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LINEAMENTS ON SKYLAB PHOTOGRAPHS

DETECTION, MAPPING, AND HYDROLOGIC

SIGNIFICANCE IN CENTRAL TENNESSEE

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Prepared in cooperation with National Aeronautics and Space Administration

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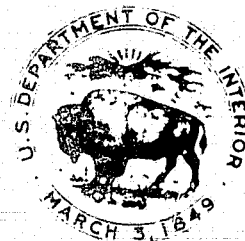
1976

UNITED STATES

DEPARTMENT OF THE INTERIOR

Geological Survey

Open-File Report 76-196



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LINEAMENTS ON SKYLAB PHOTOGRAPHS--
DETECTION, MAPPING AND HYDROLOGIC
SIGNIFICANCE IN CENTRAL TENNESSEE

By Gerald K. Moore

Open-File Report 76-196

Original photography may be purchased from:
EROS Data Center
10th and Dakota Avenue
Sioux Falls, SD 57198

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order H-2810B.

Sioux Falls, South Dakota

March 1976

**ORIGINAL CONTAINS
COLOR ILLUSTRATIONS**

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CONVERSION FACTORS

<u>To convert:</u>	<u>Multiply by:</u>	<u>To obtain:</u>
Micrometres	39.37	Inches per million ($\text{in}/10^6$)
Millimetres (mm)	.03937	Inch
Centimetre (cm)	.3937	Inch (in)
Metres (m)	3.281	Feet (ft)
Kilometres (km)	.6214	Miles (mi)
Metres per Kilometres (m/km)	5.280	Feet per mile (ft/mi)
Square Kilometres (km^2)	.3861	Square miles (mi^2)
Hectares	2.471	Acres
Kilograms per Metre (kg/m)	.6721	Pounds per foot (lbs/ft)
Litres per second (l/s)	15.85	Gallons per minute (gal/min)
Litres per second per square Metre [$(\text{l/s})/\text{m}^2$]	88.40	Gallons per minute per square foot [$(\text{gal/min})/\text{ft}^2$]

WAVELENGTHS OF VISIBLE AND NEAR VISIBLE LIGHT

	<u>Micrometres</u>
Ultraviolet	0.01 - 0.4
Violet	0.4 - 0.45
Blue	0.45 - 0.5
Green	0.5 - 0.57
Yellow	0.57 - 0.59
Orange	0.59 - 0.61
Red	0.61 - 0.7
Near Infrared	0.7 - 3.0

PHOTOGRAPHS AND IMAGERY

All NASA photography and imagery may be ordered from EROS Data Center, Sioux Falls, South Dakota, 57198.

LINEAMENTS ON SKYLAB PHOTOGRAPHS---DETECTION, MAPPING
AND HYDROLOGIC SIGNIFICANCE IN CENTRAL TENNESSEE

By Gerald K. Moore

ABSTRACT

The test site is underlain by dense, fractured, flat-lying limestones. Soil cover averages 1.2 metres (4 feet) thick in the Central Basin and about 12 metres (40 feet) thick on the Eastern Highland Rim. Ground water occurs mostly in horizontal, sheetlike solution cavities, and the trends of these cavities are controlled by joints. Most lineaments, which can be detected on SKYLAB photographs also are caused by joints.

Lineaments are composed of short, discontinuous segments. Whether or not the human eye fuses these segments into a lineament depends mostly on the resolution, scale, and contrast of the photographs. Sixty-nine percent more lineaments were found on SKYLAB photographs by stereo viewing than by projection viewing, but longer lineaments were detected by projection viewing. Most SKYLAB lineaments consist of topographic depressions and they follow or parallel the streams. The remainder are found by vegetation alignments and the straight sides of ridges.

Lineament locations and trends apparently are not related to contours or anomalies on gravity, magnetic, or geologic-structure maps. Some lineaments could be used to explain losing or gaining reaches of streams, but other lineaments do have a detectable relation to streamflows.

For water well yields of 1.6 litres per second (25 gallons per minute), or more, significant savings could be achieved by locating future wells on SKYLAB lineaments, rather than by random drilling. The best single detection method, in terms of potential savings is stereo viewing. Larger savings might be achieved by locating wells on lineaments detected by both stereo viewing and projection. Comparison also indicated that larger well yields could be obtained by locating future wells on SKYLAB lineaments rather than on

lineaments detected on either high-altitude aerial photographs or Landsat imagery.

Test drilling showed that the median yield of wells located on SKYLAB lineaments is about six times the median yield of wells located by random drilling.

INTRODUCTION

This is the final report of an investigation that was funded by NASA (National Aeronautics and Space Administration) through purchase order H-2810B. The study was originally titled "Hydrologic significance of faults in the Great Smoky Mountains National Park." The test site (fig. 1) was moved to central Tennessee when SKYLAB photographs of the Blue Ridge Mountains proved to be too cloudy and hazy for a definitive study.

The objective of the investigation was to determine the feasibility of mapping lineaments on SKYLAB photographs^{1/} of central Tennessee and to determine the hydrologic significance of these lineaments, particularly as concerns the occurrence and productivity of ground water.

The author gratefully acknowledges the cooperation and assistance of NASA personnel at Marshall Space Flight Center and Johnson Manned Spacecraft Center throughout the investigation; John Bensko (NASA technical monitor) and Martin Miller deserve special mention. Appreciation also is expressed to Tennessee Department of Conservation, Division of Water Resources for data on water well yields and locations. Dr. C. W. Wilson, Jr., Tennessee Department of Conservation, Division of Geology kindly furnished the investigator with structure-contour maps based on surficial geology.

The Problem

Central Tennessee has an irregular occurrence of available water resources. Many of the streams are flashy with high flows

^{1/} For the sake of convenience the term "SKYLAB lineaments" is used in this report.

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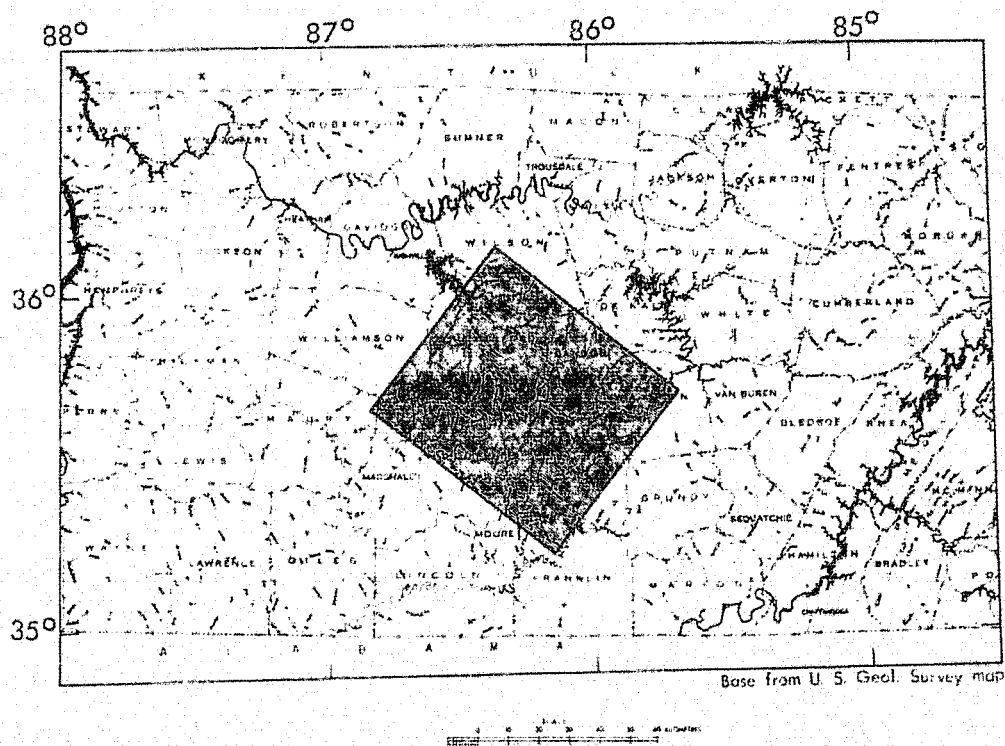


Figure 1.--The test site is in central Tennessee and covers about 5,550 square kilometres (2,140 square miles).

during floods and with poorly sustained flows during droughts. Recent economic growth has been almost entirely along the largest rivers and around existing reservoirs and public water supplies where ample water is available. Pipelines from these sources and installations will be able to supply part of the expanding water needs of small towns, rural utility districts, and rural industries. New reservoirs on the smaller streams also may supply part of these future demands for water, as well as water for supplemental irrigation and other agricultural uses. However, both long pipelines and storage reservoirs require large capital investments. In many cases, an alternative and cheaper source of additional water is from wells.

Some wells in central Tennessee tap aquifers in the thick subsoil of the Highland Rim or in alluvium along the largest streams. Most wells, however, produce water from solution cavities in the underlying limestone bedrock. Solution cavities have a large size range; thus wells have a large range in water yield. Wells in limestone are likely to yield less than 0.63 ℓ/s (litres per second) or 10 gal/min (gallons per minute), but some wells yield more than 3.2 ℓ/s (50 gal/min), and a few wells yield more than 63 ℓ/s (1,000 gal/min). Locating the largest solution cavities by random drilling is costly and time consuming. Reliable methods of detecting and tracing these large cavities (before drilling begins) are needed for the most economical development of the ground-water resources.

Seismic, electrical conductivity, and gravity surveying (for example, see Moore and others, 1969, p. 48-54; Lavin and Alexander, 1972, p. 33-36) have been used to locate solution cavities on an experimental basis, but all such geophysical methods are time consuming. Several man-days of work on the ground are needed for detailed gravity or seismic surveys over a 20 hectare (50 acre) field, for example.

Nearly all natural features form amorphous, irregular, or curved lines and patterns on aerial photographs. Exceptions are

straight-line features that are related to joints and faults in the bedrock. Lattman (1958, p. 569) proposed the term lineament for "a natural linear feature consisting of topographic (including straight stream segments), vegetation, or soil tonal alignments, visible primarily on aerial photographs or mosaics, and expressed continuously for at least one mile [1.61 kilometres], but which may be expressed continuously or discontinuously for many miles." Similarly, he defined fracture trace as a linear feature less than 1.61 km (kilometres) in length. "Only natural linear features not obviously related to outcrop pattern of tilted beds, lineation and foliation, and stratigraphic contacts are classified as fracture traces and lineaments" (Lattman, 1958, p. 569).

Joints and faults commonly control the locations and trends of solution cavities. Thus, linear features on aerial photographs may indicate joints and faults that mark the locations of solution cavities in the bedrock. Aerial photographs covering fairly large areas can be examined for fracture traces and lineaments in a few hours or days. This method of ground-water prospecting is both fast and cheap; it may prove to be the most cost effective method in many limestone terranes.

Previous attempts to correlate fracture traces and lineaments with ground-water occurrence have not been successful in central Tennessee. Bedrock is at or just beneath land surface over much of the Central Basin, and many joints that do not reflect solution at depth are visible as fracture traces on 1:20,000 scale aerial photographs (Moore and others, 1969, p. 47).

The number of lineaments that can be seen on aerial photographs depends mostly on the resolution and scale of the photographs. Fewer lineaments should be visible on high-altitude and space photography; those that are visible, however, should be the largest and the most significant for ground-water exploration. This hypothesis was tested with SKYLAB photography during the present study.

Previous Investigations

Although jointing in limestones was noted from the air and described in the literature as early as 1928 (Rich, p. 861-862), the significance of fracture traces and lineaments on aerial photographs to geologic structures generally was not investigated in detail until the 1950's. The incentive at that time was the location of petroleum traps (for example, Desjardins, 1952; Blanchet, 1957), particularly those associated with salt domes in the Gulf Coastal Plain.

The close relationship between rock fractures and ground-water occurrence and movement in limestone terranes generally has been recognized and accepted since at least the early 1900's (for example, Fuller, 1908; Meinzer, 1923; Piper, 1932). Specific studies relating fracture traces and lineaments to joints and faults did not begin in the field of ground-water hydrology until 1958 (for example, Lattman and Nicholson, 1958; Hough, 1960; Boyer and McQueen, 1964). Studies suggesting the application of fracture traces and lineaments to ground-water prospecting soon followed.

Lueder and Simons (1962, p. 50-51) presented some evidence that most wells with relatively high yields in Limestone County, Ala., are found close to fracture traces and lineaments, whereas wells with medium and low yields are more randomly distributed.

The first study to indicate the large potential advantages to be obtained by drilling wells on fracture traces was by Lattman and Parizek (1964) in central Pennsylvania. This study was based on a sample of 13 wells and suggested (Lattman and Parizek, 1964, table 2) that wells located on fracture traces may have from 4 to 1,000 times the yield (for each foot of drawdown of water level) of wells located between fracture traces.

Trainer and Ellison (1967, p. 198), from results obtained in the Shenandoah Valley of northern Virginia, suggested that the relative abundance of fracture traces may be related to the porosity and permeability of the rocks. In addition, Trainer (1967,

p. C186-C188) suggested that contours of fracture trace frequency are an indication of total fracture porosity. If this idea could be proven, it would have considerable implication for modeling of flow systems in fractured limestone aquifers, as well as for the selection of well locations to obtain maximum yields.

Moore and others (1969, p. 46-48) attempted to test the 1964 results of Lattman and Parizek in the upper Stones River basin (part of the present study area). They concluded that (1) fracture traces on 1:20,000 scale aerial photography did not correlate with high well yields, and (2) the correlation of high-yield wells with lineaments and linear belts was unproven. However, somewhat better results were obtained near Tusculumbia, Ala. (Moore and others, 1969, p. 47). The solution-cavity system that feeds the Big Spring can be traced on aerial photographs by a combination of topographic and vegetative lineaments. Also, pronounced lineaments or linear belts were detected near some of the wells that produce more than 19 ℓ/s (300 gal/min).

Analyzing an Apollo 9 photograph of central Alabama, Powell and others (1970, p. 18-24) found that fracture traces could not be seen on space photography, but a number of major lineaments (that were not obvious on low-altitude photographs) could be detected easily. They also showed that several large capacity wells and springs were located on or near the major lineaments.

Siddiqui and Parizek (1971), following up on the previous work in central Pennsylvania, published the first definitive study relating well yields to hydrogeologic factors; their results, from a sample of 80 wells (Siddiqui and Parizek, 1971, p. 1302), are summarized in table 1. They found that wells on fracture traces have a median productivity 55 times greater than wells between fracture traces and 9.4 times greater than randomly located wells. The minimum productivities of wells in all structural classes are similar, however. This means that a few wells, even in the most favorable locations, have poor yields.

Table 1.--Well yields correlate with hydrogeologic factors in central Pennsylvania (from Siddiqui and Parizek, 1971, p. 1302)

$$\text{WELL PRODUCTIVITY}^{\text{a/}} = \frac{\text{SPECIFIC CAPACITY (GAL/MIN)/FT}}{\text{AVAILABLE DRAWDOWN (FT)}} \times 1,000$$

	MINIMUM	MAXIMUM	MEDIAN	GEOMETRIC MEAN ^{b/}
Wells on fracture traces	0.31	4,360	79.6	72.2
Wells between fracture traces	.11	52.6	1.45	1.74
Rock type:				
Shale	.56	85.6	3.10	3.98
Limestone	.31	324	7.89	11.1
Upper sandy dolomite	.70	2,200	122	123
Structure:				
Anticline	.11	4,360	52.6	45.2
Syncline	.14	930	7.00	7.41
Dip of rock:				
0° - 15°	.31	4,360	128	126
15° - 30°	.14	193	12.4	8.72
30° - 60°	.11	491	2.00	3.78
60° - 90°	.70	324	5.87	10.0

^{a/} Equivalent metric units of $10^3 \text{ l/s(m}^2\text{)}$ may be obtained by multiplying the numbers in the table by 0.01131.

^{b/} Geometric means computed from grouped data.

Purpose and Scope

This report describes the results of a study to evaluate the geologic and hydrologic significance of lineaments that are visible on SKYLAB photographs. The main study element was a comparison of the yields of wells on or near these lineaments with the yields of wells located between lineaments; the goal was to develop a cheap, practical tool that can be used to obtain larger-than-average well yields, both in central Tennessee and in other, similar terranes. The lineaments were detected by two different methods and the hydrologic significance of each method was compared.

In order to choose the best resolution and scale for detecting hydrologically significant lineaments, the number and significance of lineaments on SKYLAB photographs were compared with lineaments visible on high-altitude aircraft photographs and on Landsat imagery. Several experiments also were made with composite viewing of photographs and imagery from different seasons of the year and with comparisons of the number of lineaments visible on black-and-white versus color photographs. Other study elements included (1) test drilling, (2) experiments with several methods to try to detect or enhance lineaments by machine, and (3) comparisons of lineament location with anomalies on geophysical maps, surface geologic structure, and low streamflows.

