Photographs on the cover show on the left, a color infrared air photograph of the western shore of Great Bay, N.H., used in identifying lineaments. The photograph on the right shows an outcrop of rock with fractures in the Kittery Formation; pencil and boot are for scale.

U.S. Department of the Interior
U.S. Geological Survey

In Cooperation with the
University of New Hampshire, Cooperative Institute for Coastal and Estuarine
Environmental Technology, and U.S. Environmental Protection Agency

Fracture-Correlated Lineaments at Great Bay, Southeastern New Hampshire

By James R. Degnan and Stewart F. Clark, Jr.

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PLATE

[Plate is in pocket]

TABLE

CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain length
centimeter (cm)	0.394	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.621	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
liter per minute (L/min)	0.2642	gallons per minute (gal/min)

Sea Level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

ABBREVIATIONS AND EXPLANATIONS OF TERMS USED IN THIS REPORT

°	degree

Fracture-Correlated Lineaments at Great Bay, Southeastern New Hampshire

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Abstract

Analysis by remote-sensing techniques and observations of exposed bedrock structure were preliminary steps taken in a study to locate potential bedrock-fracture zones that may store and transmit ground water near Great Bay, N.H. To help correlate lineaments on the surface with fractures, structural measurements were made at exposed bedrock, largely along the shoreline of the bay, and analyzed to identify fracture trends and fracture characteristics. With these fracture data, lineament-filtering techniques, such as (1) buffer analysis around individual lineaments, (2) discrete-measurement analysis by domain, and (3) spacing-normalized analysis by domain, identified "fracture-correlated lineaments." Of the 927 lineaments identified in the study area (180 square kilometers), 406 (44 percent) were evaluated because they either were located within 305 meters of an outcrop with fracture data or intersected one of five 3,300-meter-square grid domain cells that encompassed the fracture data. Of the 406 lineaments, 190 (47 percent) are fracture correlated, although only 15 percent were correlated by more than one filtering technique.

The large number of lineaments found in areas of thin glacial overburden and high densities of fractured outcrops suggests that filtering techniques are useful in these areas to selectively identify fracture-correlated lineaments. Fractures parallel to bedding in the Kittery Formation are open locally and often associated with vugs, with up to 1-centimeter aperture, and may provide appreciable secondary porosity in this rock unit. Discrete-measurement analysis by domain identified fracture-correlated lineaments with orientations parallel to these open and vug-filled fractures. Fracture-correlated lineaments related to closely spaced fractures were identified by the spacing-normalized analysis by domain. Analysis results may be used to indicate the potential bedrock pathways for ground-water-discharge points along the shoreline of Great Bay.

INTRODUCTION

Great Bay is an estuary in southeastern New Hampshire (fig. 1, plate 1) in the 1:24,000-scale Dover West, Dover East, Newmarket, and Portsmouth, 7.5-minute quadrangles. The U.S. Geological Survey (USGS), in cooperation with the Civil Engineering Department at the University of New Hampshire, the Cooperative Institute for Coastal and Estuarine Environmental Technology, and the U.S. Environmental Protection Agency, is assessing ground-water flow to Great Bay. A better understanding of the ground-water-flow system is necessary to identify and locate potential sources of nutrient loading to the bay by ground-water discharge. Identification of fracture-correlated lineaments may indicate bedrock-fracture zones that could serve as ground-water-flow paths and potential points of discharge to the bay. Certain types of fracture-correlated lineaments have been correlated with high bedrock well yields in fractured-bedrock aquifers (Moore and others, in press).

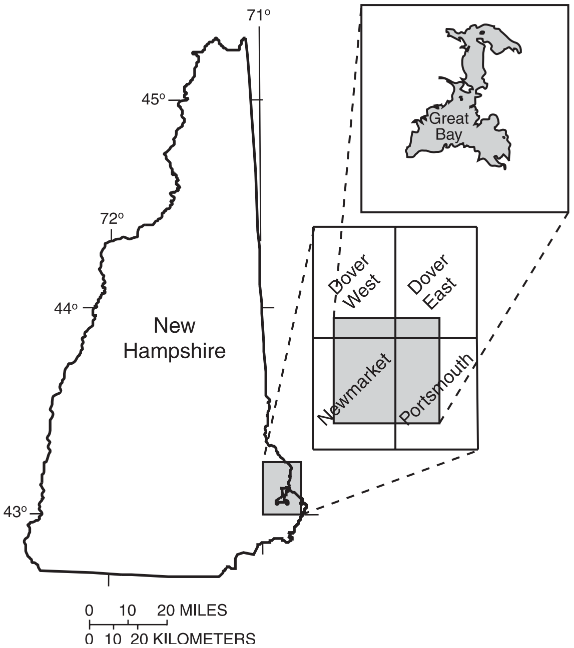


Figure 1. Location of the lineament and outcrop study area in the Dover West, Dover East, Newmarket, and Portsmouth 1:24,000-scale quadrangles in southeastern New Hampshire.

