. The computer program and the interactive modeling procedure are described in Appendix B.

The three depth sounding curves are shown in Fig. 3-5. The apparent resistivity is plotted versus the half electrode separation L/2 on double logarithmic coordinates. The depth to which the apparent resistivity, corresponds, increases with an increase in L/2. The models derived from the best fitting model curve are shown at the top of Fig.3-5, where the horizontal axis is used for the depth on the same logarithmic axis. All curves represent four-layer cases. A shallow low-resistivity surface layer is underlain by the highly resistive unsaturated zone that causes the maximum on all curves, while the saturated zone causes the minimum. This zone is particularly thick.
underneath VES#2, over the center of the glacial stream channel. The ascending limbs for large electrode separations, from L/2 = 200 to 800 feet, are controlled by the resistivity of the bedrock. At a slope of 45 degrees with the horizontal axis the bedrock resistivity is infinitely high. This slope is approached with VES#2 at large electrode separations. Bedrock resistivities obtained from the other two depth soundings (VES#1 and 2) are below 10,000 Ohmfeet. This is satisfactory evidence that the magnetic lows occur over fracture zones, while relative highs are over compact bedrock.

A bedrock resistivity of 8000 Ohmfeet can be compared with the water conductivity measured in the URI-well near the northwestern edge of the map shown in Fig.3-3. The conductivity was 150 mhos/cm. Archie's Law (1943) allows an estimate of the rock porosity with the simple relationship:

\[ \Phi_b = \Phi_w \cdot \Phi^{-n} \]

\( \Phi_b \) is the bulk resistivity of the bedrock (compact or fractured) that is derived from geoelectrical depth soundings.

\( \Phi_w \) is the resistivity of the water in the pores and joints.

\( \Phi \) is the porosity

\( n \) is a constant known as the "cementation factor".

For \( \Phi_b \) a value of 8000 Ohmfeet (=2440 Ohmm) was used. The water resistivity was calculated from the observed water conductivity. For \( n \) a low value of 1.5 seems to be appropriate, which is similar to the values used for unconsolidated sand (Frohlich, 1976). For a comparison, a higher value for \( \Phi_w \) (=300 \( \mu \) mhos/cm) was used, since the nearby landfill may have lowered the water resistivity in the fractures (Kelly, 1977 and Sanders, 1982). Table 1 shows ranges for the porosity \( \Phi \) in % derived from Archie's Law.
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A bedrock resistivity of 8000 Ohm feet can be compared with the water conductivity measured in the URI well near the northeast extremity of the map shown in Fig.3.3. The conductivity was 150 mhos/cm. Archie's Law (1943) allows an estimate of the rock porosity with the simple relationship:

\[ \sigma_b = \sigma_w \cdot \phi^{n} \]

\( \sigma_b \) is the bulk resistivity of the bedrock (compact or fractured) that is derived from geoelectrical depth soundings.

\( \sigma_w \) is the resistivity of the water in the pores and joints.

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Table 1 shows ranges for the porosity \( \phi \) in % derived from Archie's Law.

<table>
<thead>
<tr>
<th>( \sigma_w )</th>
<th>150</th>
<th>300</th>
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<td>( \sigma_b )</td>
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Table 1: Fracture porosities derived from Archie's Law.

An estimate of the fracture porosity in the range between 5 and 10 % is in excellent agreement with fracture porosities derived from gravity profiles across the Narrow River (Frohlich and Fisher, 1985). The gravity-derived fracture porosities ranged between 2.5 and 3.7 % as a minimum estimate and an average for a fracture zone of at least 1 km depth. The values derived from the geoelectrics at the URI Turf Farm correspond to the upper part of the bedrock, where fractures are expected to be more abundant than at depth.

3.22 EVIDENCE OF LATERAL INHOMOGENEITIES RELATED TO BEDROCK FRACTURES

Generally, irregular and nonsteady geoelectrical depth sounding curves are observed if the structure of the substratum deviates substantially from a horizontal layer case. On the other hand, a steady field curve is not necessarily evidence for a horizontally layered substratum. Other criteria were observed that indicated the presence of lateral inhomogeneities as they are expected over fractured bedrock. One important indicator of lateral inhomogeneities is a substantial change of the apparent resistivity if the potential electrodes are expanded while the current electrodes remain stationary. For a horizontally layered substratum the apparent resistivity, obtained with different potential electrode spacings, b, should be small to negligible if b is less than 5% of L, the current electrode spacing. Most
depth soundings were conducted with a b=2, 6, and 8 feet. The depth soundings
over magnetic lows, (VES#1, 3, and 4) show substantial differences between
readings taken at different values for b. It was also apparent that the values
did not converge for larger L, as it is the case over horizontal layers.