PHYSICAL SETTING

The test site is in central Tennessee, southeast of Nashville, and covers $5,550 \text{ km}^2$ or $2,140 \text{ mi}^2$. It includes parts of the Central Basin and Eastern Highland Rim sections of the Interior Low Plateaus physiographic province (fig. 2). The Central Basin ranges from about 140 to 240 m or 450 to 800 ft above sea level; the Highland Rim is 290 to 370 m (950 to 1,200 ft) in altitude.

Physiography

Land surface in the Central Basin generally is flat to rolling west of lines connecting Shelbyville, Murfreesboro, and Smyrna; elsewhere, the land is deeply dissected. Sinkholes are abundant near

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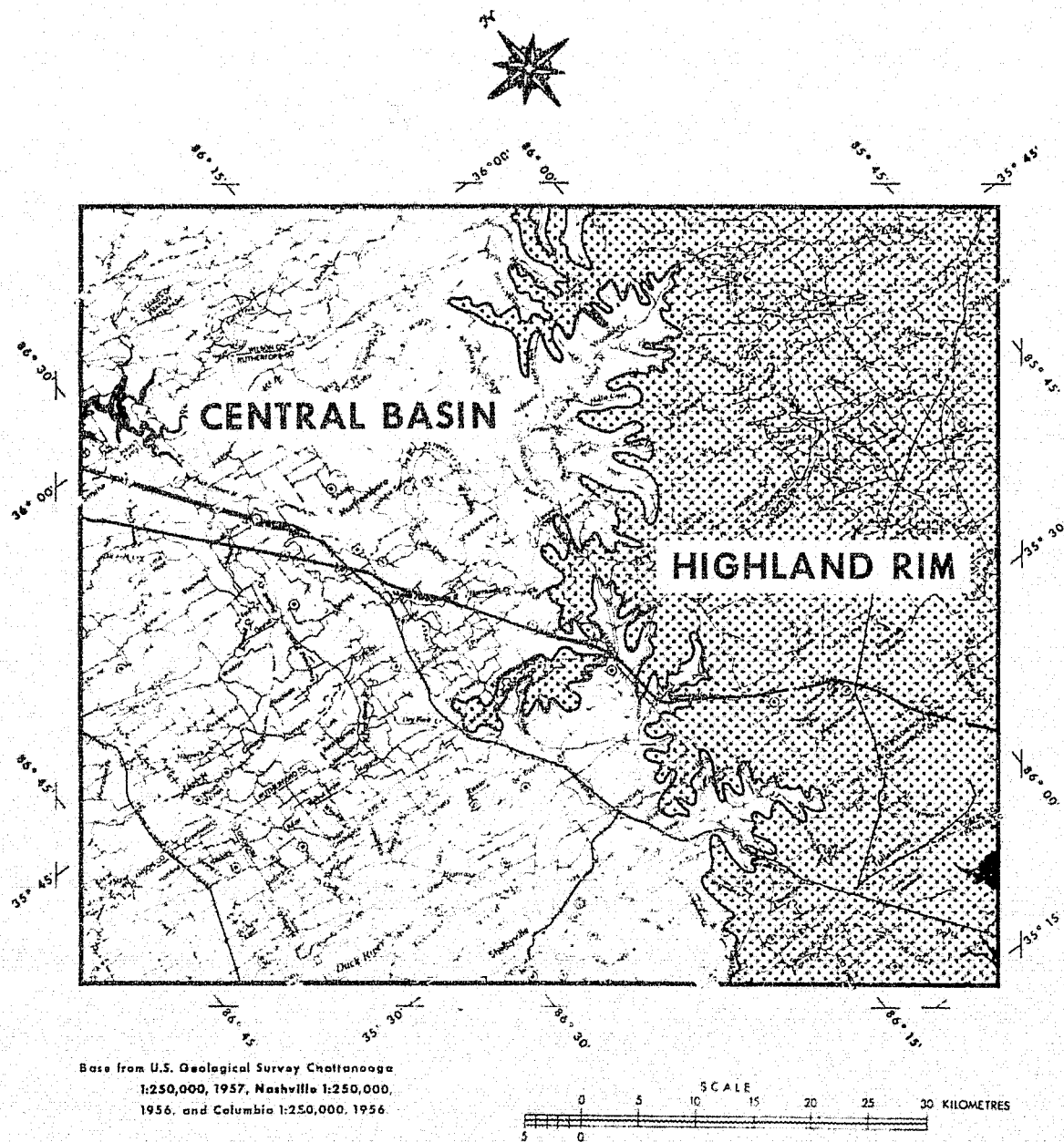


Figure 2.--Physiographic subdivisions of the study area.

the bases of some ridges (particularly near Murfreesboro) and rare to common elsewhere. Soil cover above bedrock averages 1.2 m (4 ft) thick, but soil-filled crevices as much as 2 m (6.6 ft) wide and 11 m (35 ft) deep are common. On the other hand, areas of bare rock or limestone rubble also are common. Areas of flat to slightly rolling land and relatively thick soil are cultivated for row crops. Also, hardwood trees grow only in areas of relatively thick soil and in soil-filled crevices and joints between blocks of limestone. Areas of thin soil are used for pasture or are covered by nearly pure stands of red cedar. Stream channels are broad and shallow; the channel depth in most cases, is determined by the soil thickness.

Topography on the Highland Rim, generally east of a line from Woodbury to Tullahoma, is slightly rolling to rolling. Stream valleys range from gentle swales to deep and V-shaped. Sinkholes and caves are rare to common. Most culture is on the uplands; valleys and depressions are wooded; many local depressions are swampy. Soil cover averages about 12 m (40 ft) thick and consists generally of silty clay and clayey chert. The percentage of chert increases with depth. In a few small areas the soil is more than 30 m (100 ft) thick, but some fairly large areas have a soil cover less than 3 m (10 ft) thick. Bedrock is exposed locally in sinkholes and stream channels and on steep slopes.

Geology

The rocks generally consist of limestones and impure limey formations. This report is concerned only with the shallow formations, because almost all ground water used in the area comes from depths of less than 90 m (300 ft).

In the Central Basin, formations are thin bedded to massive limestones of Ordovician age. Impurities are scattered through the rock in some formations; in other formations, impurities are concentrated as thin layers of clay or shale between thicker layers of limestone.

Bedrock formations beneath the Highland Rim are mostly cherty limestones or limey cherts of Mississippian age. Virtually all formations are thick bedded to massive. In the northeastern corner of the study area, these formations are overlain by shale, limestone, and sandstone.

Alluvial gravel, sand, and silt up to 10 m (33 ft) thick occur in the valleys of the largest streams. This report, however, is concerned only with bedrock formations and aquifers.

Formations are almost horizontal in the study area. On an average, they dip (generally to the east and southeast) at about 3.8 m per km (20 ft per mi). Locally there also are small folds in the rocks with dips up to several degrees; these folds can be traced for distances of a few tens of metres to several kilometres (50 ft to 2 mi). Generally it is agreed that many local folds result from solution of some rock layers by ground water and settling of the overlying rock layers (The history of this theory and the operation of the process are discussed in Moore and others, 1969, p. 13 and 21.) Anticlines occur where this process has been least active, and synclines occur where the largest amount of settling has occurred.

A number of faults are known in the study area (Jewell, 1947, p. 16), but the throw typically is very small. As a result, faults are difficult to recognize in the field. Also, faults generally are not mappable at 1:24,000 scale, and thus are not shown on published geologic maps. Virtually all faults follow the regional joint system and thus trend northeast or northwest (Jewell, 1947, p. 16).

All of the rock formations are dense (They do not yield water by gravity drainage.) In the limestone bedrock, ground water occurs only in fractures and solution cavities.

Hydrology

Precipitation in the study area averages from 1,200 mm (millimetres) per year (47 in per year) in the Central Basin to 1,500 mm (60 in)

per year in the northeast corner. An estimated average water budget (based on previous studies in central Tennessee by Burchett and Moore, 1971; Moore and Wilson, 1972; C. R. Burchett, U.S. Geol. Survey, written commun., 1975) is shown in table 2.

Table 2.--An estimated water budget shows that about 200 mm (8 in) of water recharges and discharges from the ground-water reservoir in an average year

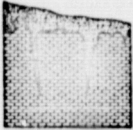
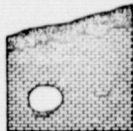
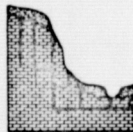
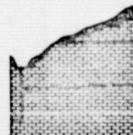
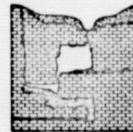


	Amount of Water		
	mm	1,000 km ³	in
Inflow:			
Precipitation-----	1,300	7.2	51
Outflow:			
Evapotranspiration-----	790	4.3	31
Streamflow-----	510	2.8	20
Overland flow-----	310	1.7	12
Ground-water discharge-----	200	1.1	8

The exact size of the ground-water reservoir cannot be determined. However, calculations in several previous studies (Moore and others, 1969, p. 34; Moore and Wilson, 1972, p. 34; Stearns, 1974, p. 39) indicate that from 0.5 to 5 mm (0.02 to 0.2 in) of water is stored in solution cavities below the level of the streams. Another 24 to 25 mm (0.95 to 1.0 in) of water may be stored in solution cavities above the level of the streams at the time of the water-table peak in March or April. An additional 25 to 30 mm (1.0 to 1.2 in) of water may accumulate in areas having a thick soil cover. At the time of the water-table low (usually between September and December), total amount of ground water in storage may decrease to about 5 mm (0.2 in).

Ground water above the streams is available both to wells and to sustain the low flows of streams. Ground water below streams is available only to wells.

Several different types of solution cavities (table 3) occur

Table 3.--Five types of solution cavities occur in the area
(after Moore and Wilson, 1972, table 3)

Type of opening	Nature of opening		Water occurrence and movement
Crevise or cutter	Vertical. One centimetre to 2 metres wide at top of rock, pinching out with depth; 2 to 300 metres long; 2 to 15 metres deep. Commonly connected in three dimensions. Almost always filled with silt and clay		Water percolates downward to water table, then horizontally along crevice. Water generally moves into another type of opening before discharging into streams. Water occurrence may not be perennial.
Tubelike	Horizontal. One centimetre to 10 metres in diameter; several metres to 1 kilometre long. Generally partly filled with rubble, silt, and clay.		Discharges water to springs above level of streams. Usually contains water only during wet periods. Movement of water turbulent; water commonly muddy.
Sheetlike	Vertical. Less than 1 millimetre to 1 centimetre wide at top of rock, pinching out with depth; 2 to 300 metres long; 2 to 100 metres deep. Commonly connected in three dimensions. May be partly filled with silt and clay.		Feeds recharge water to other types of openings, and discharges most ground water into streams. Prominent near steep hillsides, where ground water moves down to below valley level. Water occurrence perennial only below stream level.
	Horizontal. Two to 800 metres wide, interrupted by rock pillars; 100 metres to 3 kilometres long; less than 0.2 to 1 centimetre high. Contains small amount of silt and clay. At least one opening of this type occurs beneath 90 percent of land surface.		Receives recharge from crevices or vertical sheet openings. Water movement generally laminar. In some cases, water discharges to springs near valley floor or to complex openings below stream channels. Water always perennial below level of streams and commonly perennial above level of streams.
Complex	A combination of two or more types of openings. Common in some areas on hillsides and in valleys beneath or near stream channels. Generally connected with other openings. Always partly filled with rubble, gravel, sand, silt, and clay.		Receives water from streams in losing reaches and discharges water to streams in gaining reaches. Generally dry on hillsides but perennially full of water below stream level. Water movement turbulent.
		<p>EXPLANATION</p> <p> Limestone</p> <p> Mixed gravel, sand, silt, and clay</p>	

in the study area. All solution cavities have some importance in transmitting ground water toward streams, and thus are important in determining the low flows of streams. Only horizontal, sheetlike openings and complex openings are important as sources of water to wells: complex openings because they yield the largest amounts of water and horizontal, sheetlike openings because of their extent

and abundance. Crevices, tubelike openings and vertical, sheetlike openings are too narrow to be intercepted by most wells, do not have enough storage capacity to supply wells with water during long droughts, and usually are dry during a part of each year.

Horizontal, sheetlike cavities occur between layers of rock and generally have the same relation to a horizontal plane as do the rock layers. The trends of these openings, however, are controlled by vertical joints in the limestone. Horizontal, sheetlike cavities occur beneath nearly all of the study area because only 7.4 percent of the wells are reported by drillers to be dry.

Complex openings are large and consist of two or more types of solution cavities (table 3). Complex openings below the level of the streams are full of water year around and are capable of yielding large quantities of water to wells. Many streams in the study area have losing and gaining reaches. In losing reaches, water from streams and from other solution cavities feeds into complex openings. These openings commonly trend downstream, and the water eventually discharges back to the stream in gaining reaches. In some areas, however, these openings carry water into other basins and other streams.

SKYLAB PHOTOGRAPHY

The primary SKYLAB photographs, which were examined for lineaments, were from the S-190B, earth terrain camera, and were taken on June 9, 1973. The format of these photographs was 5 in (nominal size), high resolution color film (SO-242) with stereo overlap. Focal length of the camera lens was 457 mm (18 in). From a nominal altitude of 435 km (270 mi), each frame covers a 109 km (67.7 mi) square on the ground. At an image size of 114 x 114 mm (4.5 x 4.5 in), the scale is about 1:950,000. The film represents a wavelength band pass of about 0.4 to 0.7 micrometres, and estimated ground resolution (Martin Marietta Corp., 1975, p. 11) at low contrast is 21 m (70 ft). Identifications of photographs that cover

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parts of the study area are: mission: SL -2, roll: 81, frames: 199,200,201, and 202 (appendix).

Selected frames also were examined from the S-190A multi-spectral cameras, as part of an experiment to enhance lineaments. These six cameras produced four B & W (black-and-white) and two color photographs of each scene as follows: 0.5 to 0.6 micrometres wavelength, green band; 0.6-0.7 micrometres, red band; 0.7-0.8 micrometres, near infrared band; 0.8-0.9 micrometres near infrared band; 0.4-0.7 micrometres, color; and 0.5-0.88 micrometres, color infrared. Each frame from the multispectral cameras covers a 163 km (101 mi) square on the ground, and estimated resolution (Martin Marietta Corp., 1975, p. 7) at low contrast ranges from 30 to 79 m (100 to 260 ft). Original format is 70 mm film with an image size of 57.2 x 57.2 mm (2.25 x 2.25 in) and a scale of about 1:2,850,000. Frames from SKYLABS 2 and 4 that cover parts of the study area are shown on table 4.

Detecting and Mapping Lineaments

The S-190B photographs were the main ones selected for analysis because (1) these photographs have somewhat better resolution (because of the long focal-length lens) than those from the S-190A multispectral cameras, (2) haze penetration seemed to be equally as good as that on the color infrared and B & W infrared films from the multispectral cameras, and (3) it was believed that lineaments could be detected easier and faster on a color film than on B & W film. Color film represents a composite of information in three separate bands (blue, green, and red); all four B & W films from the multispectral cameras might have to be examined to obtain more information than that available on one of the color films. However, this was a judgement decision and it was not tested during the study.

For comparison purposes and to test a possible enhancement technique, lineaments also were delineated on selected frames from the multispectral cameras. The method (described later in this report) involved composite viewing of B & W photographs from

Table 4.--Both SKYLAB mission SL-2 and SL-4 produced photographs from the multispectral cameras that cover parts of the test site

Mission: SL-2

Date: June 9, 1973

Roll	Wavelength (micrometres)	Frames
12	0.5-0.6	144, 145, 146, 147
11	0.6-0.7	144, 145, 146, 147
7	0.7-0.8	144, 145, 146, 147
8	0.8-0.9	144, 145, 146, 147
10	0.4-0.7	152, 153, 154, 155
9	0.5-0.88	152, 153, 154, 155

Mission: SL-4

Date: November 30, 1973

Roll	Wavelength (micrometres)	Frames
53, 54	0.4-0.7*	63, 64, 65
49, 50	0.35-0.9*	63, 64, 65
52	0.4-0.7*	63, 64, 65
51	0.4-0.88*	63, 64, 65

*Without filter; approximate band limits.

missions SL-2 and SL-4. However, because the filters were missing during the SL-4 mission, this involved composite viewing of (1) red band (0.6-0.7 micrometres), B & W photographs from the SL-2 mission and (2) broad band (about 0.4-0.7 micrometres), B & W, panchromatic photographs from the SL-4 mission. A similar method was tried using (1) near infrared band (0.7-0.8 micrometres), B & W photographs from the SL-2 mission and (2) very broad band (about 0.35-0.9 micrometres), B & W photographs from the SL-4 mission. The latter method was unsuccessful because the very broad band, SL-4 photographs were too dense (lacking in contrast) to be usable for the intended purpose.