Purpose and Scope

This report describes the results of a lineament study and outcrop-fracture investigation of the bedrock along the shore of Great Bay and adjacent areas. Lineament-identification techniques used in the study are well documented by Brown (1961), Clark and others (1996), and Lattman (1958). Additional references on this topic are included at the end of this report. Lineament and fracture data are correlated to indicate potential discrete zones of fracturing in the bedrock (referred to as fracture zones in this report), which may serve as ground-water-flow paths. Ground-water flow in bedrock fractures may be more readily identified where permeable surficial aquifers are thin or absent, such as the western shore of Great Bay. The extent of the study area is the perimeter of Great Bay and the immediately adjacent areas.

Previous Studies

Previous studies identifying fracture-correlated lineaments in the northeastern U.S. include those by Walsh (2000), Moore and others (in press), and Mabee and others (1994). Walsh found that 24 percent of lineaments near outcrops correlate with brittle structures including joints, fracture zones, and faults in Windham, N.H. Moore and others (in press) statistically identified specific types of fracture-correlated lineaments that were related to high-yielding bedrock wells in the Pinardville and Windham quadrangles, New Hampshire. Mabee and others (1994) identified 3 percent of lineaments as fracture correlated in a similar setting on Georgetown Island, Maine, and noted that nearby bedrock wells generally had high transmissivities.

Geologic Setting

Physiographic settings in the study area range from marshlands to hills. Over the region, elevations range from 0 to 85 m. Bedrock is exposed at numerous locations along the west shore of Great Bay between the mouth of the Oyster and Lamprey Rivers and along the east shore of Furber Strait from the headlands near Welsh Cove to Woodman Point (plate 1). The south shoreline, from Weeks Point westward for 2 km, also has a considerable number of bedrock outcrops (plate 1).

Crystalline metamorphic and igneous bedrock geology in the study area is shown on plate 1. The bedrock outcrops on the west side of the bay are primarily the Silurian-Ordovician Kittery Formation. The Silurian-Ordovician Eliot Formation crops out along the east and south side of the bay. The contact between the two metasedimentary formations is mapped through the bay from the mouth of the Squamscott River in the southwestern corner, across Fox Point and the west edge of Hen Island in the northeastern corner of the bay (Novotny, 1968, Lyons and others, 1997). Devonian Exeter Diorite is exposed in a few outcrops along the west shore of the bay, and is the dominant rock type inland from the shoreline. The contact between the Exeter Diorite and the Kittery Formation is approximately parallel to the shoreline on the west side of the bay (Novotny, 1968).

Unconsolidated glacial, glaciofluvial, and marine sediments generally cover bedrock in the study area. Most of the west side of the bay is covered by unsorted to poorly sorted glacial till (Delcore and Koteff, 1989) that generally ranges in thickness from 0 to 5 m (Bradley, 1964). Stratified sand and gravel overlies bedrock or till on the east side of the bay.

The extent or distribution of till beneath the stratified sand and gravel is not known. The thickness of stratified drift inland to the east side of the bay ranges from 0 to 18 m (Stekl and Flanagan, 1992).

Acknowledgments

The authors thank Gregory Walsh and Richard Bridge Moore, U.S. Geological Survey, for providing thorough and constructive colleague reviews of the report. Their reviews improved the conclusions on the nature and occurrence of fracture-correlated lineaments and helped create a more useful, and legible map. Appreciation is expressed to the cooperators from the University of New Hampshire's Civil Engineering Department for providing logistical support for the data collection.

METHODS

Remotely sensed lineaments seen on the surface of the Earth on various scales of high- and low-altitude air photographs and satellite imagery potentially are related to structural features in bedrock and high-yielding bedrock (Mabee and others, 1994; Moore and others, 1998). This report describes how analysis of fracture measurements, in conjunction with buffer analysis and domain analysis, were used to identify fracture-correlated lineaments.

Fracture Measurements

Fracture data were collected using mapping techniques described by Walsh and Clark (2000). Isolated fractures and fracture sets were selected by inspecting each outcrop in a process that is referred to as "subjective" by Spencer and Kozak (1976). A representative sample of measurements covering the range of fracture orientations was recorded. Orientations (strike and dip) of (1) isolated fractures, and (2) fracture sets (regularly spaced, parallel fracture planes) were measured and values recorded using the "right-hand rule." The orientation measured when looking down-strike, with the down-dip direction to the right, is the "right-hand-rule." One representative orientation was measured for each fracture set at an outcrop. Fracture spacing, the perpendicular distance between parallel and subparallel joints (Segall and Pollard, 1983), was measured for all fracture sets. Thirty-five fractures were noted to be open or vug filled.

