CRITERIA AND METHODS FOR FRACTURE-TRACE ANALYSIS OF THE NEW HAMPSHIRE BEDROCK AQUIFER

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CRITERIA AND METHODS FOR FRACTURE-TRACE ANALYSIS OF THE NEW HAMPSHIRE BEDROCK AQUIFER

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Abstract

Ground water in New Hampshire bedrock is found in open fractures. Locating bedrock fractures is one step in locating zones in bedrock that may yield high amounts of ground water. Fracture-trace analysis is the primary technique used to locate steeply-dipping fractures at a regional or local scale. This technique uses established criteria for identifying photolinear features that are likely the result of underlying zones of fractured bedrock. The criteria applied to the photolinear features are based on physical, chemical, and biological processes that produce recognizable patterns on the land surface, such as aligned gaps in ridges, straight stream and valley segments, tonal variations of soils, and anomalous vegetation patterns.

Criteria for fracture-trace analysis were applied to two scales of aerial photography (1:20,000- and 1:80,000-scale), side-looking airborne radar imagery (1:250,000-scale) and Landsat imagery (1:1,000,000-scale). Photolinear features in the different images that met the established criteria were recorded as lineaments. The position and length of lineaments from two independent observers were compared at each scale in an attempt to limit interpretation biases or omissions.

Maps of the lineament data, scheduled to be published between 1996 and 1998, will be produced in digital format and on fourteen plates covering the State of New Hampshire. The maps show lineaments that are likely to be related to vertical or nearly vertical fractures in bedrock and thus may have potential as locations for ground-water development. Field verification of lineament position and additional investigation is prudent before siting ground-water wells.

INTRODUCTION

Surface and ground water are withdrawn in New Hampshire to meet domestic, municipal, and commercial needs. Increasing costs of surface-water treatment have placed increasing demands on ground-water sources. High-yielding sources of ground water in New Hampshire are stratified-drift aquifers composed of sand and gravel, and zones of highly fractured bedrock. The stratified-drift aquifers were assessed in a series of thirteen studies covering all of New Hampshire that are summarized by Medalie and Moore (1995). Demand for ground water from the bedrock aquifer, however, is increasing where stratified-drift aquifers are not present, where the stratified-drift aquifers are unable to meet growing water-supply demands, or where the proximity of stratified-drift aquifers to urban areas have made them unsuitable as a source of drinking water.

As a result, in 1994 the U.S. Geological Survey (USGS) began a statewide bedrock-aquifer assessment, in cooperation with the New Hampshire Department of Environmental Services, Water Division. The purpose of the study, the New Hampshire Bedrock Aquifer Assessment, is to identify zones in the bedrock where there is a greater probability of locating high-yielding wells and to analyze the quality of water from the bedrock. A ground-water-supply fact sheet (Moore and Clark, 1995) provides an overview of all phases of that study. The focus of the current report is on part of the process of identification of potential high-yielding zones in the bedrock.

Purpose and Scope

The purpose of this report is to document the technique used by the USGS in New Hampshire to identify lineaments that are likely the result of underlying zones of fractured bedrock. Geologic and hydrologic background is provided to enable the user to understand the importance of fracture-trace analysis as a tool in prospecting for water. Criteria and methods used to study the New Hampshire bedrock aquifer are described so that others can assess the usefulness of the data. Application of the data, related work, and map products are discussed to enable users to plan efficient use of information.

Terminology

Terms from geology, structural geometry, and remote-sensing interpretation are used interchangeably among people working with the fracture-trace analysis method. The following description of terms outlines usage in this report.

Fracture, a term from geology, refers to a surface along which a break has occurred in bedrock. An ***open fracture*** is a fracture with measurable distance (aperture) between sides of the fracture. A ***fault*** is a fracture along which there is displacement parallel to the fracture surface. Points originally adjacent on either side of the fracture are displaced. If there is no displacement between adjacent points on opposite sides of the fracture, the fracture is called a ***joint***.

Fracture trace, a term from structural geometry, is the line that marks the intersection of a fracture with the surface of the Earth. ***Fracture-trace analysis*** is the search of remotely sensed images for linear features related to open fractures in the bedrock.

Photolinear feature, a term from aerial-photographic interpretation, refers to any linear pattern seen on aerial photographs and other remotely sensed imagery. A ***lineament*** is defined here as a photolinear feature that meets the established criteria for features that are likely the result of underlying zones of fractured bedrock.

HYDROGEOLOGIC SETTING

New Hampshire's landscape is underlain by bedrock, which makes up the crust of the Earth, and by surficial deposits, most of which were left behind by the continental ice sheet during glaciation. Geomorphological patterns in the surface of the landscape are controlled by the distribution of surficial deposits, the distribution of bedrock types, and the resistance to weathering and erosion of geologic materials.