Stereo viewing and projection viewing.---Study of linear features was divided into five steps. They are: (1) enlargement of original film, (2) stereo examination of photographs, (3) examination of photographs by projection, (4) reexamination of lineaments on high-altitude aerial photographs, and (5) transfer of lineaments to convenient base maps.

The first step was to enlarge the original film to a 9 in (nominal size) format and thus to a scale of about 1:480,000. Both color transparencies and color prints were made at this scale.

Second, adjacent color transparencies were examined on a light table with a mirror stereoscope. This is called the stereo-viewing method in this report, and lineaments found by this method are called stereo lineaments. Both 1.5X and 4.5X magnifications were used, and lineaments were drawn on transparent overlays (fig. 3, for example). The photographs have about 60 percent overlap, so a final step was to examine alternate photographs with the stereoscope. This step produces a three-dimensional model with more vertical exaggeration, and a few additional lineaments were detected.

In the third step, other lineaments were found by a projection method, and these are called projection lineaments in this report. Thirty-five-mm slides were made both of entire SKYLAB frames and of enlarged parts of these frames. Projected slides were viewed

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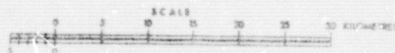


Figure 3.--Black and white reproduction of a NASA SKYLAB photograph (SL-2, roll 81, frame 200) showing the lineaments that were detected by stereo viewing in this part of the study area.

at various distances from the screen (increasing or reducing the resolution of the scene). Also, the slides were viewed both in focus and out of focus. Finally, a Ronchi ruling (5.9 lines per mm or 150 lines per in) was held against the projector lens and rotated slowly in order to enhance lineaments that were not obvious previously. Lineaments that were noted on the projected slides were transferred onto prints of the same frame (fig. 4, for example).

Sixty-nine percent more lineaments were found by stereo viewing than by projection, but the lineaments detected by projection are longer on an average (table 5). As a result, the total length of lineaments found by the two methods is nearly the same. Several observations, which were made while detecting lineaments, may be helpful in future studies:

1. If there are few obvious lineaments in an area, the observer tends to look harder and to mark more obscure features. There is a strong tendency to produce a fairly uniform spatial frequency of lineaments.

2. There are only a few obvious lineaments in uniform forests and uniform agricultural areas. Most lineaments are in mixed forest and farm and in mixed forest and urban areas. Perhaps land use in mixed areas is more likely to be related to the characteristics of the land (poorly or well drained, flat or steep, and thick or thin soil, for example). Thus, some lineaments may be created or enhanced by land-use patterns.

3. Rights-of-way, such as roads interrupt cultivation and, commonly, vegetation patterns. A sizeable percentage of lineaments end at rights-of-way.

4. Few lineaments cross topographic highs.

5. Stereo viewing is advantageous in lineament detection because more detail is visible and the nature of features and patterns that form the lineaments usually can be determined. There was less tendency to include man-made features such as railroads and rights-of-way. Long lineaments were seen best at 1.5X magnification, but short lineaments were seen best at 4.5X magnification.

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Figure 4.--Black and white reproduction of a NASA SKYLAB photograph (SL-2, roll 81, frame 200) showing the lineaments that were detected by projection viewing in this part of the study area.

Table 5.--Number and length of lineaments detected on SKYLAB photographs by stereo viewing, projection viewing, and composite viewing.

	Number	Total length km (mi)	Minimum length km (mi)	Maximum length km (mi)	Mean length km (mi)	Median length km (mi)
Stereo viewing	118	820 (510)	1.3 (0.81)	52 (32)	6.9 (4.3)	5.1 (3.2)
Projection viewing	70	840 (522)	2.5 (1.6)	46 (29)	12 (7.5)	11 (6.8)
Composite viewing	32*	493 (306)*	4.5 (2.8)	62 (39)	15 (9.3)	9.5 (5.9)

*Data adjusted to show results that would have been obtained if composites covered the entire study area.

6. Stereo viewing at 4.5X magnification was the most productive method in areas of scattered clouds and haze. This method proved best for tracing lineaments across and between clouds and cloud shadows.

7. Projection was a considerably faster process than stereo viewing. Once the slides were prepared, projection required only 4 man-hours to detect all lineaments in the study area, whereas stereo viewing required about 12 man-hours.

The fourth step was to reexamine most lineaments on high-altitude aircraft (U-2) photography in stereo. Aerial photography is available for only the eastern 68 percent of the study area, so all lineaments could not be checked. Several projection lineaments proved to be powerline or pipeline rights-of-way and were deleted from further consideration. Some SKYLAB lineaments also are very obvious on high-altitude aerial photographs, whereas others are visible but obscure. On the other hand, some obvious lineaments on aerial photographs are not found on SKYLAB photographs.

Finally, all SKYLAB lineaments were transferred to 1:250,000 scale base maps (figs. 5, 6, and 7). The trends of all lineaments were measured on the maps, and results (fig. 8) were compared.

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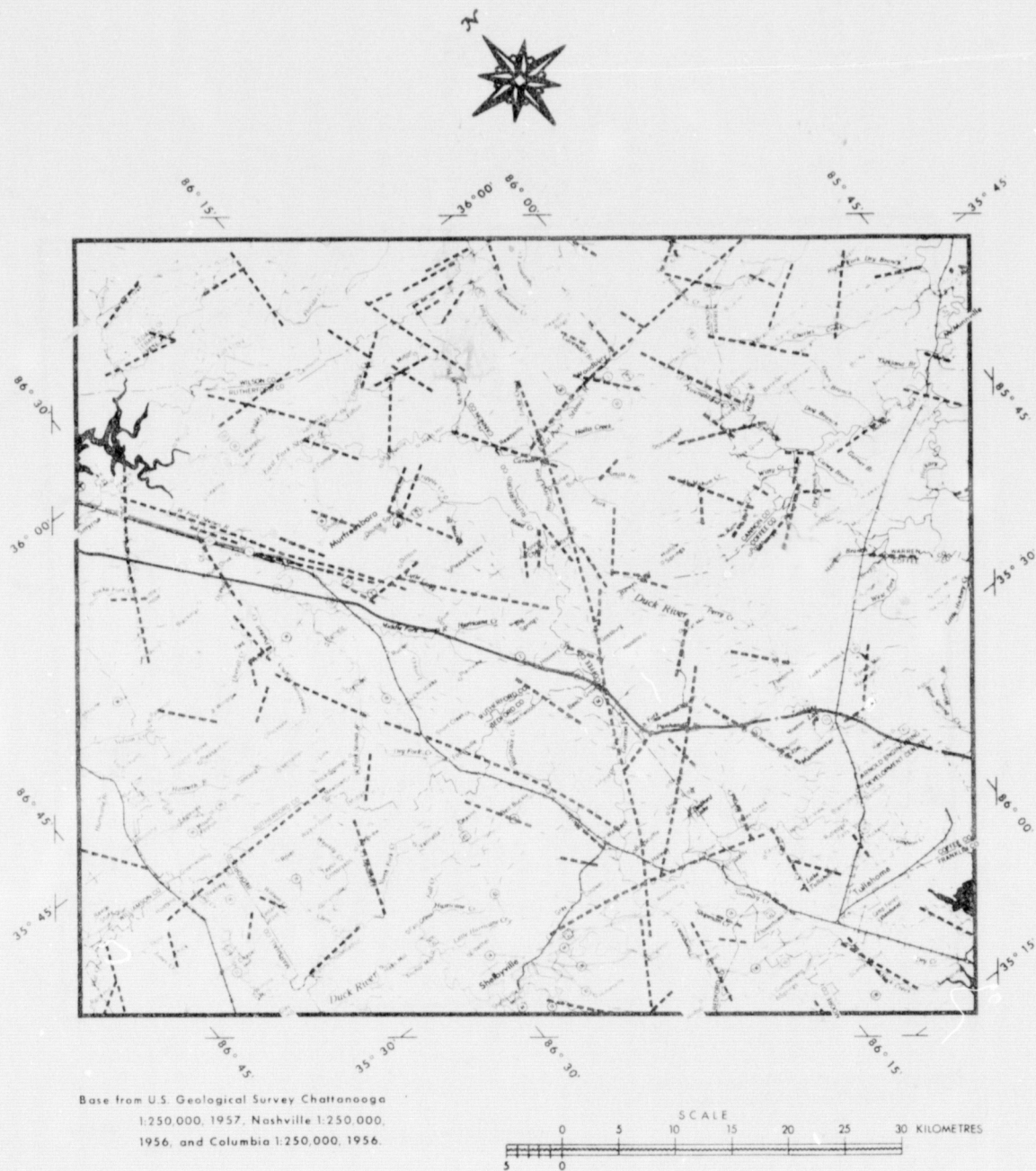


Figure 5.--Lineaments detected by stereo viewing of SKYLAB photographs.

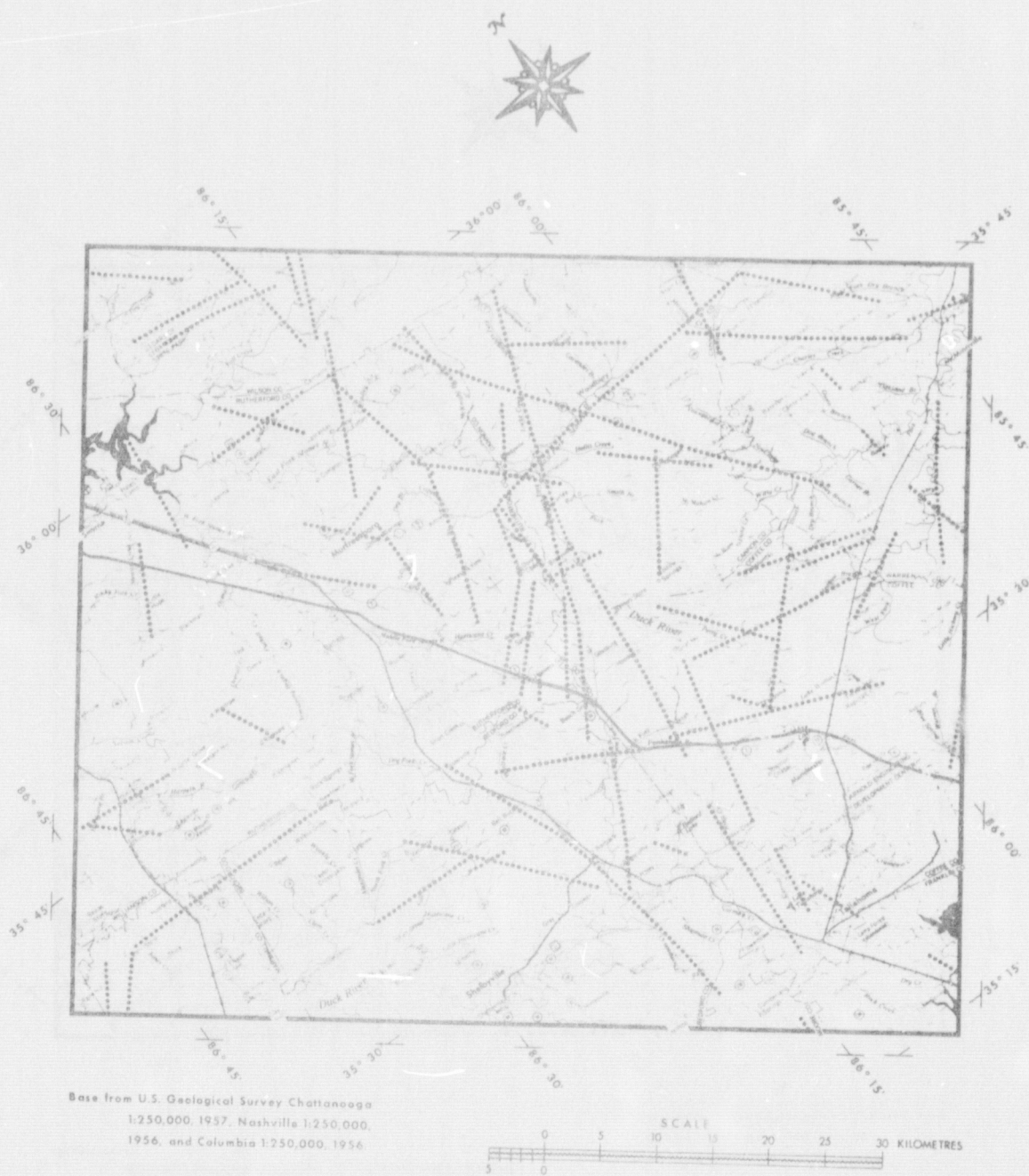


Figure 6.--Lineaments detected by projection viewing of SKYLAB photographs.

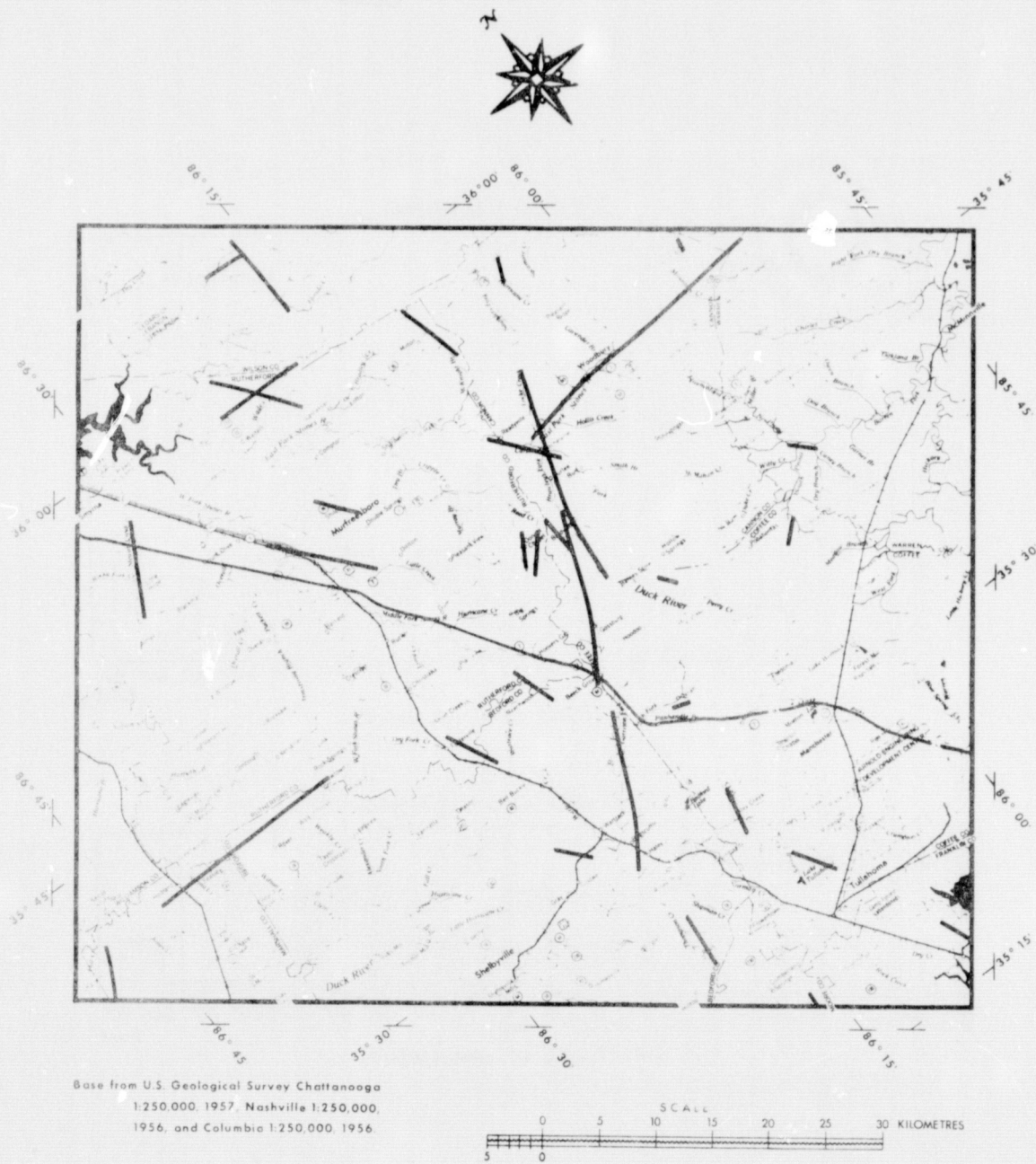


Figure 7.--Lineaments detected both by stereo viewing and projection viewing of SKYLAB photographs.