Bedrock outcrops around the perimeter of the bay were located and plotted on 1:24,000-scale topographic maps. Bedrock-fracture data were measured from Newington Station, near the Piscataqua River along the shore of Great Bay, to Durham Point on the Oyster River (plate 1). Forty-four percent of the bedrock outcrops identified along the shoreline were examined. Over the study area, 287 fracture orientations, and other bedrock characteristics (bedding, and foliation), were measured at 49 separate outcrops. Two hundred and one of the orientations represented fracture sets with a spacing of 2 m or less, 86 of the measurements were individual fractures. Inland mapping along roads and traverses of fields and woodlands were made at 5 additional bedrock outcrops and provided 25 fracture measurements.

Lineament Identification

Coincident and confirmed lineaments identified by Ferguson and others (1997), from independent stereo observations of high- and low-altitude black-and-white air photographs, side-looking airborne radar, and satellite-imagery platforms, were included in the lineament analysis. Criteria used to define the lineament data set is published in Clark and others (1996) and includes straight-line patterns on the land surface formed from gaps in ridges, streams, valleys, tonal variations in soil, and anomalous vegetation patterns.

Additional lineaments from three independent stereo observations of 1:58,000-scale color-infrared (CIR), 1:20,000-scale low-altitude, and 1:80,000-scale high-altitude black-and-white stereo photographs were added by this study. The criteria for the CIR lineaments, in addition to published criteria, included swales and tonal differences on the bay floor that were visible beneath the water surface in shallow water (less than 5 m deep). The previously published, and newly acquired lineaments form the data set from which fracture-correlated lineaments were extracted.

Fracture-Correlation Techniques

Three types of analysis that allow for fracture correlation by orientation were used to analyze lineament and fracture data. The buffer analysis correlates fractures observed in bedrock outcrops with individual lineaments (Walsh, 2000). Domain analysis, including discrete-measurement and spacing-normalized analyses presented in this section, identifies statistical fracture trends in a given region, or domain (Burton and others, 2000) and correlates lineaments if they match the statistical trends (Moore and others, in press). Fractures with dips of 45° or greater were selected for the analysis because straight-line lineaments are assumed to be formed by steeply dipping features.

Buffer Analysis

The buffer analysis (Walsh, 2000) is a technique by which a lineament is fracture correlated if fractures in bedrock outcrops have strikes similar to the trend of an individual lineament within a specified "buffer" zone, 305 m around each lineament. Those lineaments whose buffers contain at least one steeply dipping fracture (greater than 45°) and have a trend within ± 5° of the strike of the fracture (Mabee and others, 1994) are classified as fracture correlated. Lineaments in plutons, observed from color infrared, high-altitude black-and-white air photography, and Landsat platforms that are fracture correlated by the buffer analysis, have been correlated with high well yields greater than or equal to 151 L/min (40 gal/min) in fractured-bedrock aquifers (Moore and others, in press). Lineaments correlated with fractures by the buffer analysis have a closer spatial correlation to fractures in outcrops than those selected by domain analysis. The number of mapped outcrops, and their distance to lineaments, can limit the effectiveness of buffer analysis because a lineament needs to be within 305 m of an outcrop to be included in the analysis.

Domain Analysis

The Great Bay area was divided into five regions, or domain cells, of equal size. These domain cells are square regions (3,300 m on a side) drawn in such a way as to contain a nearly equal distribution of outcrops (fig. 2). Two techniques of domain analysis were used. Discrete-measurement analysis gives an equal weight to each fracture orientation at an outcrop. The second technique, spacing-normalized analysis, multiplies a fracture-set observation by a spacing factor, if an outcrop has regularly spaced parallel fractures. This technique gives fracture-set orientation more representation in the analysis.