David Owen, graduate student, worked on a computer program using the
finite difference method to estimate lateral inhomogeneities caused by
conductive fracture zones. The method of flow nets, described by Freeze and
Cherry (1979), is also applicable to the flow of an electrical current, as the
differential equations and boundary conditions for water and electrical
current flow are analogous. This technique, while tedious, is very useful for
illustrating the concept of current flow constrained by geometries associated
with a conductive fracture zone in nonconductive bedrock. Application of the
finite difference method after Mufti (1976) showed no significant change (≠
5%) of the equipotential lines (perpendicular to the lines of current flow) if
the width of a fracture zone is smaller than the depth of the homogeneous
overburden. In this model the resistivities of the overburden and the fracture
zone are the same. Multiple layer cases with different resistivities have not
yet been considered, but are expected to enhance rather than to subdue the
effect from the fracture zones. If the potential electrodes are over the
center of the fracture zone, an expansion of the potential electrodes will
result in larger apparent resistivities. This effect has been observed over
fractures.

3.23 NONLINEAR CURRENT-VOLTAGE RELATIONS OVER FRACTURES

A new geoelectrical phenomenon was observed over the fracture zone
associated with the magnetic anomaly low B. Repeated geoelectrical depth
soundings over the same location were conducted to observe these effects (VES
# 4, see Fig.3.3). The effects occur at large electrode separations L/2 and
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3.23 NONLINEAR CURRENT-VOLTAGE RELATIONS OVER FRACTURES

A new geo-electrical phenomenon was observed over the fracture zone associated with the magnetic anomaly low B. Repeated geo-electrical depth soundings over the same location were conducted to observe these effects (VES # 4, see Fig.3.3). The effects occur at large electrode separations L/2 and originate from the saturated zone and the bedrock. The most frequently reoccurring events are:

1. The apparent resistivity changes if the current is reversed, i.e. the reversed current produces a different voltage at the potential electrodes.

2. With increasing L/2 the difference of the apparent resistivities, observed for both polarities, increases.

3. At large L/2 the voltage may not reverse with the current, but will show a polarity that is opposite to the electrical current (see Fig.3.3 in Frohlich and Fisher, 1985).

4. The value of the apparent resistivities, observed with both current polarities, will change with the size of the current.

5. The intensity of the above-mentioned nonlinear effects is small during the winter and early spring. They build up during late spring and last until the late fall. There seems to be a dependence of these abnormal effects on the amount of precipitation, which controls the water pressure in the fracture zone.

Because of the influence of precipitation, a series of depth soundings was repeated over VES #4 to study the change of these effects with time. In 1985, after a very dry winter, the nonlinear effects were observed as early as April 1st. In 1986, during a rainy spring and summer, the effects were observed for the first time as late as June 30. Prior to this date four successive depth soundings showed systematic changes in the unsaturated and saturated zones. Fig. 3.6 shows the four depth sound curves and the best fitting resistivity depth models. The results of the interpretation are summarized in Table 2, which also shows the transverse resistance of the unsaturated zone \( R_{t} = \frac{\gamma_{t}}{D_{t}} \) and the conductance of the saturated zone \( S_{s} = \frac{D_{s}}{\gamma_{s}} \). They are the Dar Zarrouk parameters that describe the electrical properties of a high- and low-resistive layer, respectively.
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Table 2: Change of geoelectrical parameters of the saturated and unsaturated zone over a fracture.

Most significant is a decrease of the resistivity in the unsaturated zone from 4/16/86 to 6/4/86. This strongly suggests an abnormal increase of the pore water salinity over the fracture zone before the nonlinear resistivity effects occurred. On June 30, the reversal effect was observed for the first time in 1986. On July 8-86 the effect has decreased in intensity due to renewed rainfall. The repeated depth soundings that show the nonlinear effects are shown in Fig.3.7. It appears that the salinity of the pore water in the fracture zone does not only change considerably with time but also has a controlling influence on the occurrence and intensity of nonlinear resistivity effects. During periods of high precipitation the pressure of fresh water seems to be dominant. During dry periods water of higher salinity seems to migrate towards the center of the fracture zone.