The trend of major bedrock units that form the regional structural pattern in New Hampshire is generally north-northeast. This trend is reflected in the dominant pattern in the geomorphology of the landscape. A second geomorphic pattern was caused by the abrasion of the landscape by the continental ice sheet as it moved from north-northwest to south-southeast. Natural processes of weathering and erosion continue to modify the geomorphic characteristics of the land. These processes act most efficiently on fractured zones in bedrock as they did when glacial ice preferentially removed blocks of bedrock from fractured zones during the Pleistocene.

The bedrock that underlies New Hampshire is composed of metamorphic and plutonic rocks (Lyons and others, 1986). The geologic history of New Hampshire's bedrock materials, their structure, and the tectonic forces and processes that formed them is part of the history of the Appalachian Mountains. Details of this history can be found in Hatcher and others (1989) and Boudette (1990).

Plutonic rocks, locally common in New Hampshire, are composed of interlocking minerals and have little or no primary pore space. Sedimentary rocks and volcanic rocks are the parent materials for many of the metamorphic rocks in New Hampshire. Pre-existing primary porosity of these parent materials has been eliminated by compaction and recrystallization during metamorphism.

Tectonic forces that accompanied metamorphism and mountain building folded and faulted the rocks in New Hampshire. These forces created many fractures, faults, and voids and, at the same time, locally sealed some of these structures (Swanson, 1988). Those tectonic events that fractured bedrock were superimposed on fractures and structures of different ages, as well as rocks of different ages and lithologies.

Despite a complex history of sedimentation and multiple events of deformation, metamorphism, and intrusion, New Hampshire's bedrock can be viewed from a broad hydrologic perspective that is independent of many unique local details of this geologic history. Water moves through, and is stored within, spaces in glacial deposits and in bedrock. The arrangement of sorted, unconsolidated material in glacial deposits creates voids where water can be stored. Interconnection among these pore spaces allows water to move through the material. In the crystalline bedrock of New Hampshire, open fractures form cracks and crevices that provide space where water can be stored or transmitted.

RATIONALE FOR FRACTURE-TRACE ANALYSIS

Fracture-trace analysis focuses on locating open fractures because these geologic structures serve as flowpaths for water in the solid crystalline bedrock of New Hampshire. Fragmentation of rock and the walls of the fracture increase the surface area exposed to passing water, which increases chemical weathering and further weakens bedrock along fractures. Increased mechanical weathering along fractures is caused by surface erosional processes such as flowing water, glacial scour and plucking, and frost wedging, which act more readily on fractured rock in contrast to surrounding solid rock.

The increased weathering, in turn, causes geomorphic changes such as development of linear depressions in topography, which may be expressed as gaps in ridges or straight stream or straight valley segments. Increased weathering and changing moisture conditions along water-bearing fractures creates changes in soil tone and supports biological processes that affect vegetation patterns. Linear patterns of geomorphic features, variation of soil tone, and linear patterns of anomalous vegetation may overlie fractured bedrock.

Fracture-trace analysis has proved useful in locating high-yielding wells, in New Hampshire and elsewhere, because specific geologic processes have acted on zones of fractured bedrock to create linear depressions in the landscape. In other states, in areas underlain by carbonate rocks, the movement of ground water along fracture zones has caused some of the rock to dissolve and overlying materials to collapse, producing discontinuous linear topographic sags (Lattman and Parizek, 1964). In the hard, crystalline, noncarbonate bedrock of New Hampshire, however, this type of collapse caused by the dissolution of minerals seldom occurs. Rather, patterns of linear depressions, similar in geomorphic form to collapse features, were formed because the physical processes of erosion acted most effectively on weakened fracture zones in the bedrock. Erosion by the continental ice sheet during the Pleistocene, following periods of warm climate and deep weathering, was an especially effective erosional force. Entire blocks of fractured bedrock were removed by freezing to the base of the glacier and then being plucked or carried away by the continued movement of the glacier. The effectiveness of the glaciers in removing blocks of bedrock was demonstrated in earlier studies (Moore, and others, 1994, p. 30; Moore and Medalie, 1995, p. 22). These forces of erosion, however, were relatively ineffective on many fractures and faults that were either sealed by subsequent metamorphism or that originally occurred at great depth within the earth and thus were never open fractures. The fracture-trace method focuses on the more easily eroded fractures that are more apt to be open and able to contain and transmit ground water rather than sealed fractures.

FRACTURE-TRACE METHOD: HISTORICAL PERSPECTIVE

Blanchet (1957) described the existence of patterns on aerial photographs, which were related to fractures in the Earth's crust. The criteria and methods for analysis of aerial photographs and for locating "fracture traces" and "lineaments", as described by Lattman (1958) provided the framework for the technique as it is applied today. Aligned topographic features, straight stream segments, gaps in ridges, and vegetation and soil tonal alignment can be used in any combination to indicate the location of "fracture traces" and "lineaments" (Lattman, 1958).

Although many of Lattman's criteria were used in this study, some of the distinctions that Lattman set forth were not applied. Lattman (1958) differentiated between "fracture trace" and "lineament" on the basis of length, origin, and technique used for discovery. According to Lattman, fracture traces are short (less than a mile long), related to local joint patterns and small faults, and are discovered on individual photographs using stereographic techniques. Lineaments are long (greater than a mile long), related to deep seated faulting or shatter zones, and are discovered by naked-eye examination of aerial mosaics (Lattman, 1958). The study described in this paper makes no distinction among lines based on length, origin or method of discovery.