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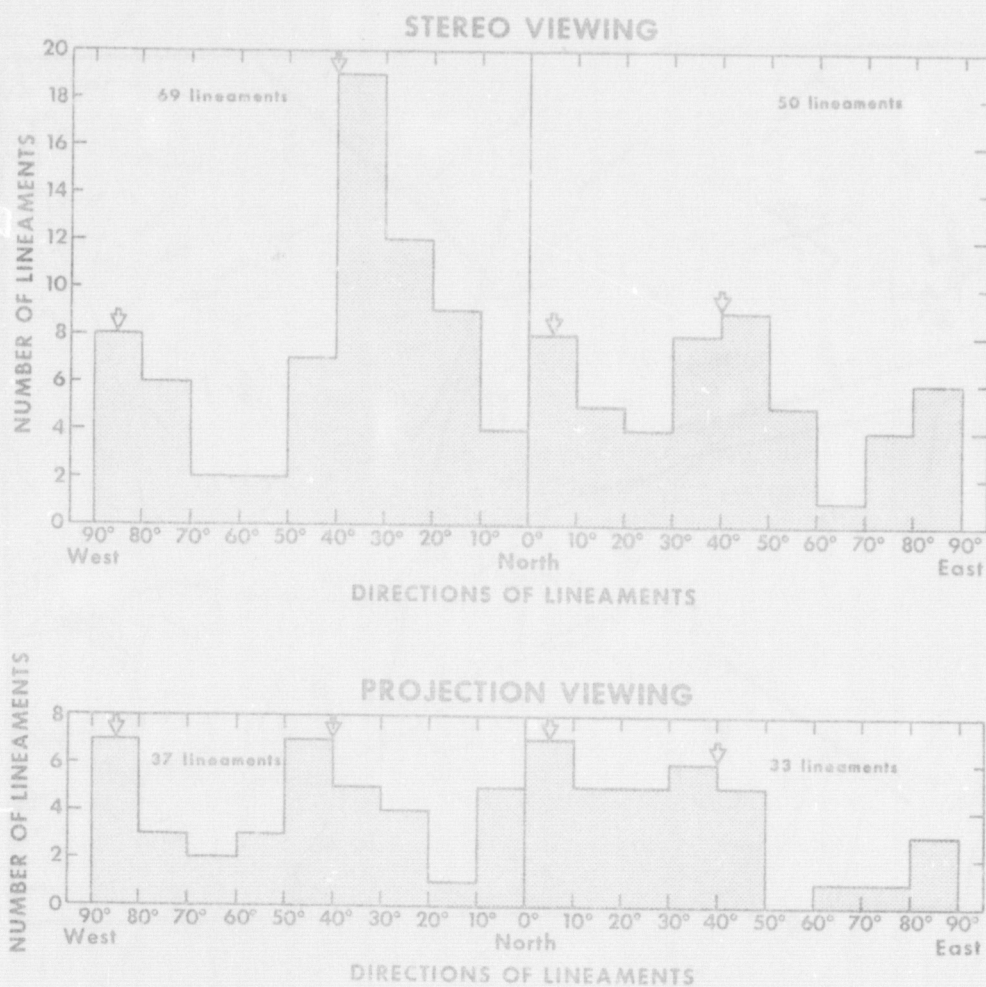


Figure 8.--More lineaments trend northwesterly than northeasterly.
The dominant trends are about N.85°W., N.40°W., N.5°E., and
N.40°E.; joints have similar dominant trends.

For both stereo and projection lineaments, more lineaments trend northwest than northeast, and the dominant azimuths are about N.85°W., N.40°W., N.5°E., and N.40°E. These results show that the two detection processes are consistent; thus, results of stereo viewing and projection should be equivalent for purposes of correlation with geologic and hydrologic data.

Composite viewing.--Two methods of composite viewing were tried. Both methods involved combining an image of an area on an SL-2 photograph with an image of the same area on an SL-4 photograph. The theory behind composite viewing is that lineaments and boundaries, which may not be apparent on a single photograph will be obvious on a composite image, if the photographs were made at different seasons of the year. *This theory will be true if (1) there are differences in types or densities of vegetation on either side of the boundaries, (2) the reflectance characteristics of the vegetation change at different rates or in different ways from one season to another, and (3) a composite image enhances the changes that have occurred.

In the first method, the SL-2 and SL-4 photographs were combined on a color additive viewer and false color, composite images were produced by colored filters. Observations were: (1) tonal contrasts are about the same as on original, separate photographs, (2) all textural contrasts in the scene are enhanced, (3) resolution of the scene is reduced (perhaps because of the high density of the SL-4 photograph), and (4) some prominent lineaments (previously detected by stereo viewing or projection viewing) are enhanced, but many of the more obscure lineaments cannot be seen (probably because of lower resolution).

The second method consisted of composite viewing with a mirror stereoscope. The ground track of the SL-4 mission was northeast of the track of the SL-2 mission; the resulting parallax produces a stereo model with a fair amount of relief. However, photographs from the SL-4 mission (and thus the stereo model) cover only 84 percent of the study area.

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For comparison purposes, lineaments were detected on the composite stereoscope images and then were mapped. Results (table 5) show that almost four times as many lineaments were detected by stereo viewing as by composite viewing, but composite lineaments are long, on an average. This result indicates that short lineaments are much less apparent on composite images and that resolution is lower on composite images. Again, this could be caused mainly by the density of the unfiltered SL-4 photograph. It does not necessarily prove that more lineaments can be detected on the S-190B photographs than on the multispectral photographs (although this result would be expected because of better resolution inherent in the S-190B photographs). Also, this result does not necessarily prove that more lineaments can be detected on color photographs than on B & W photographs.

Comparison of lineament detection with previous studies.--Most of the Beech Grove lineament (Hollyday and others, 1973), which was first discovered on Landsat images (trace shown on fig. 14) also is obvious on SKYLAB photographs. It is not as obvious on SKYLAB photographs that this lineament is continuous over a distance of 145 km (90 mi). SKYLAB photographs do show that the Beech Grove lineament is not a simple line or thin belt; the lineament branches and is intersected by other, transverse lineaments, which are not obvious on Landsat images.

The small fracture traces--that were mapped previously from 1:20,000 scale aerial photographs and were shown to be not significant for ground water (Moore and others, 1969, p. 47)--cannot be seen on SKYLAB photographs. The so-called pronounced linear belts, detected on these aerial photographs, are visible as lineaments on SKYLAB photographs.

Experiment with machine enhancement and processing.--Several experimental techniques were tried in an attempt to enhance lineaments for easier detection and to evaluate the possibility of automatic machine processing. The first method was composite viewing (as discussed previously). This method did not produce

results as good as stereo viewing or projection viewing with SKYLAB photographs; it proved very useful as is described later for detecting lineaments on Landsat images. More and shorter lineaments were visible on composite Landsat images than on single frames of imagery. Thus, in some cases this method may enhance lineaments for easier detection; composite viewing alone, however, will not lead to automatic machine processing.

The second method was simple density slicing of S-190B photographs. The density-slicing equipment uses a 525 line television camera and has a capacity of displaying eight color-coded density levels at one time. Only a few lineaments were detectable on the color-coded display screen, although short segments of several major lineaments were enhanced. This method does not seem promising for either enhancement or machine processing; one of the major problems is the large loss of resolution that occurs between the film and the television display screen. Other problems are (1) most lineaments are composed of short, discontinuous segments; the human eye can fuse these segments but machines cannot, (2) film density varies between different segments of the same lineament and between adjacent lineaments, (3) many other features in the scene have the same film densities as particular lineament segments, and (4) vignetting causes progressive lateral changes in film density in areas bordering the longer lineaments.

The third method was density slicing of film sandwiches. Film sandwiches of S-190B photographs were prepared in the manner suggested by Weller (1970); these sandwiches then were density sliced with the video equipment described above. Results were similar to those of simple density slicing. Several of the most obvious lineaments were enhanced, but only these few lineaments could be seen.

Relationship of Lineaments to Geology and Streamflow

If lineaments mark zones along which ground-water solution has occurred, dominant lineament trends should correspond with

dominant joint trends (because trends of solution cavities are determined by joints). Similarly, geophysical anomalies (such as those on gravity and magnetic maps) might indicate areas where fracturing of the rocks has been of more than average intensity (leading to increased ground-water solution); the locations and trends of these anomalies might correspond with lineaments. Also, the locations and trends of near surface synclines may correspond with lineaments, because many folds result from underground solution, sapping, and subsidence. Finally, lineaments may mark the location of complex solution cavities that transmit water from one stream basin to another (beneath drainage divides); thus lineaments may explain uncommonly large or small streamflows in some locations. These theoretical correlations were tested.

Joint and sinkhole trends.--Previous workers agree (for example, Galloway, 1919 and Jewell, 1947) that regional joints are vertical and trend about northeast and northwest. However, measurements in the upper Stones River basin (Moore and others, 1969, p. 15) showed a secondary joint system with average strikes of about north and east. Also, measurements of the long axis of sinkholes (which generally corresponds with joint direction) in the Center Hill Lake region (Moore and Wilson, 1972, fig. 8) showed dominant trends at about N.85°W., N.55°W., N.40°W., and N.40°E. Two dominant trends of stereo and projection lineaments (fig. 8) are at about N.40°E. and N.40°W.; these probably are the regional joints mentioned by previous workers. The other two dominant trends of stereo and projection lineaments are N.85°W. and N.5°E.: both directions approximately correspond with secondary joints measured in the upper Stones River basin; the N.85°W. direction also corresponds with a dominant sinkhole axis trend in the Center Hill Lake region. These results indicate that most lineaments are related to joints and suggest that the lineaments are caused by joints.

Geophysical anomalies.--Locations and trends of the lineaments were compared with anomalies on a Bouguer gravity map (U.S. Air Force, 1968) and a magnetic map (Zietz and Others, 1968) of the

transcontinental geophysical survey (Lat. 35°-39°N.). The lineaments seem to be randomly distributed, both with respect to the axes of anomalies and with respect to the locations and trends of steep contour slopes. This lack of correlation may not be significant because (1) both maps are generalized; they have large contour intervals and little local detail, and (2) many lineaments may represent near surface joints that do not extend to the depths represented by the anomalies.

Surface folds.--The lineaments also were compared with geologic structure. For this purpose, axes of anticlines and synclines were added to structure-contour maps based on surface geology. The locations and trends of these axes then were compared with locations and trends of the lineaments. There was no apparent correlation, and the lineaments seemed to be randomly distributed. This was a surprising result because (as noted previously) many near surface folds are believed to result from ground-water solution. If lineaments mark joints where ground-water solution has been active, then structural theory implies that the lineaments should correspond with synclinal axes. In the study area, however, synclinal axes and lineaments apparently are not related. There must be flaws in the assumptions that are not understood and not considered.

Low streamflows.--Locations of the lineaments were compared with results of several seepage runs on the rivers and streams. Seepage runs are closely spaced measurements of streamflow to detect and locate losing and gaining reaches of stream channels. Some SKYLAB lineaments (both stereo and projection) may explain some uncommonly large or small flows of water, if the lineaments mark solution cavities that transmit water from one sub-basin to another. Also, some lineaments may explain several gaining and losing reaches. However, other lineaments have no detectable effects on streamflows, and other losing and gaining reaches are located where no lineaments were seen.

The relationship of lineaments to streamflow is uncertain. Nevertheless, maps of lineament location are a possible source of

information for problems such as interbasin transport of water and should be considered in future studies of this type.

Relationship of Lineaments to Well Yields

The significance of stereo and projection lineaments for the occurrence and productivity of ground water was determined by (1) comparing yields of existing water wells located on and near the lineaments with yields of other wells located between lineaments, and (2) drilling and testing new wells. These results then were compared with those of previous studies.

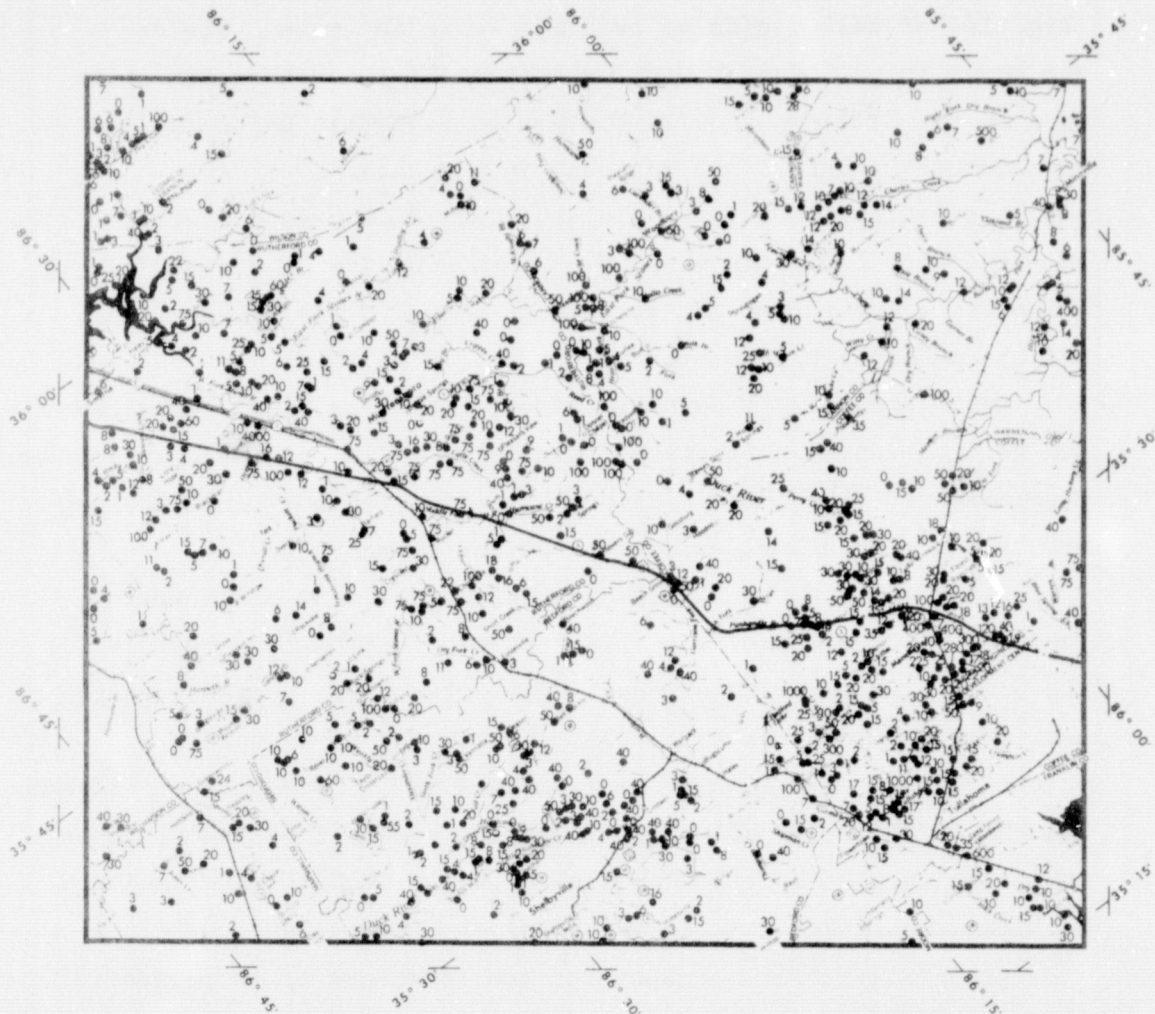
Existing wells.--Records are available for 940 wells in the study area. These records represent wells drilled for domestic use (almost entirely) between 1963-73. Based on distributions drawn for previous studies (Moore and others, 1969, p. 21; Moore and Wilson, 1972, p. 38), about 50 percent of the wells are less than 24 m (80 ft) deep, and about 90 percent of the wells are less than 52 m (170 ft) deep. Because drilling was stopped at the shallowest solution cavity producing the desired amount of water, these well depths approximately represent the median and 90 percentile depths of solution cavities in the study area.

Existing wells do not have truly random locations because (1) most people live on lowlands in the Central Basin and on uplands in the Highland Rim, (2) some areas grew faster than others (and more wells were drilled) during the 10-year period represented by the records, and (3) more well locations were determined in areas included in a previous study than in other areas. As a result the yield and location map (fig. 9) shows clusters of well data in some areas and sparse data in other areas. Nevertheless, as both high and low well yields occur in nearly all parts of the study area, well locations are assumed to be random, for the purposes of the report.

Well yields of less than 0.063 l/s (1 gal/min) are shown as zero on the map (fig. 9). Where two or more wells are so close together that the locations cannot be plotted separately on figure 9, only the largest well yield is shown. All well yields

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Base from U.S. Geological Survey Chattanooga
1:250,000, 1957, Nashville 1:250,000,
1956, and Columbia 1:250,000, 1956.