Nonlinear current-voltage effects are not unknown to physicists. They occur as boundary effects in semiconductors and are utilized in the transistor. They were also observed across membranes that separate high- from low-concentration saline solutions. Kobatake and Fujita (1964) investigated these effects on charged membranes and suggested that similar processes are associated with membranes in the nerve system. Though such phenomena have never been described in the geophysical or hydrogeological literature, it is very likely that similar membrane effects are the cause of the observed
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3.3 GRAVITY STUDIES

The gravity map of Rhode Island showed evidence of a potential gravity low on the quadrangle of Slocum. A glacial stream channel intersects the northeastern extension of the Watch Hill Lineament. Detailed gravity observations were conducted at this intersection. A similar condition was expected, which exists further south on the Carolina Quadrangle. A glacial stream channel underneath the Lower Wood River intersects the Watch Hill Lineament. A local gravity low suggests an extensive deposition of glacial deposits at the intersection forming a high yield aquifer. The site on the Slocum Quadrangle at the SODGRASS Turf Farm is also located over the intersection of a glacial stream channel with a fracture system.

The Bouger Gravity (see Fig.3.8) shows a strong gravity gradient of the regional field. This may have subdued the more local effect of glacial stream channels and fractures. The regional field was separated with a least squares two-dimensional plane (see Appendix C). Fig. 3.9 shows the residual gravity map which emphasizes the local anomalies. To the southeast of the map a northeast striking gravity low is parallel to a fracture- related surface depression (see Fig.3.1). The large closed gravity low in the northern part of the map is exactly at the intersection of both lineaments, i.e. the glacial stream channel and the Watch Hill Lineament. The cause of the gravity low is believed to be related to a large deposition of glacial outwash.
3.5 FIGURE CAPTIONS CHAPTER 3

Fig. 3.1: Location of geophysical survey in South County, R. I.

Fig. 3.2: Groundmagnetic map over the URI Turf Farm at 100 ft station intervals with 20 nT contour intervals. Anomaly lows depict buried fracture zones.

Fig. 3.3: Groundmagnetic map with location of geoelectrical depth soundings.

Fig. 3.4: Comparison of a magnetic profile across the URI Turf Farm with model anomalies derived from a fracture model.

Fig. 3.5: Geoelectrical depth soundings after Schlumberger over fracture zones (VES # 1 and 3) and over compact rock (VES # 3).

Fig. 3.6: Geoelectrical depth soundings over the same location (VES # 4) conducted at different times during the spring of 1986. Changes of the resistivity in the saturated zone suggest an increase in pore water salinity in the fracture zone prior to the occurrence of nonlinear geoelectrical effects.

Fig. 3.7: Geoelectrical depth soundings over VES # 4 at different times of the year showing nonlinear resistivity effects. For large electrode separations the resistivity changes with a change of current polarity. Circles indicate voltage reading that is opposed to the electrical current.

Fig. 3.8: Bouguer gravity map over the SODGRAS Turf Farm, Slocum Quadrangle.
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Fig. 3.9: Residual gravity over the SODGRAS Turf Farm showing a NE striking fracture-related gravity low. A closed NNW trending gravity low in the northern part indicates an increase in the thickness of high porosity glacial outwash.
Fig. 3.7
4. TIVERTON BEDROCK WELL CONTAMINATION (Fisher, J.J., R.K. Frohlich, J. G. Savarese)

4.1 REMOTE SENSING, HYDROGEOLOGIC AND GEOPHYSICAL APPROACH:

Seven private wells in Northeastern Tiverton have been contaminated with fuel oil, as reported by the Rhode Island Department of Environmental Management's Ground Water Section. Since the contamination is located in buried bedrock wells, the aquifer is the fracture zone of the granitic bedrock. A common procedure for determining fracture zones in bedrock is to use a step-wise approach of interpreting lineaments derived from aerial photography, satellite and radar imagery, and topography to determine their location. Interpretation of well records would then be necessary for construction of hydrogeologic models. The use of ground geophysical methods would then allow the determination of more specific hydraulic characteristics of the fracture zones, such as: porosity, permeability and fracture density.

Investigation of this area is important due to the potential rapid movement of contaminated water in fractured bedrock. The threat of contaminated water flowing to additional private wells in addition to the possible impact on nearby Stafford Pond, a municipal source of public water supply.

The remote sensing methods are used to determine the location and pattern of lineaments. Once lineaments have been mapped, results from ground magnetic geophysical surveys can verify the presence of the subsurface fracture zone from which the lineaments were formed. Similar types of investigations undertaken in Rhode Island have been conducted for subsurface interpretations. Previous geophysical studies include those by Frohlich,
1982; Frohlich and Barosh, 1982; Frohlich and Fisher, 1985; and Sanders, 1983. Magnetic surveys were initially conducted in the proposed area of research. This technique has been used specifically for location of fracture zones (Henkel and Guzman, 1977). Hence, direct correlation of hydrogeological and remote sensing analysis with geophysical results allow refinement of the hydrogeologic model using knowledge of subsurface conditions and hydraulic characteristics of fracture zones.