Meiser and Earl (1982) presented a notable summary and review of the fracture trace technique of Lattman. Mabee, Hardcastle, and Wise (1994) summarized the lineament-data-collection technique and described techniques for filtering the data to produce a subset of lineaments that are more likely related to transmissive zones in bedrock.

CRITERIA AND METHODS FOR FRACTURE-TRACE ANALYSIS OF THE NEW HAMPSHIRE BEDROCK AQUIFER

Fracture-trace analysis of the New Hampshire bedrock aquifer is currently (1996) being performed by hydrologists in the New Hampshire -Vermont District of the U.S. Geological Survey (USGS). Criteria and methods used in other fracture-trace studies (Lattman, 1958; Meiser and Earl, 1982; Mabee, Hardcastle, and Wise, 1994; Wise and others, 1985) were adapted and applied to the New Hampshire hydrogeologic setting. Details of this work are described in the following sections.

Criteria

Fracture-trace analysis is the search of remotely sensed images for linear features related to open, high-angle fractures in bedrock. Established criteria make analysis of photolinear features and lineament identification as objective as possible. These established criteria, alone or in combination, identify photolinear features that are lineaments and include:

- aligned topographic features,
- straight stream segments,
- aligned gaps in ridges, and
- vegetation and soil tonal alignment.

The following list qualifies objective criteria and ranks them by assumed order of importance for accurately identifying lineaments:

- straightness of feature;
- precise, sharp, narrowly defined valleys, stream segments, or gaps in ridges;
- features that cut a regional geologic structure;
- soil tonal variation; and
- anomalous vegetation height.

Fracture-trace analysis does not seek to identify all fractures. Geometry dictates that fractures with horizontal orientation will not intersect the Earth's surface if they lie below the depth of greatest erosion in the local topography. Structural geometry also dictates that curved fracture traces will result from low to moderately dipping fractures or folded fractures. Clear, objective criteria for identifying curved fracture traces have not been established. Curved fracture traces are, therefore, not considered as part of this study. The fracture-trace technique restricts the search for lineaments to only steeply dipping or vertical fractures that produce straight-line intersections with the surface of the Earth.

Some geologic processes and geologic structures produce photolinear features that have a low probability of being related to fractures. Photolinear features are likely unrelated to fractures where they are observed parallel to the outcrop pattern of stratigraphic contacts or tilted beds (Lattman, 1958). This study considers straight photolinear features parallel to regional structural trends as lineaments, however, if they meet a number of criteria for lineaments and if these features are well developed.

The continental ice sheet that abraded New Hampshire moved from north-northwest to south-southeast. It is likely the continental ice sheet enhanced topographic relief along fracture traces. Glacial grooves were cut in bedrock but are too short and too shallow to be detected on imagery used for this study.

Map patterns that are the product of human culture can be identified as photolinear features but not as lineaments. For example, photolinear features formed by roads and railways are not indicators of lineament position. Property lines indicated by linear patterns of changing vegetation type and varying vegetation density, and commonly marked by the presence of low stone walls, are also not indicators of lineament position. Clear-cut or selective logging that terminates at linear property boundaries can form photolinear patterns that should not be identified as lineaments. Alignments of tall trees in suburban housing developments are questionable lineament indicators. Tall trees aligned parallel to roads or parallel fences or property boundaries that outline geometric forms are not lineament indicators. Lineaments are not identified using the edges of fields. Incisions in the forest canopy that connect to roads and trails are probably just other roads and trails.

Culture obscures and does not define lineaments; however, fracture traces may coincide with cultural features. If a photolinear feature shows as a continuous straight line from an area exploited by culture through an area not occupied by culture and meets the criteria for a lineament in the area beyond the culture, then the lineament is considered legitimate in the area overprinted by culture.

Forest vegetation may be arranged in patterns that can be incorrectly interpreted as lineaments because linear patterns in vegetation can form where changes in slope steepness or changes in direction of slope occur. These vegetation patterns have been noted in mountainous regions in the Woodstock, North Conway West, and Jackson quadrangles where soil and precipitation patterns affecting growth change with slope and aspect.

The break-in-slope at the base of a hill may appear as a photolinear feature but is an unlikely spot for a fracture trace. The photolinear feature at the intersection of a valley wall and valley floor marks a position controlled by the elevation of the top of the accumulated unconsolidated material in the valley and topographic gradient of the hillslope.

Methods

The methods of fracture-trace analysis includes consideration of (1) what is viewed (the kind of image and scale of image), (2) how it is viewed (magnification, viewing direction, lighting, and stereoviewing or viewing with the unaided eye), and (3) the properties of the features viewed that form criteria for selecting lineaments.