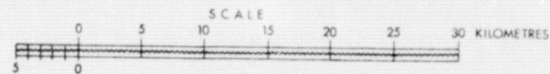


Figure 9.--Yields (in gallons per minute) of existing water wells.
(Yields may be converted to litres per second by multiplying
by 0.0631).

were used to determine the hydrologic significance of lineaments (fig. 12 and table 6, for example).

The well yields on figure 9 were estimated (mostly) or measured by the well drillers and thus represent reported data. The yield of an individual well may not be exact, but the distribution (fig. 10) of well yields is believed to be accurate. Yields are shown in gallons per minute because (1) these were the units used by the drillers and (2) conversion to metric units implies an accuracy^{2/} that is not inherent in the data.

A distribution of well yields (fig. 10) shows that about 10 percent of the wells yield less than 0.03 l/s (0.5 gal/min) of water, about 10 percent yield more than 2.5 l/s (40 gal/min), and the median yield is about 0.63 l/s (10 gal/min).

Maps (appendix) showing lineament locations, well locations, and well yields were prepared. Yields of wells on and near lineaments were compared with the yields of all wells (randomly located) and with the yields of wells located between lineaments.

In evaluating the significance of comparisons of lineament location with well yields, it is important that swaths where wells are considered to be on or near lineaments occupy a significant part of the study area (fig. 11). Twenty-three percent or 215 of the 940 wells fall on or near lineaments. In comparison, SKYLAB lineaments cover 30 percent of the study area. These two figures are close enough to conclude that the wells probably are randomly located with respect to the locations of lineaments.

SKYLAB lineaments account for the locations of 40 percent of all wells that yield 3.2 l/s (50 gal/min) of water or more and 46 percent of all wells that yield 6.3 l/s (100 gal/min) or more. Thus, lineaments explain a significantly larger percentage of high yield wells than would be expected, based on the area occupied by lineament swaths.

^{2/} A well yield of 10 gal/min would have to be shown as 0.63 l/s to be distinguishable from a yield of 9 gal/min (0.57 l/s). However, yields of this size are not accurate to more than one significant figure.

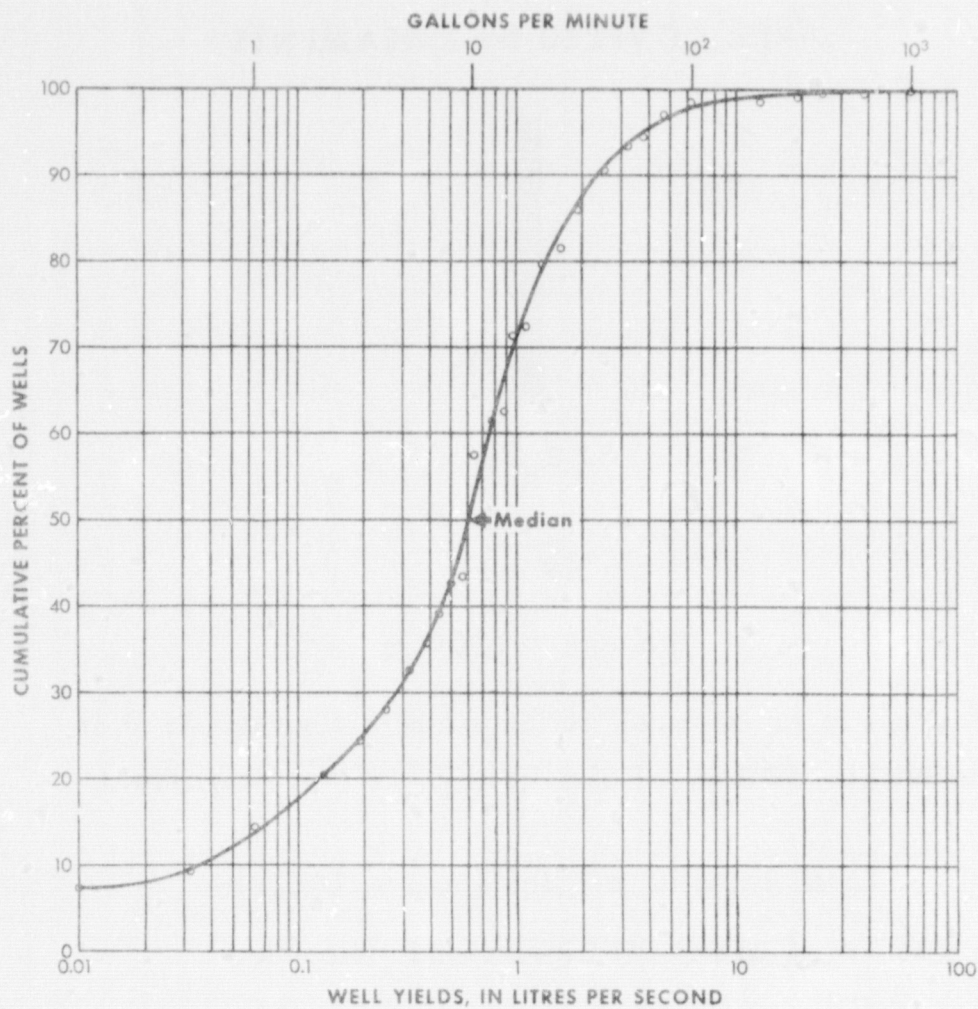
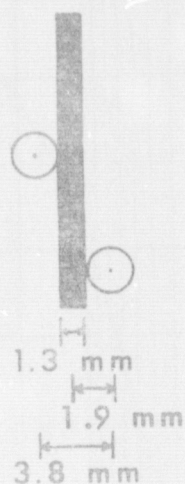


Figure 10.--A cumulative distribution of well yields shows that the median yield is about 0.61 l/s (9.7 gal/min).

AREA COVERED BY LINEAMENTS



$$3.8 \text{ mm} = 1000 \text{ m}$$

A well is considered to be near a lineament if it is within 500 m of the center of the lineament.

Total length, all lineaments: 1660 km

Total area, all lineaments: 1660 km²

Percent of study area covered by lineaments: 30

Figure 11.--Well locations are defined as being on or near lineaments where the well is less than 500 metres from the center of the lineament.

When well yields are distributed by percent (fig. 12), there is little difference between the lower halves of curves representing wells located between lineaments and wells located on or near lineaments. For example, the median yield of wells between lineaments is about 0.59 l/s (9.3 gal/min), whereas wells on or near lineaments have a median yield of about 0.66 l/s (10.5 gal/min). Significantly larger differences are found in the upper halves of the curves. Thus, 20 percent of the wells between lineaments yield 1.3 l/s (21 gal/min) or more, whereas 20 percent of the wells near lineaments yield 2.1 l/s (33 gal/min) or more. This result shows that well locations near SKYLAB lineaments are most productive when relatively large amounts of water are needed.

The effects of well location and lineament-detection method (as well as photographic resolution) can best be compared by means of a matrix (table 6). Although this comparison is based on yields of existing wells, the data could be used to predict results of drilling future wells. Stereo viewing proves to be the single best method of selecting sites for well yields of 1.6 l/s (25 gal/min) or more. Either stereo viewing or projection methods provide advantages over random drilling where yields of more than 0.63 l/s (10 gal/min) are desired. For yields of more than 1.6 l/s (25 gal/min), additional advantages are obtained where the lineament is detected both by stereo viewing and by projection (table 6).

Results of test drilling.--Twelve test wells (fig. 13 and appendix) were drilled to determine the utility of lineament mapping as a tool for ground-water prospecting. About half the wells were drilled for this study; the remainder were part of a ground-water study for the city of Murfreesboro. As a result, most of the wells are near Murfreesboro.

Eight test wells were located on or near lineaments detected on SKYLAB photographs, high-altitude aerial photographs, or Landsat images. Locations of the remaining four wells were selected for other reasons, including favorable topography and geologic structure

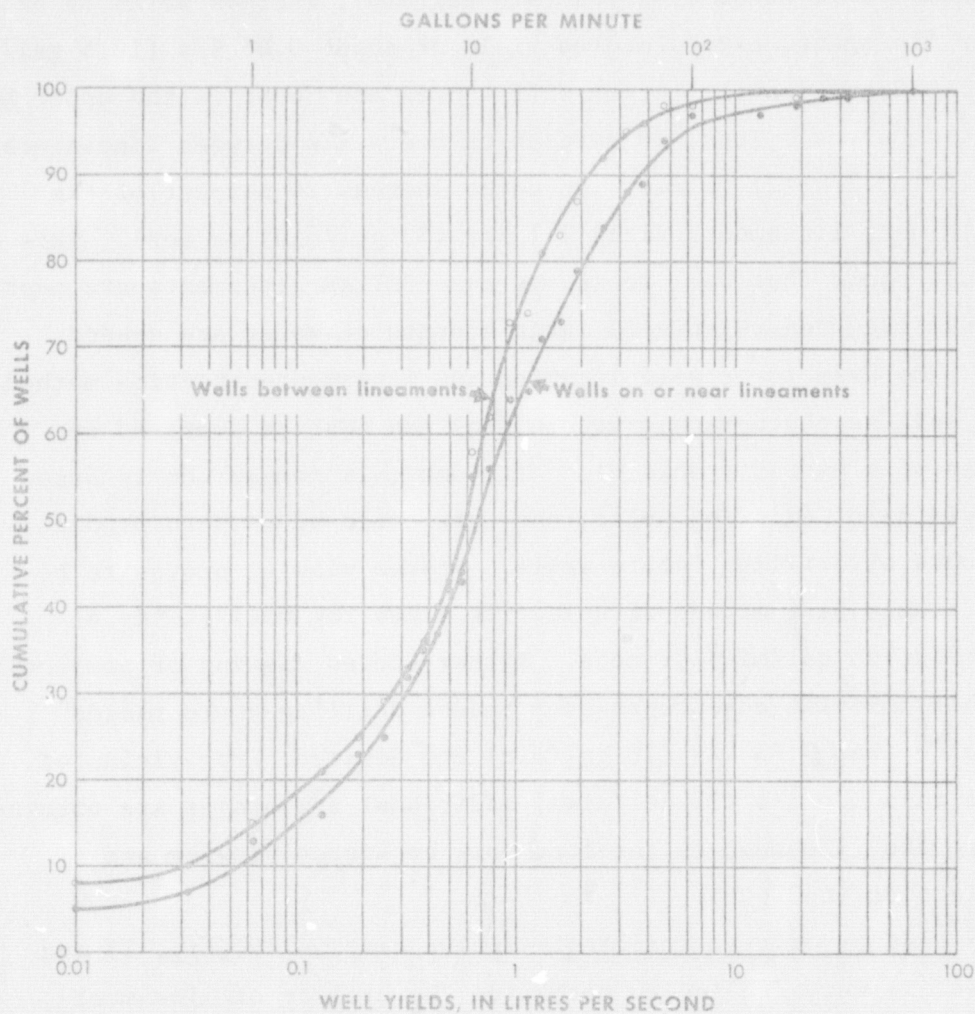


Figure 12.--Distributions of well yields showing that relatively large differences in yield occur in the upper halves of the curves. Well yields of less than 0.03 l/s (0.5 gal/min) are plotted as 0.01 l/s.

Table 6.--Comparison of results of random drilling with locations on or near lineaments. Shows, on an average, the number of wells that would have to be drilled to obtain a yield larger than that shown.

	Well yields in ℓ/s (gal/min)			
	0.63 (10)	1.6 (25)	3.2 (50)	6.3 (100)
Wells randomly located	1.8	5.0	11	33
Wells on or near SKYLAB lineaments:				
Stereo lineaments	1.6	3.3	5.0	14
Projection lineaments	1.9	3.7	7.7	20
Either stereo or projection lineaments	1.8	3.4	6.2	17
Stereo and projection lineaments ^{a/}	1.6	3.3	3.8	5.3
Wells between SKYLAB lineaments	1.8	5.6	14	50
Wells on or near Landsat lineaments	2.2	3.7	6.3	43
Wells on or near aerial-photograph lineaments	1.6	3.4	6.6	40

^{a/} Lineaments that were detected both by stereo viewing and by projection.

and the relatively large yields of nearby wells. All wells represent favorable locations for ground water, so that yields of wells on and near lineaments can be compared with results obtained by using conventional methods to select well sites.

All wells were drilled by the air-rotary method (appendix) to a depth (with one exception) of at least 46 m (150 ft). Small well yields were estimated; larger yields were measured with a flume (during well development, after drilling had been completed). Yields of the four best wells were measured accurately by pumping tests. The largest well yield obtained by test drilling (fig. 13) was 19 ℓ/s (300 gal/min), and three wells had yields too small to estimate; yields of the three poorest wells are shown as zero.

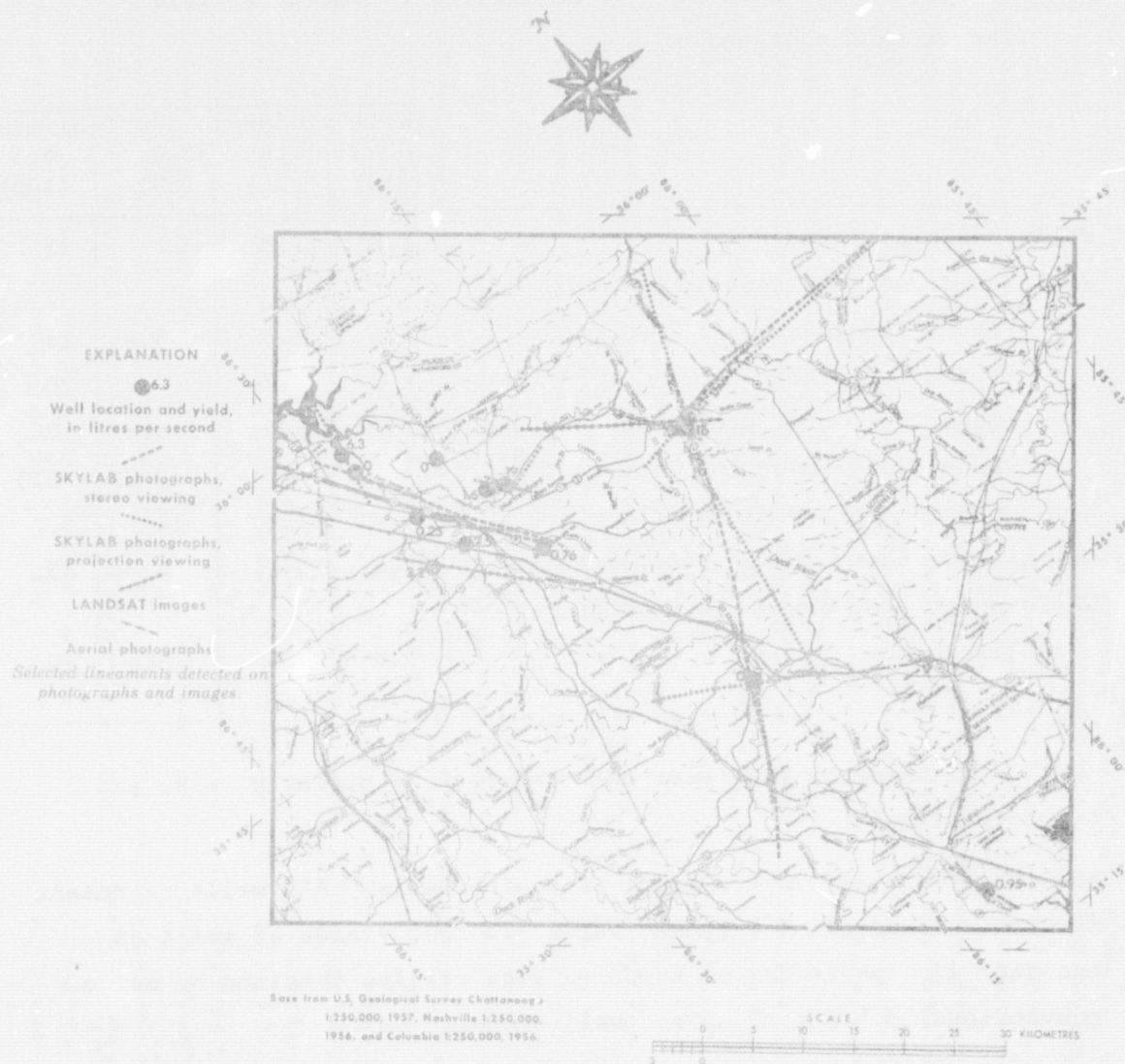


Figure 13.--Test wells located on lineaments detected on SKYLAB photographs, Landsat images, and high-altitude aerial photographs. Locations for other wells were selected by conventional methods.

The results of test drilling (table 7 and fig. 13) show (1) a few wells with low yields are obtained in all types of favorable locations, (2) larger well yields can be obtained (probably) from locations on lineaments than from locations based on other considerations, (3) large well yields can be obtained by locating wells on SKYLAB lineaments; three out of seven wells or 43 percent yield more than 6.3 ℓ/s (100 gal/min), and (4) the median yield of test wells on SKYLAB lineaments is about six times the median yield of all random wells. The number of wells in table 7 add up to more than 12, because some wells are on or near lineaments detected by more than one method (fig. 13).