4.2 LINEAMENT ANALYSIS

Delineation of lineaments in Tiverton help determine areas of highly fractured bedrock through which a considerable amount of groundwater flows. Many investigators have studied and evaluated the importance of fractured rock located by lineaments as an important ground water resource (Lattman and Parizek, 1964; LeGrand, 1949, and Parizek, 1976). Major lineaments in Tiverton and the surrounding area: Little Compton, RI; Fall River and Westport, MA; were mapped from aerial photography (1985, 1939), SLAR (Side Looking Airborne Radar) and Landsat Satellite Imagery and projected to a 1:100,000 U.S.G.S. topographic base map using a Bausch and Lomb Transfer Scope and Art-O-Graph Image Projector.

Lineaments in the Tiverton area trend predominantly north-north-west by south-south-east (Fig. 4.1). The system of lineaments are parallel to subparallel. Significant parallel systems occur between Sakonnet Point and Little Compton (A, Fig. 4.1) and just south of Davol Pond, just east of the Rhode Island border (B, Fig. 4.1). The parallel lineament systems near Sakonnet Point are more widely separated (0.5 -0.7 mi), although the same length (2.0 mi) and control the development of the step-wise pattern of the shoreline east of Sakonnet Point. The parallel lineament system south of
1982; Frohlich and Barosh, 1982; Frohlich and Fisher, 1985; and Sanders, 1983. Magnetic surveys were initially conducted in the proposed area of research. This technique has been used specifically for location of fracture zones (Benkel and Hamm, 1977). Hence, direct correlation of hydrogeological and remote sensing analysis with geophysical results allow refinement of the hydrogeologic model using knowledge of subsurface conditions and hydraulic characteristics of fracture zones.

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All these three lineament systems bracket the contamination site and suggest that NW - SSE trending bedrock fractures exist in the contamination site. The similarity in lineament trend throughout the Tiverton-Little Compton area is probably due to the fact that one rock type, Bulgarmarsh granite underlies almost the entire area (Quinn, 1971). The border of Narragansett Bay is bordered by Pennsylvania sedimentary rocks and lineaments of a different trend, northeast by southeast, occur in this area(F, 4.1) around Nannquasket Pond in Tiverton.

4.3 HYDROGEOLOGICAL ANALYSIS

Collection of Well Completion Reports, 1972-1985, from the Rhode Island Water Resources Board and Well Inventory Forms from the U.S.G.S. was necessary to obtain subsurface geologic and hydrologic data. Research of well owners and use of 1:400 aerial plat/lot maps at the Tiverton Town Hall Tax Assessor’s Office was required to locate and plot well locations on a topographic base to supplement limited data of the Fall River (Allen and Ryan, 1960) and Tiverton (Schiner and Gonthier, 1965) U.S.G.S Groundwater Maps. Well records provided
data to produce maps of the contoured piezometric surface of bedrock wells; and superposition of potential flow directions on piezometric surface (Fig. 4.2).

Evaluation and interpretation of the lineament map and water record data from well logs provide the information from which the hydrogeologic conditions may be appraised. Subsequently, preliminary interpretation of potential groundwater movement may be documented.

The above hydrogeologic evaluation and remote sensing analysis can be correlated with geophysical results; i.e., magnetic surveys available in this area. Use of geologic and hydrologic data from well records aid in determination of hydrologic conditions, groundwater flow potential, and subsequent potential for the spread of contaminated groundwater.

Evidence from remote sensing analysis and geophysical surveys for location of fractures constrain groundwater movement within these fracture zones further define the proposed hydrogeologic model, helping to indicate areas susceptible to present and future contamination.

Water table contours trend north and south indicating a uniform slope from the higher terrain on the west down to South Watuppa Pond on the east. However, in the contamination study area there is a complete closure of the water table contours. This indicates a higher than average water table which can occur only if the bedrock has a higher porosity and permeability. Bedrock fractured more than the immediate surrounding area is how this higher porosity/permeability developed. The north-south elongation of the water table contour closure indicates that the zone of higher fractured bedrock follows the same trend indicated by the remote sensing lineament study (see section 4.2).
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Flow lines of subsurface water indicates a flow primarily from west to east down the hydraulic gradient. However in the area of greater fractured bedrock there are local zones of both north and south groundwater flow. This is because the high fracture zone can even act as a recharge area to the surrounding less fractured bedrock. In fact, subsurface water will mound up in this recharge area and flow out in an outward direction in a pattern that will deform the normal flow patterns.
4.4 MAGNETIC STUDY