Lineaments can be identified with the unaided eye or with a stereoscope. Both techniques are used to provide every opportunity to discover these features. The photolinear features seen with the unaided eye and photolinear features seen with stereoviewing are the same features produced by the same processes. Lineaments can be observed with the unaided eye because of the contrast in tone in the photographs. Stereoscopic viewing of images, which enables the observer to see the land surface in three-dimensions, is used because this technique allows recognition of subtle relief differences produced by topographic features.

Preparation Before Viewing Images

Before the images are examined for lineaments, other sources of information are considered to help choose photolinear features that meet the criteria for lineaments. Existing geologic and geomorphic data on bedrock geologic maps, topographic maps, and surficial geologic maps are examined.

Bedrock geologic maps are used to identify lithologies present; determine the location of lithologic contacts, folds, and faults; and note the trend of bedding and foliation. The regional trend of the major structural features also is noted. Surficial geologic maps are used to determine the distribution and types of materials present.

The orientation of large valleys and the orientation and location of bodies of surface water are noted on topographic maps. These maps also provide clear locations for cultural features.

Data Sources

Images of the Earth are used to find lineament locations because patterns in vegetation and soils are shown, and relief is shown with greater precision than on topographic maps. Different images created with wavelengths from different parts of the electromagnetic spectrum are available. Remotely sensed data is available from satellite and aerial positions at different elevations above the Earth. Each sensor position (platform) creates an image that covers a different amount of area and presents data at a different scale. As a general rule, the larger the fractional scale, the smaller the area covered by the image, and the greater the detail in features depicted.

Imagery at many scales is needed because fractures occur over a wide range in lengths. Low-altitude aerial photography, enlarged to a scale of 1:20,000, high-altitude aerial photography (1:80,000-scale), side-looking airborne radar (1:250,000-scale), and Landsat imagery (1:1,000,000-scale) are each used in every area to identify lineaments. All imagery was obtained from the USGS Earth Resources Observation Systems (EROS) Data Center in Sioux Falls, South Dakota.

Experience has shown that lineaments identified on images covering large areas are generally not recognizable on images covering small areas. A particular fracture may not display the same features at all scales because the images are at different levels of resolution. Small-scale images cover areas so vast that some lineament criteria simply cannot be seen. Conversely, long, relatively wide, fracture zones may be more deeply weathered or may have discontinuous expression, and may be more apparent on imagery that covers large areas. The amount of weathering, combined with greater thicknesses of glacial outwash and alluvium that cover small areas may, on the large-scale imagery, hide some features that are distinguishing criteria for large lineaments.

Aerial photography

Low-altitude aerial photographs of New Hampshire, obtained as part of the National Aerial Photography Program (NAAP), were taken over the period of 1990-94 during the month of April when foliage was absent from deciduous trees. Standard 9x9-inch aerial photographs with a scale of approximately 1:40,000 flown at about 20,000 feet above land surface were enlarged to 19519-inch matte-finish prints with a scale of about 1:20,000.

Ten of these 19×19 inch photographs are required to provide complete stereoscopic coverage of one 7.5×7.5-minute 1:24,000-scale quadrangle map. The ten photographs covering each quadrangle originally were taken in an arrangement of two columns of five, so that the center point of each photograph is located as shown in figure 1. Locations of the lineaments are recorded on the second and fourth photograph in each column. The first, third, and fifth photographs are used only to provide the overlapping perspective required for stereoscopic viewing (fig. 1).

High-altitude aerial photographs were taken during the late 1970s and early 1980s, during the month of April when foliage was absent from deciduous trees. Three 9×9-inch aerial photographs, with a scale of approximately 1:80,000 flown at an altitude of about 40,000 feet above land surface, provided complete stereoscopic coverage of one 7.5×7.5-minute 1:24,000-scale quadrangle map. The central photograph served as a base for recording lineament locations (fig. 2).

Viewing with the unaided eye allowed selection of long, straight lineaments on the low- and high-altitude photographs. On high-altitude photographs, narrow lineaments were particularly well defined by differences in color, texture, and shading along straight line patterns. However, in these unaided-eye situations, it was difficult to identify the individual geomorphic and botanical elements that serve as lineament criteria without the use of a stereoscope. Natural lighting at moderate angles of incidence was used for viewing these photographs with the unaided eye.

A mirror stereoscope, with × 1.8 magnification, was used to search the low- and high-altitude photography for lineaments. Moderately bright lamps, set at appropriate angles to avoid glare, were used for viewing this aerial photography with the stereoscope. On this imagery, aligned topographic features, straight stream segments, gaps in ridges, and vegetation and soil tonal alignment all contributed to lineament identification.

Lineaments were recorded on mylar overlays attached to the imagery. Three-mil thick mylar, frosted on one side, was used for low- and high-altitude photographs. The mylar was lifted and the photograph viewed through the stereoscope, unobstructed by mylar. The mylar was then repositioned and lineaments were drawn in proper position with respect to features on the photographs.