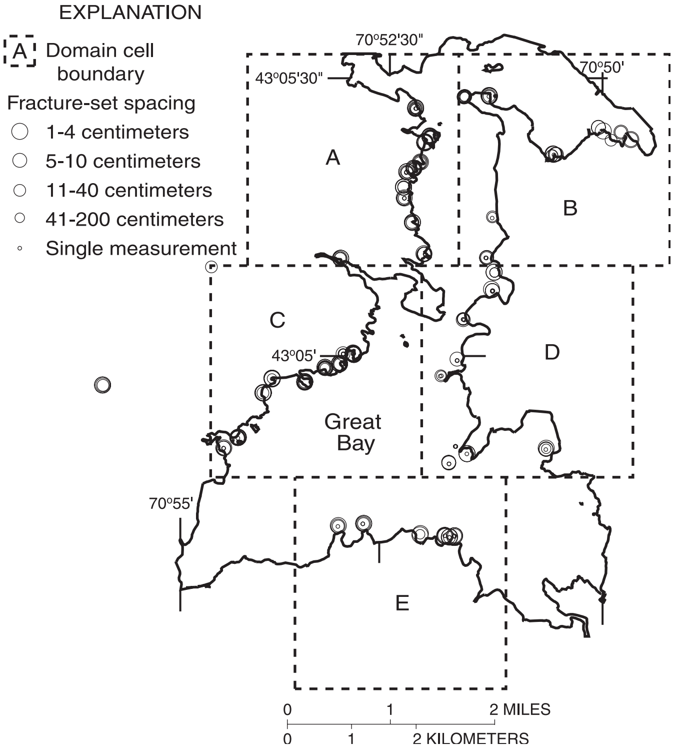


Figure 2. Location of domain cells and the distribution of fracture-set spacing in relation to the shoreline of Great Bay, N.H.

Both techniques described in the previous paragraph are based on the statistical identification of fracture families. Fracture families (principal trends of fractures) were defined for each domain by plotting normalized azimuth-frequency (rose) diagrams using software (DAISY) by Salvini (2000). A Gaussian curve-fitting routine is used in DAISY for determining peaks in directional data (Salvini and others, 1999) that first was described for lineament analysis by Wise and others (1985). Peaks and the standard deviation for each peak were calculated with DAISY. Peaks with normalized heights greater than 50 percent of the highest peak were considered in this study to be principal trends (Walsh and Clark, 2000). Lineaments in the domain are classified as fracture correlated by domain analysis if their trend is within one standard deviation of a family peak trend (Moore and others, in press).

Discrete-Measurement Analysis

In discrete-measurement analysis, fracture orientations are weighted equally without considering fracture spacing, or number of fractures at an outcrop. Each fracture orientation measured at any given outcrop is represented as one observation in the analysis. Fractures that are not part of a fracture set are weighted equally in the discrete-measurement analysis. If a given fracture orientation is observed throughout the domain cell, it may contribute to the development of a fracture family because it is observed at numerous outcrops.

Spacing-Normalized Analysis

Closely spaced fractures potentially may provide a greater number of flow paths for water per unit cross-sectional area of a bedrock aquifer than more widely spaced fractures (Mabee and Hardcastle, 1997). A single measurement of fracture orientation can underrepresent a closely spaced fracture set when plotting rose diagrams that summarize fracture orientations observed in a given region, because a fracture-set orientation represents many fractures. The occurrence of regular and closely spaced fracture sets throughout all five domains (A-E) provides justification for the number of fractures counted using the spacing-normalized analysis (fig. 2).

Spacing-normalized analysis requires a unit cross-sectional length, which is equal to the largest spacing observed among all fracture sets. The unit cross-sectional length divided by the fracture spacing determines fracture frequency. To normalize the number of fractures for spacing, the number of fracture orientations analyzed with DAISY for a given region was multiplied by the calculated fracture frequency. For example, the greatest spacing observed in any fracture set was 2 m. One representative measurement was used for this orientation in the data analysis. In contrast, a fracture measurement from a set with a 20-cm spacing would have 10 orientations included in the spacing-normalized technique.

BEDROCK AND FRACTURES

The Kittery Formation, where exposed along the bay, consists of metasandstone with 0.05- to 0.20-m-thick beds. The Eliot Formation, where exposed along the bay, is composed of gray to green interbedded phyllite and fine-grained sandy, calcareous phyllite in 0.01- to 0.02-m, thinly laminated beds. The Exeter Diorite includes diorite and gabbro, with some granodiorite and granite that is light-gray to black in color, and fine- to coarse-grained in texture (Novotny, 1968; Lyons and others, 1997). Mesozioc diabase dikes are seen in outcrops along the shore of the bay and ranged from 0.2 to 30 m thick, trending primarily northeast.

The bedding in the Kittery Formation has a peak trend of 106° (fig. 3a). The bedding and dominant foliation trend of the Eliot Formation is 26° (fig. 3b). A regional overturned anticline is mapped near the contact between the Kittery and Eliot Formations, near the middle of the bay (Lyons and others, 1997).