Results of test drilling (table 7) are better than the results obtained with data from existing wells (table 6). None of the test wells were located on hilltops or steep slopes (generally unfavorable topographic locations) or close (within 90 m or 300 ft) to known wells with poor yields, for example. This is probably the explanation for the large mean and median yields obtained by test drilling. The results indicated by data from existing wells (table 6) probably can be expected when the only criterion for well locations is a nearby SKYLAB lineament. If topography and yields of nearby wells also are considered, results may be similar to those of table 7.

Comparison with other studies.--Only two reports on other areas show data with which this study can be compared, and those depend on a small number of wells. Based on a sample of 13 wells, Lattman and Parizek (1964, table 2) indicate that wells located on fracture traces in central Pennsylvania have from 4 to 1,000 times the yield (for each foot of drawdown of water level) of wells located between fracture traces. Similarly, Sonderegger (1970, p. 24) reports that in Limestone County, Ala., 3 test wells on fracture traces have a mean yield of 7.6 ℓ/s (120 gal/min), whereas 13 wells between fracture traces have a mean yield of 1.5 ℓ/s (23 gal/min). These results may be compared both with yields of existing wells and with results of test drilling in the present study.

Table 7.--Test-drilling results comparing yields of wells located on lineaments of various types and yields of wells located by other criteria

Lineament type	No. wells	Minimum yield ℓ/s	Maximum yield ℓ/s(gal/min)	Mean yield ℓ/s(gal/min)	Median yield ℓ/s(gal/min)
SKYLAB photographs					
Stereo method	7	0	19 (300)	6.3 (100)	3.8 (60)
Projection method	6	0	19	7.6 (120)	.82 (13)
Aerial photographs	5	0	19	8.2 (130)	6.3 (100)
Landsat images	3	0	16 (250)	5.7 (90)	.95 (15)
None	1	---	---	3.2 (50)	---
	4	0	2.5 (40)	1.1 (18)	.95
All wells on lineaments	8	0	19	5.7	1.9 (30)
All wells in favorable locations	12	0	19	4.4 (70)	1.3 (20)

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The mean yield of existing wells between lineaments is 1.5 l/s (23 gal/min). In comparison, mean yields of existing wells on or near SKYLAB lineaments are:

Stereo lineaments	1.9 l/s (30 gal/min)
Projection lineaments	2.5 l/s (40 gal/min)
Detected by both methods	3.4 l/s (54 gal/min)

Based on these data, wells located on lineaments detected by both stereo viewing and projection have a mean yield about twice the mean yield of wells between lineaments; there is even less difference in mean yield for wells located on or near projection lineaments and stereo lineaments. Obviously, these results are not as good as those reported for central Pennsylvania and northern Alabama. Nevertheless, this comparison is based only on mean yields; it does not reflect the advantages (table 6) obtained by locating wells on SKYLAB lineaments, when larger than average well yields are desired.

The mean yield of test wells (table 7) on or near SKYLAB lineaments is 6.3 l/s (100 gal/min), whereas the mean yield between lineaments is 1.1 l/s (18 gal/min). Thus, wells on SKYLAB lineaments have about 6 times the mean yield of wells between lineaments. These results are slightly larger than those reported by Sonderegger (1970, p. 24): wells on fracture traces in northern Alabama have 5 times the mean yield of wells between fracture traces. Present results also are in the range (near the lower end) reported by Lattman and Parizek (1964, table 2).

COMPARISON OF SKYLAB PHOTOGRAPHS WITH LANDSAT IMAGERY AND HIGH-ALTITUDE AERIAL PHOTOGRAPHS

In order to determine whether or not SKYLAB photographs have the best resolution and areal coverage for ground-water prospecting in central Tennessee, lineaments also were delineated on Landsat imagery and on high-altitude aerial photography. Lineaments on Landsat images (fig. 14) were detected by composite viewing (with a mirror stereoscope using two color composite Landsat images, which were obtained at different seasons of the year). Lineaments were

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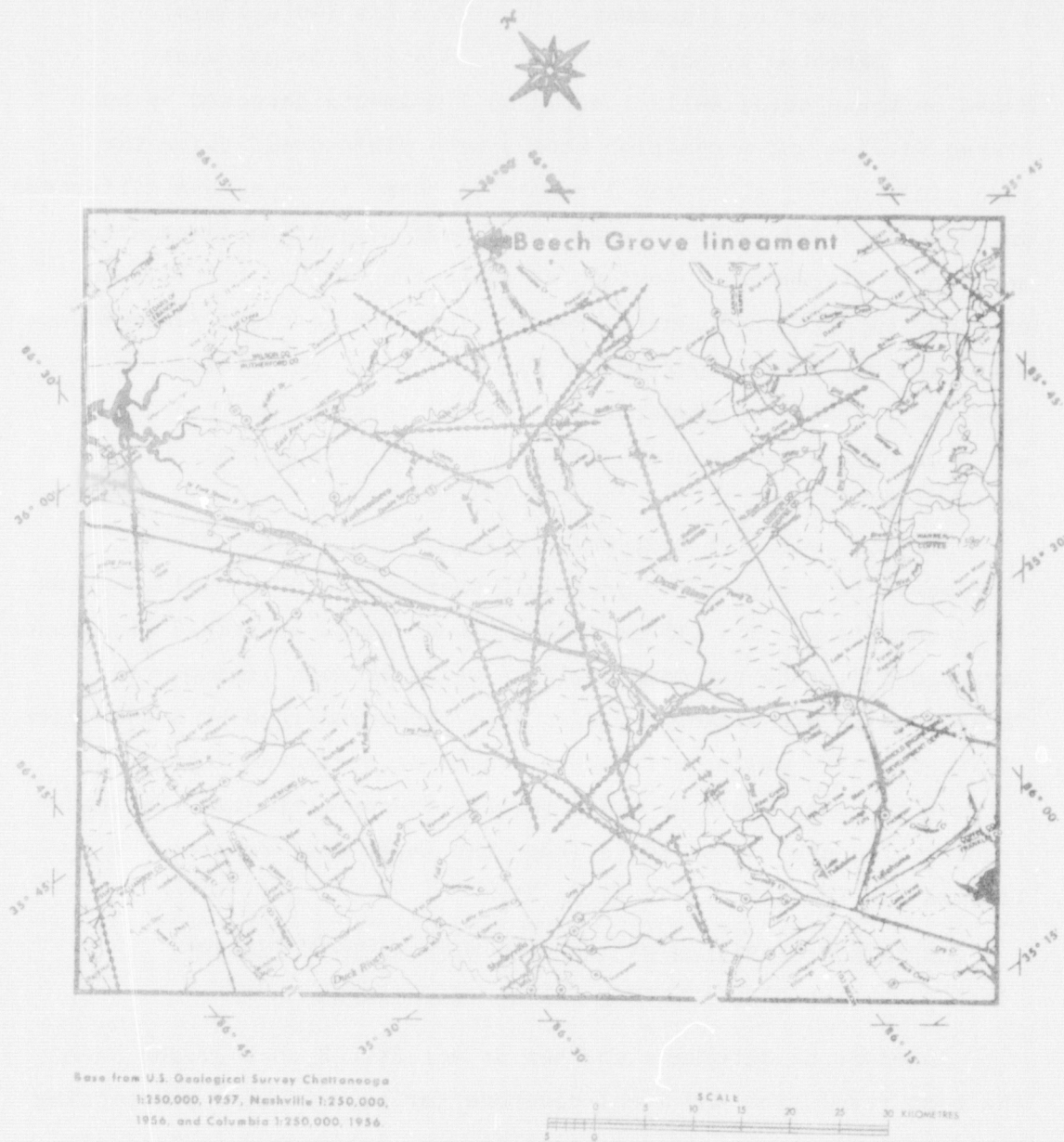


Figure 14.--Lineaments detected on Landsat imagery.

found on high-altitude, color infrared aerial photographs (fig. 15) by stereo viewing, but fracture traces (shorter than 1.6 km or 1 mi) were not included. About 4 man-hours were required to map Landsat lineaments, and about 12 man-hours were needed for aircraft lineaments (About 18 man-hours would be needed if aerial photographs were available for the entire study area.)

Only a few, relatively long lineaments were found on Landsat imagery, and the total length of these lineaments is only about 25 percent of the total length of the SKYLAB lineaments (table 8). This result was expected because Landsat imagery has poorer resolution than SKYLAB photography.

More but shorter lineaments were found on high-altitude aerial photographs (table 8). The effect of excluding fracture traces is shown by the fact that total length of lineaments found on aerial photography is only slightly more than that found by stereo viewing of SKYLAB photography.

A comparison of results obtained by locating wells on Landsat lineaments, aerial-photography lineaments, and SKYLAB lineaments with the results of random drilling (table 6) shows (1) well locations on Landsat and aerial-photography lineaments provide some benefits where yields of 1.6 to 3.2 l/s (25 to 50 gal/min) are desired, but (2) neither method produces results as good as can be obtained with SKYLAB photography (table 6).

Only four test wells were drilled on lineaments detected on aerial photographs and Landsat images (fig. 13 and table 7). The mean yield is 5.0 l/s (80 gal/min) as compared to a mean yield of 6.3 l/s (100 gal/min) for test wells on SKYLAB lineaments. This result is interesting, but the sample size is too small to be conclusive for purposes of ground-water prospecting. Test drilling shows (table 7) that (1) large well yields can be obtained by locating wells on Landsat and aerial-photograph lineaments, and (2) larger well yields probably can be obtained from locations on these lineaments than from locations based on conventional considerations.

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Figure 15.--Lineaments detected on high-altitude aerial photographs.

Table 8.--A comparison of the number and lengths of lineaments detected on Landsat images, aerial photographs, and SKYLAB photographs

	Number	Total length in km (mi)	Minimum length in km (mi)	Maximum length in km (mi)	Mean length in km (mi)	Median length in km (mi)
Landsat images	18	410 (250)	10 6.2)	70 (43)	23 (14)	20 (12)
High-altitude aerial photographs	235*	890 (550)*	1.3 (0.81)	11 (6.8)	3.8 (2.4)	3.8 (2.4)
SKYLAB photographs (stereo viewing)	118	820 (510)	1.3	52 (32)	6.9 (4.3)	5.1 (3.2)

*Data adjusted to show results that would have been obtained if aerial photographs covered the entire study area.

NATURE OF LINEAMENTS

Elements, locations, and trends of lineaments were examined and analyzed on SKYLAB photographs, Landsat images, high-altitude aerial photographs, on maps, and on the ground; comparisons were made with locations and trends of known faults and sinkhole belts, vegetation trends, stream-channel alignments, and other topographic alignments. The purpose was to determine the make-up and character of the lineaments.

All lineaments are composed of short, discontinuous segments. The ability of the human eye to fuse several segments and to form a lineament depends on several factors. The most important factors apparently are the resolution, scale, and contrast of the photographs. Thus, a lineament detected on a SKYLAB photograph generally can be seen best on that photograph; it is less obvious or not apparent on Landsat images or on high-altitude aerial photographs. For example, the Beech Grove lineament, which appears to be a single line or narrow belt on Landsat imagery, consists of a number of discontinuous, branching, and intersecting lineaments on SKYLAB photographs.

Other factors in lineament detection are (1) the detection method (various methods may enhance or reduce scene contrast, reduce resolution, and enhance topographic relief or make it less apparent), (2) uniform or mixed land use (resulting in uniform or contrasting scene elements), (3) topography (flat to rolling or dissected), (4) thickness of soil cover (fewer lineaments are visible in areas having a thick soil cover), and (5) season of year (causing various vegetation types to appear similar or distinctly different on the photograph). For these reasons, more differences than similarities should be expected between lineament maps based on interpretations of SKYLAB photographs, Landsat images, and aerial photographs; these results were obtained in the present study.

Effects of detection method are shown by differences in lineament locations (fig. 5 and 6), by differences in maximum and average lengths of lineaments (table 5), and by similarities and differences

in total lengths (table 5). For example, total lengths of stereo and projection lineaments are similar, but only about half of these lineaments (by length) were detected both by stereo viewing and by projection (fig. 7 compared with figs. 5 and 6).

Effects of using S-190A instead of S-190B photographs or B & W instead of color photographs were not tested for this study, but similar differences in locations and lengths of the lineaments would be expected.

Most SKYLAB lineaments consist of topographic depressions; the remainder are other topographic forms and vegetation alignments. The largest single group of lineaments is formed by surface drainage: stream-channel alignments, straight valley walls, and linear depressions in areas of relatively flat terrain. Thus, many SKYLAB lineaments follow or parallel the streams. Almost all aerial-photograph lineaments are formed by valley and stream-channel alignments, but only about half of the Landsat lineaments follow stream valleys.

A few SKYLAB lineaments are formed by the nearly linear bases of ridges, and a few other lineaments follow belts where sinkholes are abundant. Vegetation alignments are mostly on the Highland Rim; some of these lineaments are near stream channels and are caused by swampy and wooded depressions that have a high contrast with adjacent agricultural lands.

Topography has other effects on location, length, and number of lineaments, particularly in detection methods that enhance relief. Thus, the great majority of SKYLAB lineaments detected by stereo viewing do not cross drainage divides (some extend up to the divides). Similarly, almost no aerial-photograph lineaments (detected by stereo viewing) cross divides. The obvious topographic relief in stereo viewing may produce a mental barrier, so that the eye does not fuse segments on opposite sides of a divide to form a lineament. Some SKYLAB lineaments, detected by projection, and some Landsat lineaments cross topographic highs, probably because topography is much less obvious in these formats.

Another effect of topography is that lineaments are somewhat more numerous in dissected areas than in flat to rolling areas. Thus, for SKYLAB photographs (stereo and projection methods) and Landsat images, lineaments are most numerous near the dissected divide between the Central Basin and the Highland Rim; they are least common on the relatively flat uplands of the Highland Rim. Lineaments detected on aerial photographs are more evenly distributed across the test site (probably because of greater vertical exaggeration in the stereo model, so that more topographic detail is visible in all areas).

Many lineaments are approximately the same length, and this length depends on resolution and detection method. The range in length for the middle 50 percent of the lineaments detected by each method is:

<u>Method</u>	<u>Length, in km (mi)</u>
Aerial photography	2.5 to 4.4 (1.6 to 2.7)
SKYLAB photography	
Stereo	3.2 to 7.6 (2.0 to 4.7)
Projection	6.7 to 14 (4.2 to 8.7)
Composite	7.6 to 18 (4.7 to 11)
Landsat imagery	16 to 22 (9.9 to 14)

The tendency to find lineaments of approximately equal length was obvious during the detection processes, and the effects may be seen on the lineament location maps (figs. 5, 6, 14, and 15).

Certain lineament trends tend to dominate in parts of the study area. In any part of the area, most lineaments seem to trend in one or two directions. Probably, it would be possible to draw boundaries separating areas of differing dominant trends. This phenomenon was not investigated in detail, but is fairly obvious from study of the lineament maps (figs. 5, 6, 14, and 15). The reason for these trend clusters is unknown but may be related to underlying geologic structure.

One SKYLAB stereo lineament follows a belt of sinkholes through Shiloh, northeast of Murfreesboro, and two projection

lineaments follow sinkhole belts in the Shiloh, Double Springs, and Dillton areas on the eastern side of Murfreesboro. Lineaments were not detected along other belts of sinkholes. Thus, the numerous closed depressions that form sinkhole belts may, in some cases, also form linear segments that can be fused into lineaments.

Only two faults are shown on published geologic maps at 1:24,000 scale: one about 3.2 km (2.0 mi) east of Readyville and the other on Carson Fork about 11 km (6.8 mi) southwest of Woodbury. Stereo, projection and Landsat lineaments pass through the Readyville fault, but only the Landsat lineament has nearly the same trend as the fault. Only a stereo lineament passes through the area of faulting and brecciation on Carson Fork.

Yields of wells on and near SKYLAB lineaments are not uniform. Thus, although well yields along 14 stereo lineaments are the same order of magnitude, well yields along 24 lineaments span 2 orders of magnitude; and along 8 lineaments, well yields span 3 to 4 orders of magnitude. In general, nearby wells (up to 4 km or 2.5 mi apart) tend to have similar yields, but wells farther apart tend to have very different yields. Also, a significant percentage of wells on and near lineaments have low yields (fig. 9 and 10). These facts probably indicate that (1) solution did not occur evenly beneath the longer lineaments, and (2) some lineaments are false; they may mark the locations, for example, where solution or erosion occurred at land surface (forming the lineament) but did not occur at the depths reached by the wells.