Side-looking airborne radar imagery

Side-looking airborne radar (SLAR) images were obtained from aircraft flown at an altitude of about 33,000 feet above sea level in May 1984. Strips of radar images were produced as an aircraft flew north or south across the area, and the radar beam was projected to the east or west. The signals were recorded after they were reflected back from the land surface from near and far ranges. These strips have been merged and smoothed (rubber sheeted) into a radar mosaic. Parts of seven 1:250,000-scale mosaic sheets corresponding to the USGS 1×2-degree series of topographic maps cover the state.

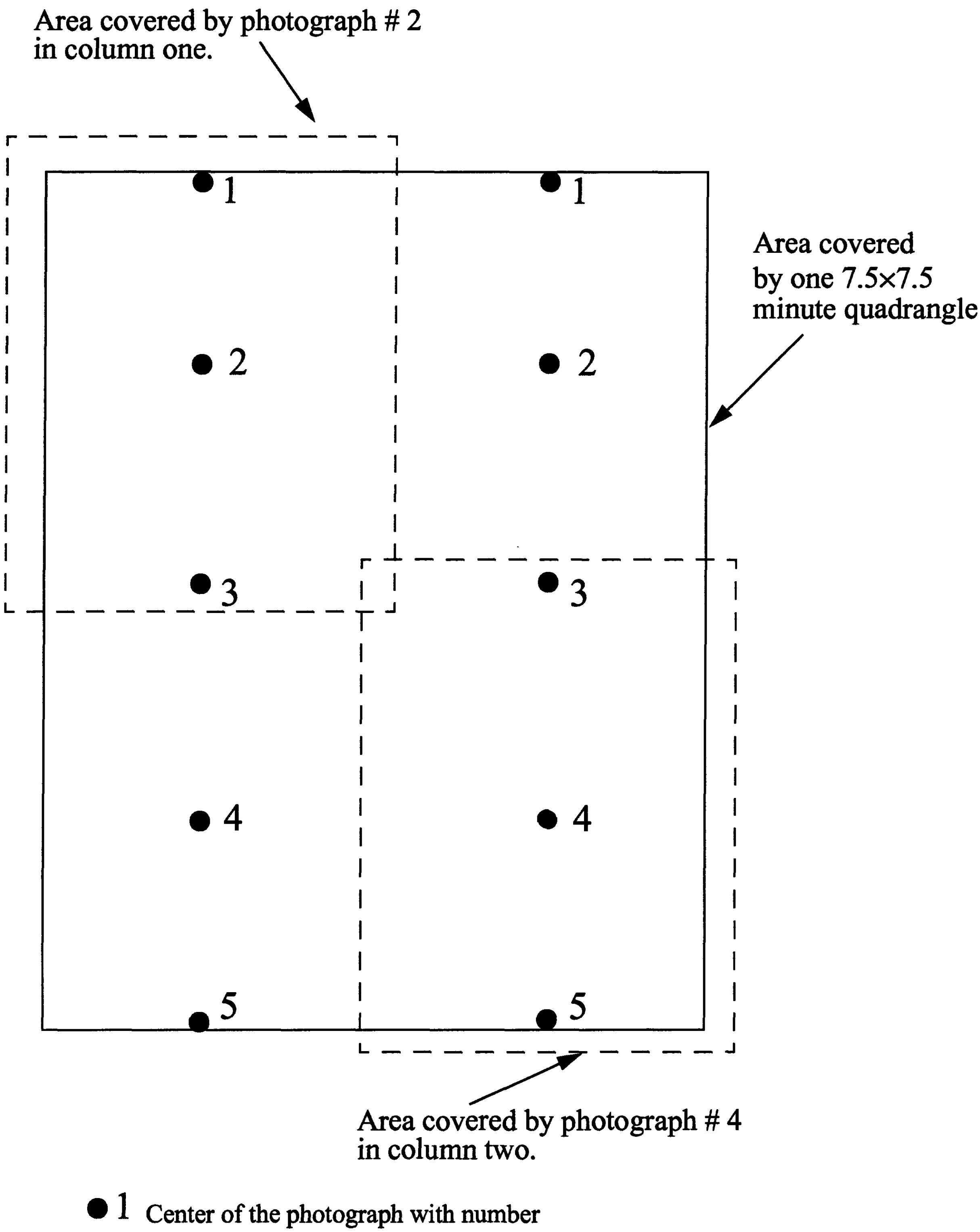

Figure 1. Pattern of 10 aerial photographs, at a scale of 1:20,000, providing stereographic coverage of one 7.5×7.5-minute quadrangle. These photographs are aligned in two columns of five. The lineaments are recorded on photograph number 2 and 4 of each column.

The tone of the images varies from black to white with intermediate shades of gray. These shades correspond to the strength or intensity of the reflected signal. Signal intensity can change from one type of reflector to another or from one surface orientation to another. Far-range airborne-radar-mosaic images were used because they show more contrast in response to the topography than does the near-range imagery. SLAR mosaics were viewed with the unaided eye using transmitted light on a light table. Both positive and negative prints of the SLAR image were used.