The metasedimentary Kittery and Eliot Formations are part of a green schist regional facies with chlorite and biotite phases. Metamorphism occurred between the Devonian and Permian (Lyons and others, 1997). The youngest deformational event, possibly the sixth, is evident as north-south trending fractures in the Exeter Diorite and the Kittery Formation (Fargo and Bothner, 1995). This trend is reflected in the maximum peak trend in all of the fracture data (fig. 4a), the Exeter Diorite and Kittery Formation (figs. 4b, c) respectively, and the peak trend of the smallest fracture spacing measured (fig. 5a).

The Exeter Diorite fracture family has a maximum fracture-family-peak trend of 6° (fig. 4b). The Eliot Formation's largest fracture family trends 144° (fig. 4d). Diabase dikes and sills and parallel fracture sets strike northeast in three peak trends—29°, 51°, and 71° (fig. 4e).

Outcrops of Kittery and Eliot Formations have approximately six fracture orientations in each outcrop, most having little apparent aperture. Four to seven fracture sets, each with uniform fracture spacing and orientation, are common in most outcrops along with up to eight isolated fractures with different orientations. Locally, intersecting fractures produce shattered cliff faces and small talus piles, which are found for example at the outcrops at the mouth of Crommet Creek. Diabase dikes and sills have northeast strikes, with parallel, nearly vertical fractures (fig. 4e).

In the Kittery Formation, the two largest fracture families trend 89° and 171° (fig. 4c). The 89° trend correlates with a peak of the open and vug-filled fractures (86°) (fig. 4f). Bed-parallel fracturing in the Kittery Formation locally (such as at the hinges of outcrop-scale folds) is silicified, vuggy, or open, with apertures as great as 1 cm in width (figs. 3a, 4f).