A short-spaced magnetic survey was conducted over an area that includes the site of contaminated bedrock wells in Northeastern Tiverton. A total of 150 magnetic stations were established along EW profiles at an average spacing of 100 m. Two groundmagnetometers of the proton precession type, model Geometrics G816 and G856, were used with resolutions of 1.0 and 0.1 nT, respectively. Each magnetic station was based on the average of three adjacent readings taken at the corners of an equal-sided triangle with 5 to 10 m sidelength. Many stations had to be abandoned and relocated because of large differences between the three readings, caused by buried pipes of iron. Large parts of this area are characterized by housing and uncontrolled dumping which includes magnetic iron scraps.

The groundmagnetic map, presented at 100 nT contour intervals (see Fig.4.3), shows two dominant NNW to SSE striking anomaly trends. The first, in the northeastern part of the map, suggests a shear zone with possible left-lateral shear faulting. Less distinctive NNE to NE striking anomaly trends are interrupted along this suggested shear zone and appear to be offset in a left-lateral sense. The second anomaly trend is a NNW to SSE striking magnetic low which extends across the site of contaminated bedrock wells (Florence Str.). This anomaly can be interpreted as direct evidence of a fracture zone. It appears to be limited in width and length. The trend of both dominant anomalies is parallel to the most prominent lineament orientation found with remote sensing methods.
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In addition to the 150 magnetic stations, two short-spaced profiles at 5 to 15 m spacings were conducted over potential fracture zones. One, profile A, extends over the southern tip of the magnetic anomaly low related to the fracture zone underneath Florence Street (see Fig.4.4). The second magnetic profile (B) extends over a second magnetic low at the southern margin of the survey, where a natural spring suggests another fracture zone (see Fig.4.5). The magnetic models underneath the observed profiles suggest a width of the fracture zones of 30 m (profile A) and 40 m (profile B), respectively. The concept and justification for this model is described in chapter 3 and in Appendix A.

This magnetic survey over the area of contaminated bedrock wells in Northeastern Tiverton is a typical example of urban geophysics. Man-made structures and extensive dumping presents serious problems for the interpretation of geophysical observations. It is therefore surprising to obtain useful and precise results from the magnetic survey which are applicable towards locating the bedrock aquifer. This was possible, since the observations had to pass two criteria for final acceptance. First, the three adjacent readings were not to show large differences. Second, the average of the three readings was accepted if the value would fit into a consistent anomaly pattern. It is imperative that these results should be supported and augmented with gravity and geoelectrics. The detailed profiles A and B at 5 - 15 m spacings provide an accuracy for the location of the contaminated aquifer that would be needed for engineering purposes. This would include the optimal location of a pumping well for remedial action. Whether this accuracy can be obtained in the vicinity of Florence Street remains to be seen, but so far the
results are better than expected. Additional gravity and geo-electrical surveys would add to the required precision. Besides, both methods would provide different hydrogeological information related to porosity and permeability of the fracture zone. Such information is needed for reliable groundwater flow modeling in the fracture zone.
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4.5 FIGURE CAPTIONS CHAPTER 4

Fig. 4.1 Lineament map of the Tiverton, R.I. area, site of present fuel 
oil contamination of bedrock fracture wells (circled). Primary 
lineaments were mapped using Landsat satellite imagery with detailed 
mapping of secondary and tertiary lineaments using aerial 
photography (recent and archival). The dominant lineament trend is 
NNW by SSW with trends passing through the contaminated area (C 
and E).

Fig. 4.2 Detailed water table contours of Tiverton fuel oil 
contamination site developed from well records and hydrogeologic 
developed flow directions. Closure of water table contours indicates 
greater bedrock fracturing and the north-south closure indicates a 
zone of higher fractured bedrock following the remote sensing 
lineament trend.

Fig. 4.3 Magnetic anomaly map of the Tiverton, R.I. area including the 
site of bedrock well contamination. The contaminated zone is over a 
N 30° W striking magnetic low that indicates a buried fracture zone. 
A left-lateral strike slip fault is suggested due to the offset of 
magnetic anomalies further northeast.

Fig. 4.4: Micromagnetic profile across anomaly A south of the site of 
contaminated bedrock wells. The comparison with a model anomaly 
suggests a 30 m wide fracture zone.