Criteria for identifying lineaments on SLAR imagery is different than that used with aerial photography. As with the photography, each observer marks natural linear features such as straight stream segments, aligned gaps in ridges, and other linear patterns of eroded or truncated geomorphic form, but variation in soil tone and vegetation patterns are not used as criteria because of the inability to resolve these details on the imagery.

Landsat imagery

Landsat imagery was obtained from satellites that orbit the Earth at an altitude of about 570 miles. Four Landsat images from cloudless early winter days were used. Images from this period were taken when the Sun's rays were at low enough angles to cast shadows and make the topography more apparent. The imagery used was created using Landsat Thematic Mapper, band 7, with a wavelength of 2.1–2.5 micro-meters, which captures electromagnetic radiation that enhances topographic and geomorphic form. Landsat images were viewed with the unaided eye using transmitted light on a light table.

Criteria for identifying Landsat lineaments were similar to those for the SLAR imagery. Each observer marked natural linear features; straight stream segments, aligned gaps in ridges, and other linear patterns of eroded or truncated geomorphic form. Variations in soil tone and vegetation patterns were not used as criteria with this imagery because of the inability to resolve these details.

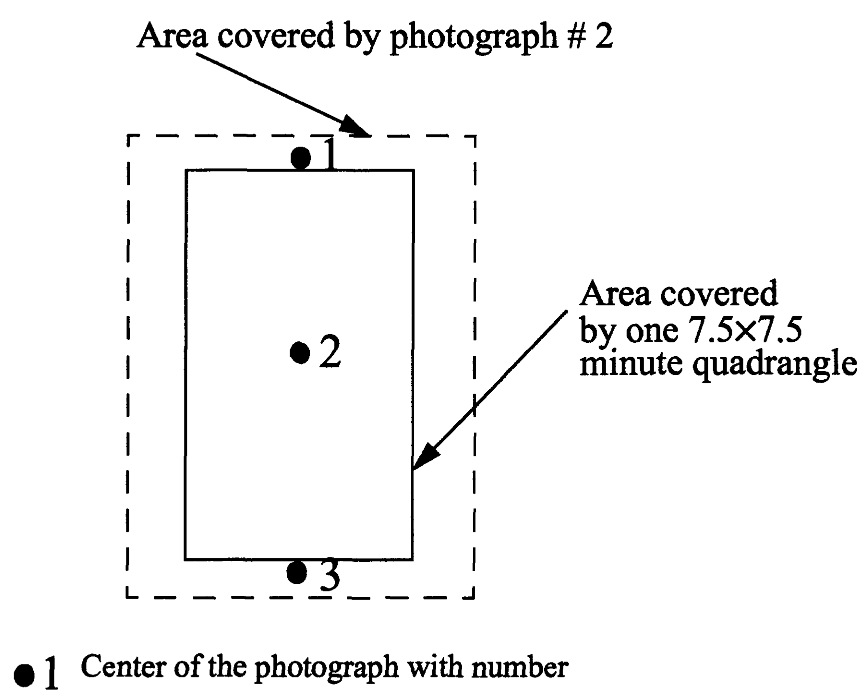

Figure 2. Pattern of three aerial photographs, at a scale of 1:80,000, providing stereographic coverage of one 7.5×7.5-minute quadrangle. These photographs are aligned in one column of three. The lineaments are recorded on photograph number 2.

Comparison of Lineaments

Selecting photolinear features that are likely caused by open fractures in bedrock has a subjective component in spite of the use of objective criteria. The position and length of recorded lineaments from two observers are compared at each scale in this study to reduce the subjective factor in choice of lineament and to limit errors of omission or interpretation.

Each observer has a chance to review the lines that the other observer identified. Two levels of agreement are possible. "Blind" agreement refers to lines that each observer has independently identified. "Confirmed" agreement refers to lines identified by only one observer but accepted by a second observer after reviewing these features and reconsidering the supporting criteria. In this way some of the lineaments overlooked by one observer are systematically brought to the attention and consideration of the other observer.

Analysis of lineament data plotted on plates one and two (fig. 3) shows 24.0 percent of the total number of lineaments accepted are in blind agreement. Looking from another perspective, 27.2 percent of the total length of lineaments accepted is in blind agreement.

Other studies (Mabee and others, 1994, and Wise and others, 1985) have also recommended the use of more than one observer to reduce the subjectivity of the identified lineaments, and to improve the correlation between identified lineaments and the location of high-producing wells. In their studies, as with the study described here, lines were retained if they were identified independently by different observers.

Plate Compilation

Plate compilation, in this study, is a process in which lineaments from all scales of imagery are recorded and stored in digital format, then plotted at one scale on the base map. Compilation of lineaments requires more than simple straight line enlargement or reduction because the scale of aerial photographs varies outward from a central point, whereas the base maps are not distorted. Radar images also appear non-uniformly distorted when enlarged to 1:24,000-scale.