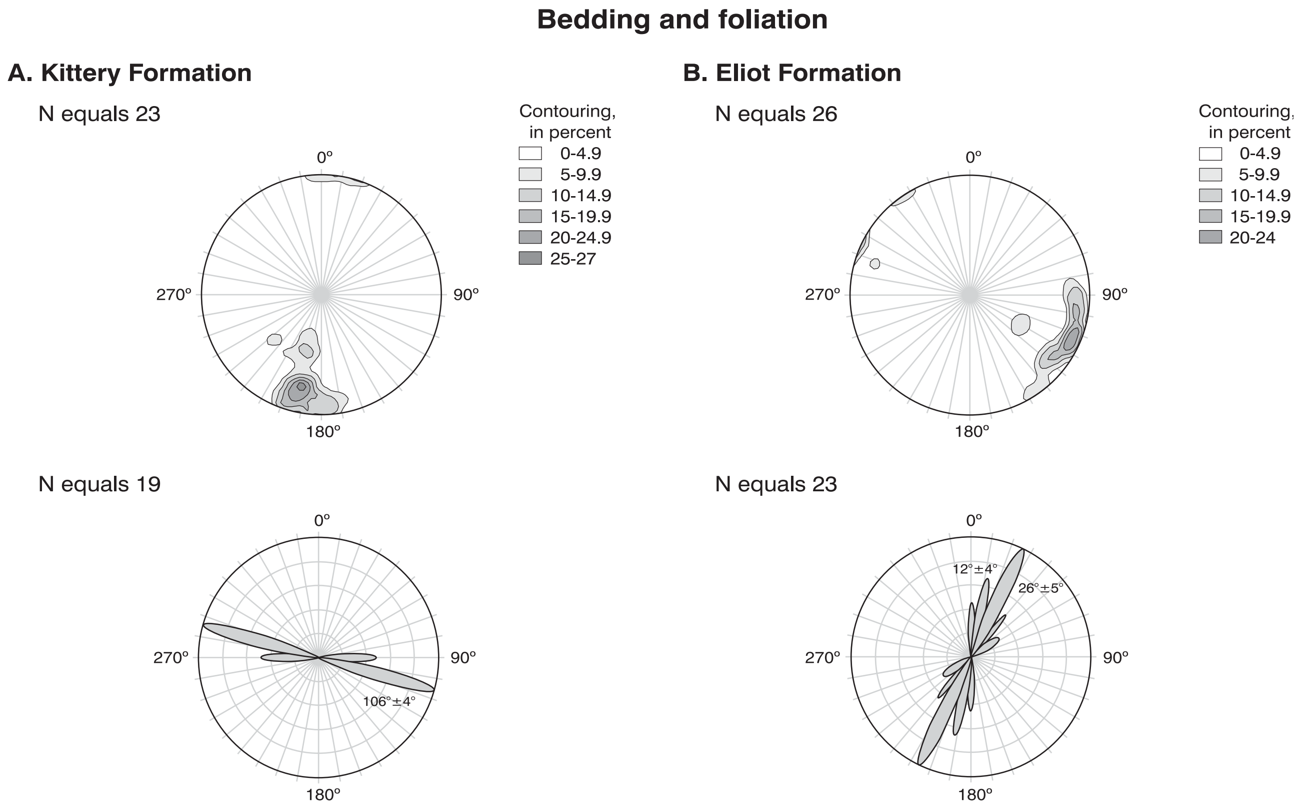


Figure 3. Contoured stereo-net plots and azimuth-frequency plots showing bedding and foliation data for (A) the Kittery Formation and (B) the Eliot Formation at Great Bay, N.H. N equals the number of bedding and foliation measurements represented. The length of the family peaks on the azimuth-frequency plots indicates the normalized height. Principal peaks with normalized concentrations greater than 50 percent are labeled. Circle interval equals 20 percent, increasing outward.

Fractures were grouped into bins based on spacing measurements; this grouping shows peak trends differ with spacing (fig. 5). Open- and vug-filled fracture peaks also have the same trend (86° and 98°) as the two largest east-west-trending fracture peaks in the widest-spaced-fracture data (fig. 5d).

FRACTURED-CORRELATED LINEAMENTS

Fracture data were collected at stations along the shoreline of Great Bay where wave-eroded horizontal and vertical exposures of bedrock provided a three-dimensional view of the bedrock. A total of 287 fracture-orientation measurements from 49 outcrop stations were analyzed and compared with the 927 lineaments. Locations of observed outcrops of bedrock are shown on plate 1 and on figures 2 and 6. Seventy-one percent of open fractures were mapped in the Kittery Formation on the west side of the bay. The highest density of lineaments and fracture-correlated lineaments was identified on the west side of the bay in the Exeter Diorite and Kittery Formation, where the till overburden generally is thin. Lithologic contact, and bedding and foliation trends were observed parallel to fracture-correlated lineaments.

Thirty-seven percent of the lineaments (53 of 143 lineaments) within 305 m of an outcrop with fractures were identified as fracture correlated by use of the buffer analysis (fig. 6). This value is the largest percentage of lineaments correlated by any of the fracture-correlation techniques used in this study. The density and location of fractured-bedrock outcrops will affect strongly the results of fracture correlation by the buffer analysis. This analysis is not applied to lineaments that fall beyond 305 m of any outcrop. Results from domain analysis identify fracture-correlated lineaments in areas far from fractured outcrops, although in this study the technique selected fewer fracture-correlated lineaments than the buffer analysis.