Fig. 4.5 Micromagnetic profile B. The magnetic low and the spring 
suggest a different fracture zone of 40 m width.
Lineaments of:
Southeastern Rhode Island and Nearby Massachusetts
Joseph G. Savarese
1986

Legend
- Road
- Contamination Bu
- State Boundary
- Lineaments:
  - Primary
  - Secondary
  - Tertiary

JS '86

FIGURE 4.1

Contoured Surface of
Hydraulic Head
(for Bedrock Wells)
and Flow Directions
Northeastern Tiverton
Joseph G. Savarese
1986

Legend
- Wells penetrating bedrock
- Wells penetrating unconsolidated sediment
- (RED) Wells constructed between 1972-1986
- (BLK) USGS GWM-7, 1960
  USGS GWM-21, 1964
- Water level data unavailable

Direction of flow

0 5 1 mi
0 5 1 km
contour interval 10 feet

JS '86

FIGURE 4.2
Fig. 4.5
5. SUMMARY - CONCLUSIONS

5.1 REMOTE SENSING

1. New Landsat Satellite 5 imagery from January 1986 showed bedrock lineament fracture zones more clearly because of the lack of vegetation and lower sun angle. Thematic mapper imagery (TM) with improved 20 m resolution from that flight enabled more precise and detailed lineament mapping than earlier multispectral imagery (MSS).

2. SLAR (Side look airborne radar) imagery proved most useful for regional and detailed mapping. It showed geologic features, including fracture lineaments, in more detail than satellite imagery because it has greater resolution and the active radar ray enhances finer terrain relief features.

3. Additional imagery used for detailed lineament fracture mapping included: a) space shuttle large format camera imagery (LFC); b) high altitude color and color infrared photography (HAP); c) low altitude large scale recent and archive (Library of Congress) aerial photography.

4. An inventory and mapping of the hydrogeologic features related to the mapped Landsat lineaments was completed. Of 136 mapped lineaments, 446 surface hydrogeologic related features were mapped on thirty state-wide 1:24,000 topographic maps. These features included: a) linear stream segments, b) aligned drainage, c) elongated lakes, d) aligned lakes, e) swamps or wetlands and f) linear valleys.

5. Groundwater aquifer systems in the buried river valleys of southern Rhode Island have now been found to be related to large-scale lineament
bedrock fracture systems as mapped on both Landsat satellite and SLAR (radar) imagery. The major fracture pattern trends northwest in western Rhode Island and northeast in eastern Rhode Island. This fracture system underlies all the major aquifer in southern Rhode Island and the lineament maps can predict their subsurface location.

6. Remote sensing mapping has indicated a north-north-west trend of bedrock lineaments passing through the fuel oil bedrock well contamination site in Tiverton, RI. This indicates increased bedrock fracturing in the immediate area. Preliminary hydrogeologic analysis of the water table in the area also indicates an elongated trending closure, the result of higher porosity and permeability. This anisotropic groundwater condition will strongly affect ground water flow direction and velocity.

Future areas of investigation based on these studies within Rhode Island should include:

a) Investigate SPOT (French) satellite imagery with its greater resolution (and greater cost) for RI water resources surface and subsurface hydrogeologic applications;

b) Use SLAR (radar) imagery for a more detailed mapping and inventory for planning purpose of hydrogeologic features related to bedrock fracture lineaments especially in the environmentally hydrologically sensitive southern and western RI areas;

c) Use SLAR (radar) imagery for lineament mapping of suggested bedrock fracture control of buried glacial deposit aquifers in central and north Rhode Island and used recent large scale aerial photographs for detailed mapping of mega-lineament system of southern Rhode Island's buried glacial aquifers.

d) Computer analysis of digitized imagery would enable detailed and rapid mapping of the above hydrogeologic research areas in Rhode Island. It would
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d) Computer analysis of digitized imagery would enable detailed and rapid mapping of the above hydrogeologic research areas in Rhode Island. It would also enable transferring all the lineament fracture data, developed to date as well as future data, to the R.I. Dept. of Envr. Management G.I.S. (Geographical Information System). This computerized data system is housed at the University of Rhode Island. The base map for the DNR/URI GIS is the 1:24,000 topographic map, which is the same base for the remote sensing lineament maps. Landsat Satellite Imagery data is available in digitized form. However, the accuracy of this imagery system, as shown in this study, is low if compared with SLAR and aerial photography. It is suggested that these latter two imagery systems should be digitized both for computer quantitative analysis and for the GIS data base.

5.2 GEOPHYSICS

1. The magnetic map at short station spacings was completed. It could be shown that fractures in crystalline bedrock can produce isolated elongate magnetic lows in the northern hemisphere. Magnetic modeling can accurately locate and estimate the width of fracture zones. This method does not seem to be affected by overburden effects.