There are other possible explanations for variations of well yield along lineaments. One is that wells tap different solution cavities, which developed along the same lineament. Another possible explanation is that underground solution in the past led to collapse and blocking of some solution cavities along lineaments. Finally, lineaments may mark locations favorable for underground solution, but not the actual locations and trends of underground cavities.

The majority of wells with relatively large yields are not on or near the lineaments detected on SKYLAB photographs. Some

of these wells (plus other wells with relatively low yields) fall along lineaments that can be detected on Landsat images and aerial photographs. Nevertheless, a sizeable percentage of locations favorable for ground water apparently cannot be determined by the techniques used in this study.

One of the things that becomes apparent, when directional trends are examined on SKYLAB photographs, is that in many localities there is a single dominant trend--here termed "geologic grain." This grain has a tendency to be uniform over fairly large areas and is not limited to a single line or a narrow belt as are the lineaments. On the other hand, geologic grain is not as obvious as the lineaments. In the vicinity of Murfreesboro, there is a N.40°W. trend of geologic grain caused by alinements of stream channels, ridges and valleys, and long axes of agricultural fields, woods, and sinkholes. Geologic grain in the Murfreesboro area can be seen by eye on SKYLAB photographs, but it generally is much more obvious when the photograph is projected, and the grain is enhanced with a Ronchi ruling (as described previously). Significance of geologic grain was not investigated during this study, but it probably is related to geologic structure; thus, it may be genetically related to the lineaments.

COSTS AND BENEFITS OF LINEAMENT DETECTION FOR TEST DRILLING

The 1975 costs of test drilling, as established by the drilling contract for this study, are shown in the table below. Costs of pumping tests (a part of the same contract) are not included, nor are small additional costs of increasing services beyond those specified in the base contract.

Drilling Costs	
Drilling (overburden and bedrock) -	\$9.84/m (\$3.00/ft)
Casing (furnishing, installing and sealing) -	\$12.30/m (\$3.75/ft)
Well development (surging and pumping) -	\$50.00/hour

Pulling casing and reaming - \$50.00/hour

Experimental and idle time - \$35.00/hour

Drilling was by the air-rotary method and consisted of a 203 mm (8 in) diameter hole through the overburden to bedrock (but to a minimum depth of 6.1 m or 20 ft) and a 159 mm (6.25 in) diameter hole through bedrock to total depth. A minimum of 6.1 m of black steel casing, with an inside diameter of 159 mm and a weight of 19.3 kilograms/m (13 lbs/ft), was installed in each well. Successful wells were developed by surging and pumping with the drilling rig for a minimum of 30 minutes and until the water was clear.

Average cost of the test wells was:

Drilling, 53.9 m (177 ft)	-	\$531
Casing, 6.1 m (20 ft)	-	75
Development, 0.54 hours	-	27
Other, 0.72 hours	-	<u>36</u>
Total		\$669

A rounded cost of \$670 per well is used for calculation purposes.

A comparison based on existing wells shows that when yields of more than 0.63 l/s (10 gal/min) are desired, costs of drilling at random locations would be considerably larger than at locations on SKYLAB lineaments (table 9). If a yield of more than 6.3 l/s (100 gal/min) is desired, for example, the average cost of obtaining this amount by random drilling is more than six times the cost at locations on lineaments that were detected both by stereo viewing and by projection.

Results of test drilling for this study suggest that even lower costs are possible by considering other factors (as described previously), which are favorable for ground-water occurrence. Thus, on an average 2.3 wells would have to be drilled to obtain one well producing 6.3 l/s (100 gal/min) or more. The cost would be \$1,541; this is less than half the lowest cost in table 9 for a well yield of this size.

Approximate costs of detecting and mapping lineaments for this study (and for other areas of similar size) are shown in

the table below. A labor cost of \$100 per man-day is assumed.

Costs of Mapping Lineaments

Four, 5 in (nominal size), color transparencies	-	\$ 24
Photo reproduction	-	76
Detect and record lineaments (stereo viewing and projection viewing)	-	250
Transfer lineaments to maps	-	<u>250</u>
Total	-	\$600

Table 9.--Costs resulting from location of future wells on SKYLAB lineaments rather than by random drilling. Assumes a cost of \$670 per well

Wells randomly located:

\$ 1,206	for	0.63 l/s	(10 gal/min)
\$ 3,350	for	1.6 l/s	(25 gal/min)
\$ 7,370	for	3.2 l/s	(50 gal/min)
\$22,110	for	6.3 l/s	(100 gal/min)

Wells on or near stereo lineaments:

\$ 1,072	for	0.63 l/s
\$ 2,211	for	1.6 l/s
\$ 3,350	for	3.2 l/s
\$ 9,380	for	6.3 l/s

Wells on or near projection lineaments:

\$ 1,273	for	0.63 l/s
\$ 2,479	for	1.6 l/s
\$ 5,159	for	3.2 l/s
\$13,400	for	6.3 l/s

Wells on or near stereo and projection lineaments*:

\$ 1,072	for	0.63 l/s
\$ 2,211	for	1.6 l/s
\$ 2,546	for	3.2 l/s
\$ 3,351	for	6.3 l/s

*Lineaments detected both by stereo viewing and by projection.

Benefits or potential savings that could accrue by locating future wells on SKYLAB lineaments (table 10) are determined by

subtracting the costs for lineament mapping from differences in costs for test drilling (table 9). The expense of lineament mapping is not justified for yields of less than 1.6 l/s (25 gal/min); on the other hand, significant to large savings result when well yields of 1.6 l/s or more are desired (table 10). Even larger savings may be possible, as discussed previously by also considering other location factors that are favorable for ground-water occurrence.

Table 10.--Potential savings that could result by locating future wells on SKYLAB lineaments rather than by random drilling

Wells on or near stereo lineaments:

[\$ 466]	for	0.63 l/s	(10 gal/min)
\$ 539	for	1.6 l/s	(25 gal/min)
\$ 3,420	for	3.2 l/s	(50 gal/min)
\$12,130	for	6.3 l/s	(100 gal/min)

Wells on or near projection lineaments:

[\$ 667]	for	0.63 l/s
\$ 271	for	1.6 l/s
\$ 1,611	for	3.2 l/s
\$ 8,110	for	6.3 l/s

Wells on or near stereo and projection lineaments*:

[\$ 466]	for	0.63 l/s
\$ 539]	for	1.6 l/s
\$ 4,224	for	3.2 l/s
\$18,159	for	6.3 l/s
[]	- deficit or loss	

*Lineaments detected both by stereo viewing and by projection.

Potential benefits of locating future wells on SKYLAB lineaments are very large when yields of more than 6.3 l/s (100 gal/min) are needed. The cost difference (table 9) between wells randomly located and wells on or near stereo and projection lineaments is \$18,759. This amount is slightly more than the entire cost of the present study (\$18,350), if test drilling costs are not included. Thus, in areas similar to central Tennessee, an entire

study of the present type may be economically justified by the need for a single well producing more than 6.3 ℓ/s (100 gal/min).

CONCLUSIONS, TRANSFER VALUE, AND RECOMMENDED PROCEDURES

Lineaments were detected on SKYLAB photographs by stereo viewing, projection viewing, and composite viewing. Sixty-nine percent more lineaments were found by stereo viewing than by projection, but segments of projection lineaments are longer; total length of lineaments found by these two methods is nearly the same.

Lineaments generally are composed of short, discontinuous segments. The ability of the human eye to fuse several segments and to form a lineament depends mostly on resolution, scale, and contrast of the photographs. Most SKYLAB lineaments consist of topographic depressions: stream-channel alignments, straight valley walls, elongated swales, and belts where sinkholes are abundant. Most of the remainder are vegetation alignments; a few lineaments are formed by the straight sides of ridges. (Most SKYLAB lineaments follow or parallel the streams. Lineaments are most common in dissected areas having a thin soil cover.

The Beech Grove lineament, first discovered on Landsat imagery, is apparent on SKYLAB photographs, but has branches and intersections with other, transverse lineaments, which can be seen on SKYLAB photographs but not on Landsat imagery. Similarly, small fracture traces, previously mapped from 1:20,000-scale aerial photographs of the study area, are not visible on SKYLAB photographs.

A comparison of trends indicates that most lineaments are related to joints and suggests that the lineaments are caused by joints. Lineament locations and trends are not related to anomalies on gravity, magnetic, or structure-contour maps.

Some SKYLAB lineaments could be used to explain gaining and losing reaches of streams, but other lineaments do not have a detectable relation to streamflows and other gaining and losing reaches are in locations where lineaments were not detected.

Larger well yields generally can be obtained in the study area by locating future wells on SKYLAB lineaments rather than on lineaments detected on either high-altitude aerial photographs or Landsat images. SKYLAB lineaments intersect 23 percent of the wells in the study area but account for 46 percent of the wells that yield more than 6.3 l/s (100 gal/min).

For well yields of 1.6 l/s (25 gal/min) or more, significant savings could be achieved by locating future wells on SKYLAB lineaments, rather than by random drilling. These advantages would not be obtained for well yields of less than 1.6 l/s, and costs of detecting and mapping lineaments would not be justified when yields of this size are adequate. The largest savings would be achieved by selecting well locations on lineaments detected by both stereo viewing and projections. Stereo viewing was found to be the best single detection method, in terms of potential savings.

Results of test drilling show (1) the median yield of test wells on SKYLAB lineaments is about six times the median yield of all existing wells, (2) three out of seven wells on SKYLAB lineaments yield more than 6.3 l/s (100 gal/min), (3) low yields are possible on lineaments as well as in other favorable locations, and (4) the largest well yields can be obtained at well locations on SKYLAB lineaments that also are favorably located with respect to topography and geologic structure, and are in the vicinity of wells with large yields.

The results of this study apply only to the central Tennessee test site; a transfer of either results or methods to other areas should be made with caution. The most important features relating results to this area probably are (1) dense, fractured limestones, (2) nearly flat-lying rock layers, (3) relative importance of horizontal, sheetlike solution cavities to ground-water occurrence, and (4) thin soil cover. The relative importance of these factors is difficult to determine on the basis of this one study. One or more of these four features also occur in most other hard rock terranes.

The Blue Grass area of central Kentucky probably is most similar to the Central Basin of Tennessee. Most of the areas in the region from northern Alabama to Illinois and Ohio have similar rocks but a thicker soil cover. Many other areas have a thin soil cover and nearly flat-lying rocks of sandstone or shale, instead of limestone.

A thin soil cover is known to be a significant factor for the results in central Tennessee because of other studies, as discussed previously. Soil cover in both central Pennsylvania (Siddiqui and Parizek, 1971, for example) and northern Alabama (Sonderegger, 1970, for example) is considerably thicker than in the Central Basin. Both previous studies successfully correlated well yields with fracture traces visible on 1:20,000-scale aerial photographs; there was no need to examine high-altitude or space-craft photography for lineaments.

The limestones of northern Alabama are similar to those of the present study, in the Highland Rim, whereas the limestones of central Pennsylvania are folded and faulted. Similar results in the Alabama and Pennsylvania studies suggest that rocks need not be flat-lying in order to obtain good correlations between well yields and lineament locations.

The relative importance of other features--that the rocks are dense and fractured, and that solution cavities are mostly of the horizontal, sheetlike form--is impossible to evaluate.

Study procedures, which are described in this report, could be applied to many other geographic areas: SKYLAB S-190B photographs are available for about 70 percent of the continental United States, and S-190A photographs are available for about 90 percent (National Aeronautics and Space Administration, 1975, chap. 11). Some well yield data are available for most areas of the country from state and federal water-resource agencies. Thus, much of the data needed for a study of this type are in the public domain for most parts of the country, and such a study would be feasible.

Most detection methods, as described previously, are relatively simple, requiring little more than a stereoscope, a slide projector, and a small amount of experience at viewing aerial photographs.

These methods thus could be used, for example, by most people already on the staffs of consulting engineering and geology firms. The main problem in mapping lineaments is to enlarge SKYLAB photographs to the scale of maps. In most areas of the country, radial displacements on SKYLAB photographs are minor (because of the spacecraft altitude) and photographic enlargement would be satisfactory.

Results obtained in this study by stereo viewing and by projection viewing seem to be complementary. Lineaments detected by stereo viewing are more commonly associated with large yields in existing wells, but the most favorable well locations are on lineaments detected by both stereo viewing and projection viewing. Also, projection lineaments were detected in many areas where stereo lineaments were not found; projection viewing thus could locate additional favorable locations for future wells. Finally, projection viewing is relatively fast and adds only a little additional time to the detection process. Both methods are recommended for future studies.

The various methods of composite viewing are promising, although they were not completely successful. In future studies, lineaments detected by composite viewing may prove to complement or verify lineaments detected by stereo viewing or projection. If suitable imagery and equipment (one method requires only a stereoscope) are available, composite viewing could be included in future studies on an experimental basis.

The relationship of "geologic grain" to topography, lineaments, fracture traces, and underlying geologic structure also could be considered for investigation in future studies.

The resolution needed to detect lineaments associated with the most favorable ground-water occurrence is difficult to determine. In the study area, better results were obtained for SKYLAB lineaments than for lineaments detected on either Landsat images or high altitude aerial photographs. (Other results are probable in areas with a thicker or thinner soil cover.) Photographs from the multispectral cameras were not studied in the same manner as those

from the earth terrain camera; thus, the slightly lower resolution on S-190A photographs cannot be evaluated directly. Indirectly, wells near lineaments detected by stereo viewing (the only viewing method that utilized the maximum inherent resolution of the film) have somewhat larger yields than wells near projection lineaments. Thus, a tentative conclusion is that the resolution of the S-190B camera is near optimum for detection of lineaments in central Tennessee that are significant with respect to ground-water occurrence.

Cloud cover and haze were a problem in this study and may be a problem in future studies. A cloud cover of 10 to 15 percent of the test site probably is the maximum that could be tolerated for a study of this type. Haze reduces the contrast of scene elements on the ground and thus, effectively reduces resolution. The study area was moved to central Tennessee mainly because of thick haze over the Smoky Mountains test site. In stereo, haze over the Smoky Mountains had a three-dimensional appearance on the photographs. In central Tennessee, haze was a significant problem only around and between clouds in the west central and southeastern parts of the study area.

Narrow-band, B & W photographs from the multispectral cameras were not examined to determine the best single band for lineament detection. Originally, this was a planned phase of study; it was deleted when it became obvious from recent reports that the best band for any purpose is strongly dependent on atmospheric conditions at the time of the photographs or imagery.

It is tentatively concluded by this author that lineaments can be detected easier on color or color infrared photographs than on narrow band, B & W photographs. This is a subjective judgment, however, which was not tested quantitatively.

Another subjective judgment by this author is that lineaments probably can be detected faster and easier on color infrared rather than color photographs, because (1) the filter for color infrared photographs theoretically provides better haze penetration and thus better scene contrast and detail, (2) streams are easier

to see on color infrared photographs (the entire photograph has a bluish-green tone with color film), and many lineaments follow or parallel streams, and (3) some lineaments are formed by vegetation, which has a nearly unique red tone on color infrared photographs, and these lineaments may be enhanced.

Topographic relief generally is not apparent on individual photographs from the SL-2 mission (appendix), because of the high sun angle (54° above horizon) at that time (0910 CST, June 9, 1973). Relief is more obvious on the SL-4 photographs (32° above horizon, 1036 CST, November 30, 1973). The effects of an apparent topographic relief on lineament detection have been discussed previously. If photographs are obtained with stereo overlap during future space missions, sun angle (time of day and time of year) need not be a major consideration for lineament detection. If only single frame coverage is obtained, topographic lineaments will be most obvious on photographs with a low sun angle (20° to 35°).

Lineaments formed by vegetation alignments theoretically should be most obvious at those times of year when vegetation types can be discriminated easily. In central Tennessee, this would be generally in April and October.

For future missions involving lineament detection, consideration also should be given to including high resolution, imaging, thermal infrared and synthetic aperture imaging radar sensors.

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**REPRODUCIBILITY OF THE
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APPENDIX

Drilling Locations and Costs

The more than 90 percent of the wells that are drilled for domestic or stock purposes are almost always located for convenience: near the home or outbuildings. Thus, the great majority of wells are located near an all-weather road on a relatively flat, well-drained site, because this type of site is preferentially selected for buildings. Some well locations still are picked by water witching, but virtually all of these sites also prove to be located conveniently.

Well drillers generally are familiar with the correlation of topographic location and well yield -- wells in valleys and other low areas commonly have larger yields than wells on steep hillsides and atop narrow ridges. If an initial well has a poor (inadequate) yield, the driller almost always suggests moving closer to a topographic low. Well drillers also generally tend to locate second wells as close as possible to older wells with large yields and as far from wells with poor yields as practical (considering property lines and decreasing convenience).