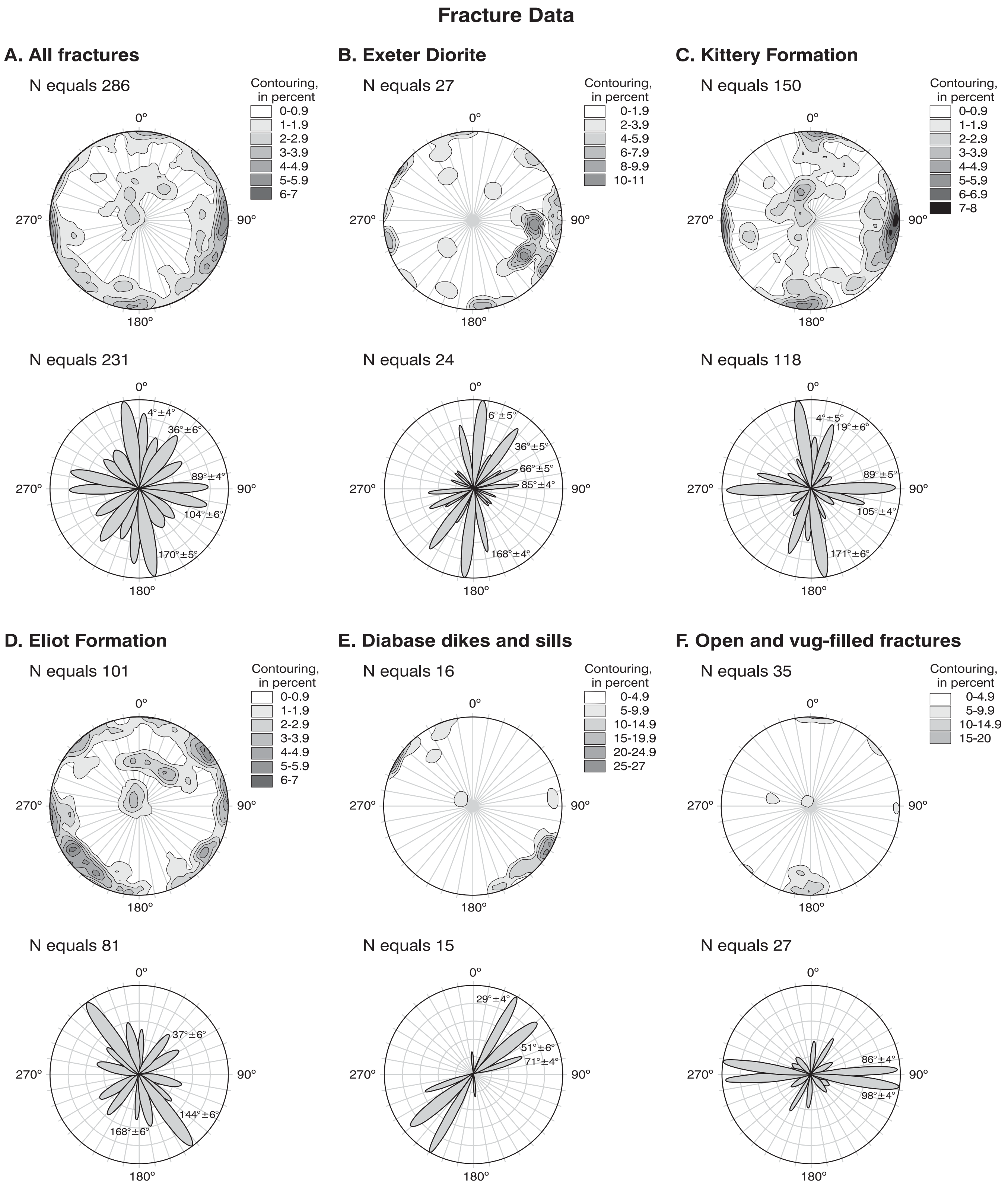
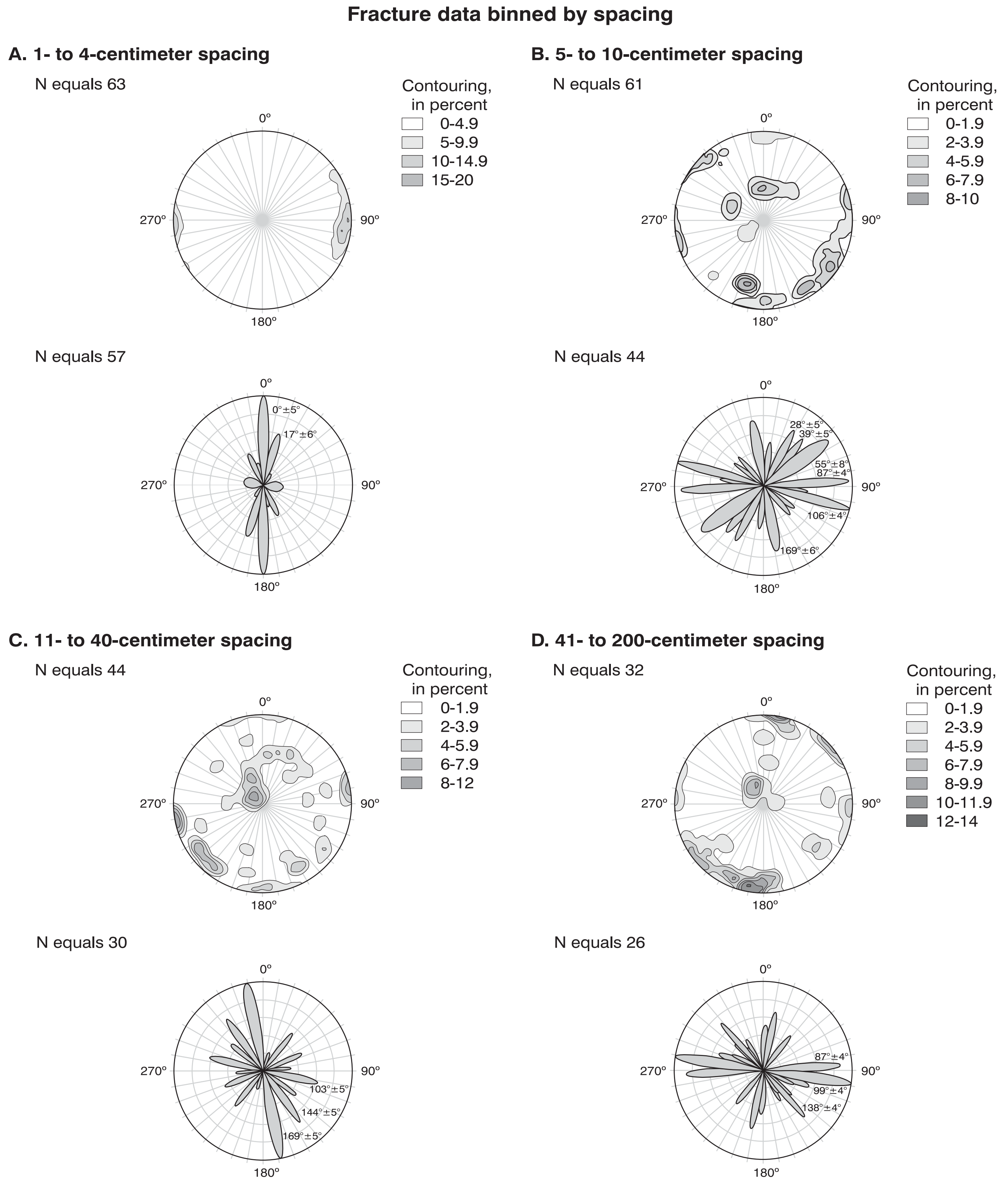