2. Geoelectrical studies confirmed the magnetic interpretation concept. Bedrock porosities in the fractured zones were estimated to be between 5 and 10 percent. This is consistent with porosities derived from gravity data. Again, estimates of bedrock porosities from geoelectrics are not affected by overburden effects.

3. Lateral effects expected over fracture zones were observed and methods were developed to distinguish them from vertical resistivity changes.

4. Nonlinear current-voltage effects were further observed over a selected fracture zone. A strong dependence of these effects on precipitation and the water salinity in the fracture zone was established. It is believed that a fracture zone acquires properties of a membrane system under above conditions.
Further studies are needed to establish the usefulness of this newly
discovered effect for the hydrogeological characterization of buried fracture
zones.

5. The gravity method yields usefull additional and complimentary information
of the fracture porosity. This method can be used in populated areas, i.e. it
is not affected by man made constructions. This method, however, also responds
to lateral changes in density due to glacial deposits.

5.3 COMBINED METHODS FOR THE CHARACTERIZATION OF FRACTURED BEDROCK AQUIFERS.

This study has shown the usefulness of remote sensing and geophysical
methods for solving water resources management problems. It was shown that
groundwater pollution from fuel oil contamination affects the bedrock
fractures.

While crystalline bedrock is commonly thought to be impermeable to groundwater
movement, this cannot generally be accepted for the crystalline bedrock of
Rhode Island. Further evidence was gathered that fractures are particularly
abundant in valleys.

The study in Northeastern Tiverton found that crystalline bedrock of
granitic composition was sufficiently fractured to supply water for domestic
needs. Therefore the bedrock is sufficiently permeable to facilitate the
migration of fuel oil. Although these rocks are normally thought to be useful
for locating landfill and hazardous waste sites, the study showed the
limitations of this concept. The most significant difference between aquifers
in fractured bedrock and unconsolidated material, such as glacial outwash, is
a strong azimuthal anisotropy. This puts considerable constraints on
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By combining geophysical with remote sensing methods for the analysis of bedrock fractures, the usefulness of this approach can be summarized as follows.

Remote sensing methods, such as Landsat Satellite Imagery, can identify patterns related to bedrock fractures and is useful for an intensity assessment. The methods allow for a coverage of large areas at minimal costs, once the maps are available.

More local detailed bedrock fracture mapping is possible with SLAR, because of greater resolution and fidelity. Detailed photo analysis of present and past aerial photos allows for more local detail.

All geophysical methods require more effort for the field work and interpretation. There seems to be a direct relationship between the properties of the fracture zone and the geophysical anomalies. The model concepts for interpreting geophysical anomalies relate directly to the material difference between fractured and compact bedrock. These differences cause a change in magnetic susceptibility, density and electrical resistivity.
6. REFERENCES


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APPENDIX: COMPUTER PROGRAMS

The programs used for this study are written in BASIC for the HP-85 personal computer.

4. The Magnetic Anomaly Over A Nonmagnetic Fracture Zone.

The magnetic anomaly-lows observed over fracture zones are explained by the magnetic edge-effect over two juxtaposed horizontal slabs of infinite extend. They are separated along their edges by a nonmagnetic gap which represents the fracture zone. The anomalies are caused by induced magnetization only.

The magnetic anomaly over a magnetized horizontal sheet is:

\[ T(x) = S \cdot \mathbf{u} \cdot \mathbf{T} \cdot \mathbf{C} \cdot \sin(A1) \approx \]

\[ \left\{ C_1 \cdot \ln \left( \frac{x - \frac{D_2 - D_1}{2}}{x^2 + D_2^2} \right) + C_2 \cdot \left[ \frac{h_2^{1/2} \left( x - \frac{D_2 - D_1}{2} \right)}{D_2} - h_2^{1/2} \left( \frac{x}{D_2} \right) \right] \right\} \]

With the following constants:

\[ C = 1 - [\cos(\theta) - \cos(\alpha)]^2 \]

\[ B = \frac{h_2^{1/2} \left[ \theta_2(\theta) / \sin(\alpha) \right]}{h_2^{1/2}} \]

\[ C_1 = \cos(A1 - 2B) \]

\[ C_2 = 2 \times \sin(A1 - 2B) \]

The model parameters are:

\[ S \] is magnetic susceptibility
\[ T \] intensity of the total magnetic field
\[ \alpha \] inclination of the magnetic field

- A1 -

\[ L \] strike direction of the edge with respect to magnetic north
\[ 1 \] field points along a profile across the edge of the slab
\[ D_2 \] depth to the top
\[ D_2 \] depth to the bottom
\[ A1 \] dip angle of the termination of the slab.