Lineaments from aerial photographs at scales of 1:20,000 and 1:80,000 were repositioned by a zoom-transfer process that places the lineaments on 7.557.5-minute, 1:24,000- or 1:25,000-scale, orthophoto quadrangles. In this process, the photo image is matched to the orthophoto quadrangle image in small, local areas by aligning natural and (or) cultural features. Lineament data were then replotted on the orthophoto quadrangle.Next, the data were digitized from the orthophoto quadrangle and reduced to plot on 1:48,000-scale plates for statewide coverage.

SLAR images published by the USGS are mosaic images that have been reformatted to fit 1:250,000-scale topographic base maps. Lineaments from SLAR (1:250,000-scale) images were not transferred directly into the digital data base because positioning these lines from the SLAR base creates an unacceptable error when positioned at the 1:24,000-scale. A template-transfer process that removes some of the error in positioning lineaments was used to place lineaments generated from radar data onto an accurate base. In this process, templates were produced for each of the 1:250,000-scale quadrangles of SLAR imagery. This was done by plotting 1:24,000-scale digital line graphs (DLGs) of water bodies at the 1:250,000-scale on clear mylar. Small, local areas on the SLAR imagery were lined up with the template by aligning water bodies. Lineaments within the areas of aligned water bodies were then transferred to the template. All data were transferred by realigning and repeating this process for every part of the image. Lineaments were then digitized using the more accurate base of the template.

Landsat data are accurately located and can be digitized directly from mylar overlays. A template with water bodies and quadrangle boundaries was used to establish reference points of known latitude and longitude. Corners of the 7.557.5-minute quadrangles within each plate area were used as points of reference for digitizing.

APPLICATION OF THE DATA

A number of assumptions and generalizations were made while performing fracture-trace analysis of the New Hampshire bedrock. Even though these assumptions do not affect the criteria or application of criteria for lineament selection, they are presented here for consideration and may have an effect on how to apply this data.

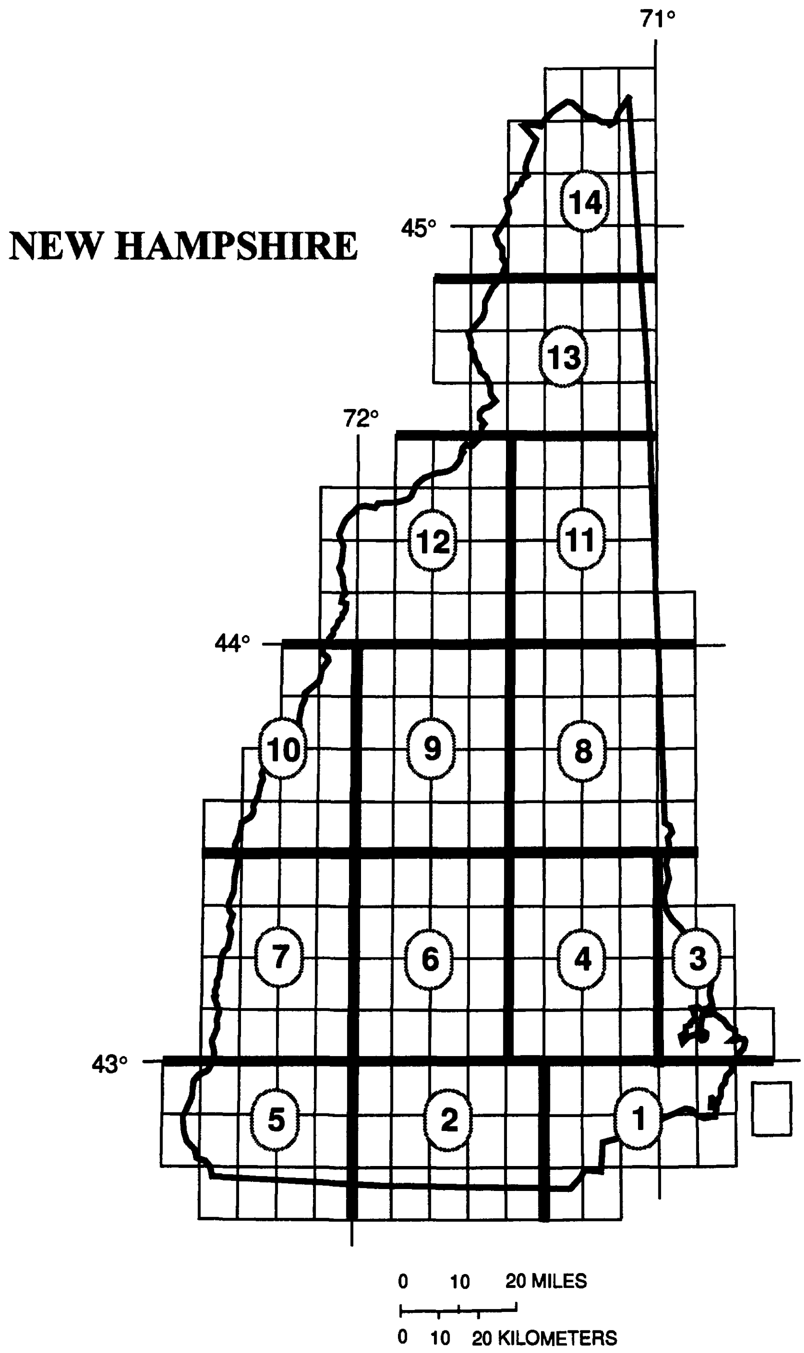

Figure 3. Distribution of plate areas and 7.5X7.5-minute quadrangles for the New Hampshire Bedrock Aquifer Assessment.