If a detailed study has been made, other factors also can be considered in the selection of well sites. The most favorable well locations in central Tennessee (Moore and others, 1969; Moore and Wilson, 1972) are (1) in areas where the percentage of wells yielding 3.2 l/s (50 gal/min) is larger than average, (2) at sites where the soil is thicker than average, (3) in areas underlain by formations of Mississippian age, (4) on gently rolling land or in a narrow valley or draw, and (5) along the azimuth of a regional joint set from an older well with a large yield.

Costs of drilling are based on the standard well in limestone rock -- 152 or 159 mm (6 or 6 1/4 in) in diameter. For at least the past 30 years, virtually all domestic and stock wells in central Tennessee have been of this size. The costs of a standard hole depend on local supply and demand, which vary both seasonally and annually. Thus, recent costs (1970-75) have ranged from \$14 to

\$20/m (\$3 to \$6/ft). The cost of pipe for casing is extra, but casing installation, a brief period of well development and a brief test of well yield generally are included in the costs of drilling and casing. Rules applied to Tennessee Code Annotated (70-2301 et. seq.) include (1) casing must be set to a minimum depth of 6.1 m (20 ft) below land surface, and (2) new casing weighing approximately 19 kilograms/m (13 lbs/ft) shall be installed. All construction costs are billed because only a few drillers guarantee an adequate water supply.

Costs are much higher for well diameters larger than the standard. Common sizes of municipal and industrial wells in central Tennessee are 203, 254, and 305 mm (8, 10, and 12 in) diameter. Costs may run \$26 to \$66/m (\$8 to \$20/ft) or more, not including casing.



Drilling test well near Tullahoma.



Developing test well south of Murfreesboro.

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Muddy water from chert gravel in test well near Tullahoma.



Clear water from bedrock solution cavity in well near Tullahoma.

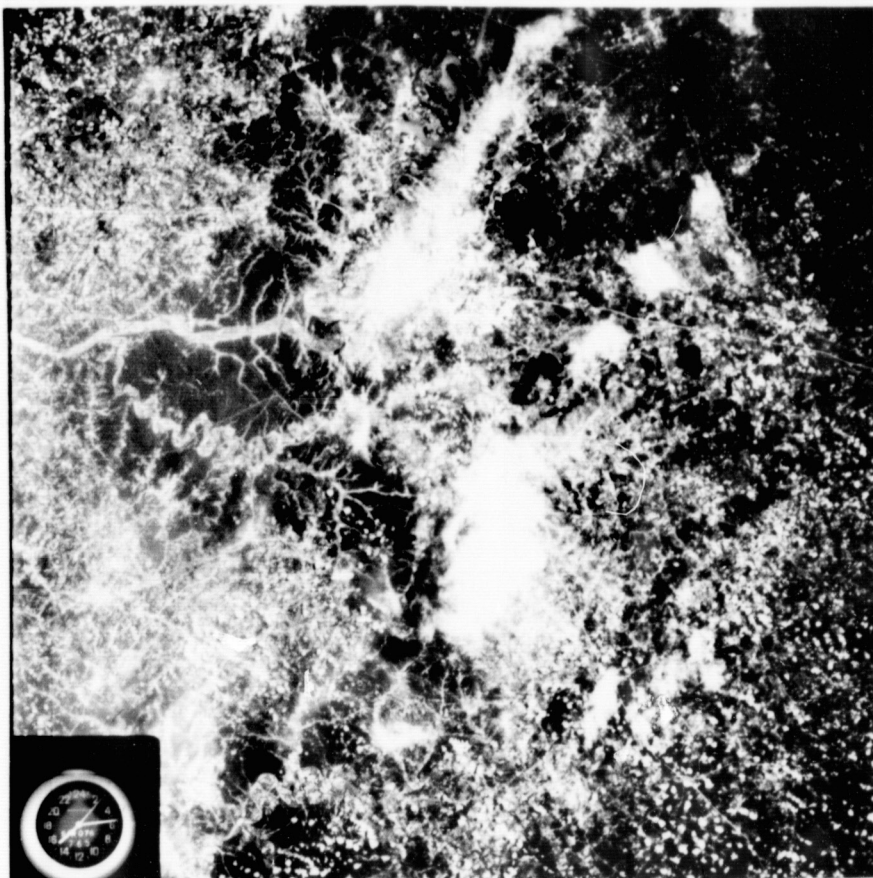
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Test well near Murfreesboro producing more than four times the average (median) yield of water.

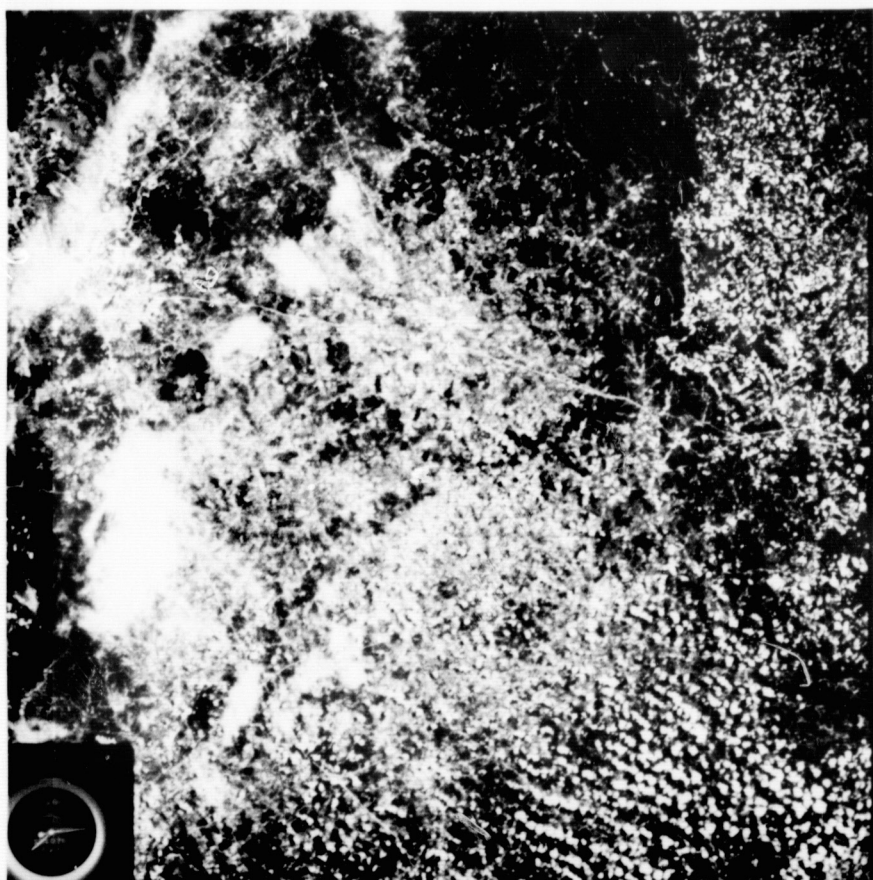


Describing drill cuttings from test well near Fairfield.



NASA SKYLAB
 PHOTOGRAPH: SL - 2,
 ROLL 81, FRAME 199

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NASA SKYLAB
 PHOTOGRAPH: SL - 2,
 ROLL 81, FRAME 200

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NASA SKYLAB
PHOTOGRAPH: SL - 2,
ROLL 81, FRAME 201

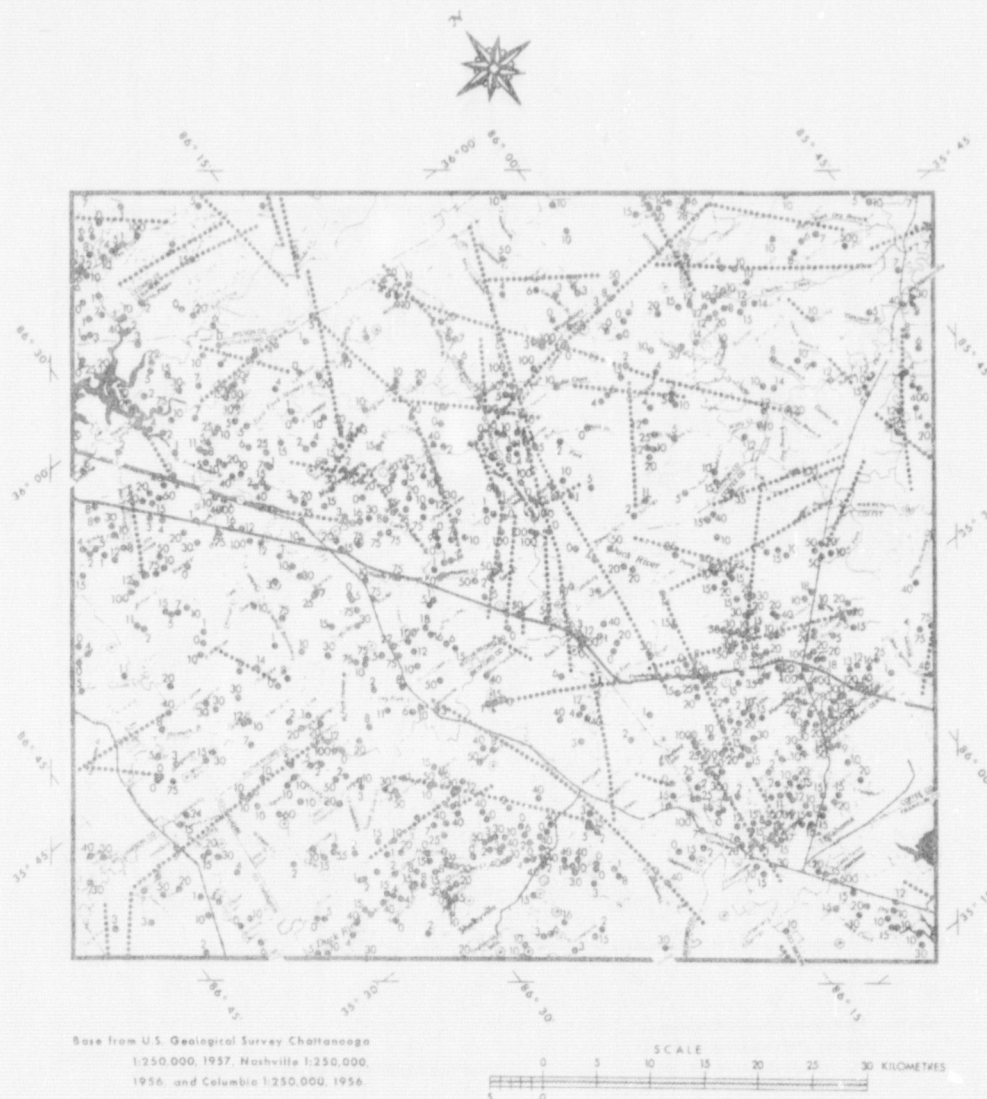


NASA SKYLAB
PHOTOGRAPH: SL - 2,
ROLL 81, FRAME 202



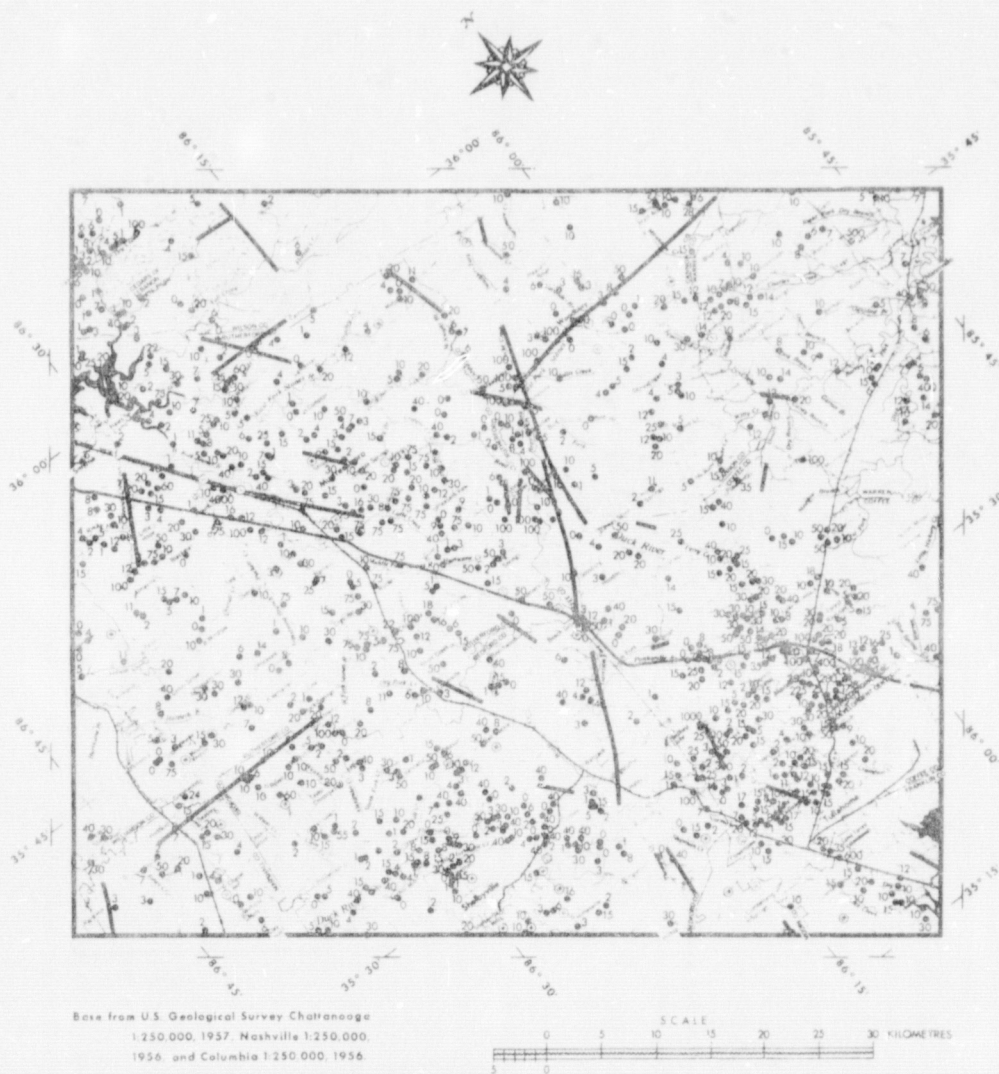
Lineaments detected on SKYLAB photographs by stereo viewing and
locations and yields (in gallons per minute) of water wells.

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Lineaments detected on SKYLAB photographs by projection viewing
and locations and yields (in gallons per minute) of water wells.

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Lineaments detected on SKYLAB photographs both by stereo viewing and projection viewing and locations and yields (in gallons per minute) of wells.

SUMMARY STATEMENT FOR SKYLAB EREP

SUMMARY VOLUME

Title: LINEAMENTS ON SKYLAB PHOTOGRAPHS -- DETECTION, MAPPING, AND
HYDROLOGIC SIGNIFICANCE IN CENTRAL TENNESSEE

Author: Gerald K. Moore

Month and Year: August 1975

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Descriptors: *Remote sensing, *Ground water, *Satellites,
Fractures, Terrain analysis, Structural geology,
Limestones, Joints, Hydrogeology, Aerial photography,
Streamflow, Tennessee, Geophysics, Drill holes,
Water horizons, Aquifer characteristics.

Identifiers: *SKYLAB photographs, *Lineaments, *Well yields,
Fracture traces, Landsat imagery, Solution cavities,
Topographic depressions, Drainage patterns, Vegetation
alignments, Land-use patterns, Central Basin,
Eastern Highland Rim, Beech Grove lineament.

Abstract: Dense, fractured, flat-lying limestone bedrock is overlain by a soil cover that averages 1.2 metres (4 feet) thick in the Central Basin and about 12 metres (40 feet) thick on the Highland Rim. Ground water occurs mostly in solution cavities, and the trends of these cavities are controlled by joints. Most lineaments, which can be detected on SKYLAB photographs also are caused by joints.

Lineaments are composed of short, discontinuous segments. Whether or not these segments can be fused into a lineament by the human eye depends mostly on the resolution, scale, and contrast of the photographs. Most lineaments consist of topographic depressions and follow or parallel the streams. The remainder are formed by vegetation alignments and the straight sides of ridges.

For well yields of 1.6 litres per second (25 gallons per minute) or more, significant savings can be achieved by locating future wells on SKYLAB lineaments rather than by random drilling. The detection method that produces the best results is stereo viewing. Results of test drilling show that the mean yield of wells on SKYLAB lineaments (6.3 litres per second or

100 gallons per minute) is about six times the mean yield of wells (1.1 litres per second or 18 gallons per minute) in other favorable locations.

The resolution of photographs made with the S190B camera probably is near optimum for detection of hydrologically significant lineaments in central Tennessee. Tentatively, it is concluded that the best film for this purpose is color infrared. Little or no cloud cover, and thin or no haze, are requirements for future missions, as is stereo overlap or low-sun-angle photography. Vegetation alinements might be enhanced in April or October photography.

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