The following program "MAGI" calculates and plots the anomaly of a single buried magnetic slab. Fig. A-I shows the plot of two slabs.

- A2 -
APPENDIX: COMPUTER PROGRAMS

The programs used for this study are written in MHEC for the HP-65 personal computer.

A. Magnetic Anomaly over a Hemispherical Fracture Zone.

The magnetic anomalies observed over fracture zones are calculated by the magnetic edge-effect over two juxtaposed horizontal slabs of infinite extent. They are separated along their edges by a hemispherical gap which represents the fracture zone. The anomalies are caused by induced magnetization only.

The magnetic anomaly over a magnetized horizontal sheet is:

\[ T(x) = 4 \pi M \cdot T \cdot C \cdot \sin(A_2) \cdot \left( C_1 \cdot \sin \left( \frac{2 \pi R_1}{D_1} \right) + C_2 \cdot \sin \left( \frac{2 \pi R_2}{D_2} \right) \right) \]

with the following constants:

\[ C = 1 - \left[ \cos \left( \frac{2 \pi R_1}{D_1} \right) \cos \left( \frac{2 \pi R_2}{D_2} \right) \right]^2 \]

\[ D = \frac{2 \pi R_1}{D_1} \sin \left( \frac{2 \pi R_1}{D_1} \right) \]

\[ C_1 = \cos \left( \frac{2 \pi R_1}{D_1} \right) \]

\[ C_2 = 2 \cdot \sin \left( \frac{2 \pi R_1}{D_1} \right) \]

The model parameters are:

- Hemispherical gap
- Intensity of the total magnetic field
- Inclination of the magnetic field

---

1. Strike direction of the edge with respect to magnetic north
2. Field points along a profile across the edge of the slab
3. Depth to the top
4. Depth to the bottom
5. Dip angle of the termination of the slab.

The following program "MAGI" calculates and plots the anomaly of a single buried magnetic slab. Fig. A-1 shows the plot of two slabs.

---

The magnetic anomaly over a buried magnetic sheet

Program "MAGI"

1. Begin
2. Define parameters
3. Calculate magnetic field components
4. Plot the anomaly
5. End

---

The effect of the magnetic anomaly over a hemispherical gap on a magnetic edge in conjunction with the parameters defining the slab and magnetic field that cause the anomaly. The output format includes an analytic expression for the anomaly, as well as the magnetic anomaly field. The output parameters for the anomaly include:

1. Field components along a profile across the edge of the slab
2. Depth to the top
3. Depth to the bottom
4. Dip angle of the termination of the slab.

The following program "MAGI" calculates and plots the anomaly of a single buried magnetic slab. Fig. A-1 shows the plot of two slabs.

---

The geoelectrical field curves were interpreted first via layer master curves to obtain a starter model. This consists of the number of layers, thicknesses, and resistivities. Further refinement was accomplished with an interactive computer program that plots field points and the model curve, as shown in Fig. 3, to find the best fit. First the half electrode spacing L/2 and apparent resistivity of the field curve is printed. The model appears in three columns: column 1 indicates the number of the layer (Schicht), column 2 the layer thickness (machtung), and column 3 the layer resistivity (Widerst.). The plot shows a double logarithmic scale for the field points and the model curve. The curve at the bottom difference between field point and model curve. The standard deviation is calculated for all given field points and printed under "STD-dev." If, on the ground of visual comparison of the log log plot, the model curve is found to be inadequate, a new model can be entered and the process repeated.

The best-fitting model is then plotted and the essential data printed under "modelcurve."
Model Parameters
SU : 6.0000 em
I : 36,000 m³
S : 2500
L : 45°

Model Parameters
SU : 6.0000 em
I : 36,000 m³
S : 2500
L : 45°

a. Model Curves for Geomaterials: Design Environments.

The geoelectrical field curves were interpreted first with the help of curves obtained from the model curves. The curves consist of a number of layers, thicknesses and resistivities. Further they were accompanied with an interactive computer program that includes the model and the observed curves, as shown in Figs. 1 to 3 to investigate the field curves together with their apparent resistivity of the field curve in general. The model appears in three different scales: the model curve, the apparent resistivity curve, and the apparent resistivity curve. The scale on the left shows the apparent resistivity of the field curve. The scale on the right shows the apparent resistivity of the field curve. The scale on the bottom shows the apparent resistivity of the field curve. The scale on the middle shows the apparent resistivity of the field curve.