Lineaments shown on the plates, which are being produced as separate USGS Open-File Reports, are photolinear features that meet the criteria for possible fracture traces. Lines shown have been confirmed by two independent observers from each scale of imagery. Every effort was made to apply criteria and assumptions in a uniform manner during a thorough examination of each region. The observers have identified the majority of features that meet the criteria for lineaments; however, there probably are additional lineaments that have not been identified.

Straight lineaments are selected in this study. Only steeply dipping, planar fractures produce straight fracture traces. Horizontal fractures, low and moderately dipping fractures, and folded fractures, which produce curved fracture traces, are not shown on the maps.

The relief along a fracture trace is not a measure of the ability of the fracture to produce water. A fracture zone that crosses a quartzite may show less relief difference than where the same zone crosses a schist or phyllite. Geologic interpretation regarding fracture or fault origin or hydrologic significance can not be made from image appearance alone.

Long, straight-line, natural photolinear features may have a greater probability of being fracture related because they cross a varied terrain. Photolinear features found in just one setting may be produced by a structure or process related to that setting. If a photolinear feature crosses more than one setting, it is more likely related to a structure that cuts through bedrock such as a fracture zone.

If these data are used as a guide in prospecting for ground water in bedrock, the field area should be examined before selecting drilling locations. Field checking the accuracy of location of the lineaments is necessary and will help determine whether the lineament feature results from natural or cultural origin. If fracture traces are locally underlain by zones of fracture concentration the fracture trace may represent a zone of some width rather than a sharp line.

Geologic techniques, such as domain overlap analysis (Mabee and others, 1994), can be used to determine which lineaments in an area are more likely to be possible locations for high yielding bedrock wells. In this method, the orientation of vertical and near vertical fractures is measured at outcrops within the region of interest. Those lineaments with orientations similar to the orientations of fractures in outcrops are considered most likely as marking true fracture traces. Geophysical techniques such as very-low-frequency (VLF) terrain resistivity, azimuthal seismic refraction, and square-array direct-current resistivity may be used to more accurately locate the fractures.

Lineament data are provided only as a starting point for exploration of ground-water resources in bedrock. Statistical tests are presently (1996) being performed by the USGS to determine which sets of lineament orientations and which platforms are the best predictors of high-yielding wells.

RELATED WORK

As part of the New Hampshire Bedrock Aquifer Assessment, fracture-trace data obtained from the aerial and satellite imagery and field observations are planned to be compared with data on water yields for more than 18,000 bedrock wells in the New Hampshire Department of Environmental Services well data base. From this comparison, statistical relationships are planned to be developed between yields of the bedrock wells, in gallons per minute, and such factors as the proximity of the fracture traces on the land surface to the wells, the orientation of the nearest fracture trace, the bedrock type, the type of sediment overburden, the physiography of the area, and the type of well construction.

A fracture-pattern survey is planned to be done for part of the State. In this survey, fractures will be observed in detail and the orientation, aperture, and roughness of the fractures will be measured at bedrock outcrops. The results of the planned survey will enable the USGS to filter the lineament data and select the sets of lineaments most likely related to bedrock fracture.

Observations of fracture zones by geophysical techniques are planned to be used at some of the highest yielding bedrock-well sites in the State. These proposed analyses will identify and demonstrate tools and procedures for identifying high-yield zones in bedrock.

MAP PRODUCTS

The State of New Hampshire covers parts or all of 213, 7.5X7.5-minute quadrangles, which have been divided into 14 plate areas (fig. 3). The base maps for the plates have a scale of 1:48,000. The base maps are made by reducing the size and adjusting the scale of the

7.5X7.5-minute (1:24,000 and 1:25,000 scale) topographic quadrangles for the entire state. Maps are compiled and produced using a computerized Geographic Information System (GIS), which provides data (maps and lineaments) in digital format.

The New Hampshire Bedrock Aquifer Assessment is divided into two phases. Each planned phase will include a series of maps for each plate area, at a scale of 1:48,000. The first planned phase includes a series of maps showing all lineament data, and a statewide digital coverage containing all lineaments shown on the maps. Attributes associated with each lineament in the digital coverage include the length of each lineament, the platform from which the lineament was observed, and the method by which the lineament was confirmed by a second observer. The second planned phase of the assessment would result in a series of maps that include interpretation and depiction of areas with high yield potential and areas with potential water-quality problems. Lineaments, zones of favorability for ground-water production, and the location and productivity of bedrock wells will be shown. The second map series would be accompanied by an interpretive report.

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