Figure 4. Contoured stereo-net plots and azimuth-frequency plots showing fracture data for (A) all fractures, (B) Exeter Diorite, (C) Kittery Formation, (D) Eliot Formation, (E) diabase dikes and sills, and (F) open and vug-filled fractures at Great Bay, N.H. N equals the number of fracture data measurements represented. The length of the family peaks on the azimuth-frequency plots indicates the normalized height. Principal peaks with normalized concentrations greater than 50 percent are labeled. Circle interval equals 20 percent, increasing outward.



Fracture data binned by spacing

A. 1- to 4-centimeter spacing

B. 5- to 10-centimeter spacing

C. 11- to 40-centimeter spacing

D. 41- to 200-centimeter spacing

Figure 5. Contoured stereo-net plots and azimuth-frequency plots showing fracture data binned by spacing for (A) 1- to 4-centimeter spacing, (B) 5- to 10-centimeter spacing, (C) 11- to 40-centimeter spacing, and (D) 41- to 200-centimeter spacing at Great Bay, N.H. N equals the number of fracture data measurements represented. The length of the family peaks on the azimuth-frequency plots indicates the normalized height. Principal peaks with normalized concentrations greater than 50 percent are labeled. Circle interval equals 20 percent, increasing outward.

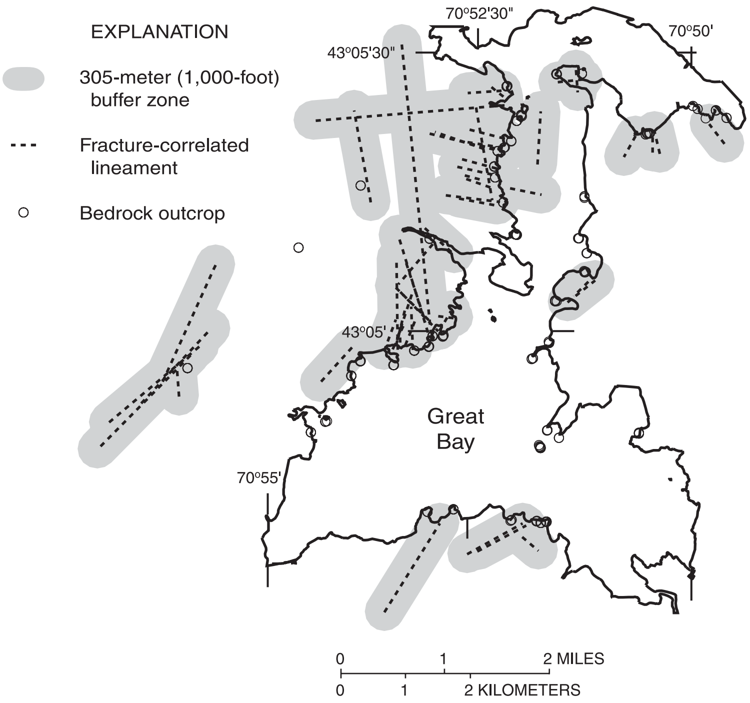


Figure 6. Location of fracture-correlated lineaments with a 305-meter (1,000-foot) buffer zone determined by buffer analysis in relation to the shoreline of Great Bay, N.H.

In the domain cells, 30 percent of the lineaments (120 of 399 lineaments) were identified as fracture correlated by the domain discrete-measurement analysis. The domain cells each had 3 to 6 different fracture family principal-peak trends with normalized heights above 50 percent (fig. 7).

Nineteen percent of the lineaments (77 of 399 lineaments) in domain cells were identified as fracture correlated by the domain-spacing-normalized analysis. The domain cells each had 2 to 4 different fracture-family trends with normalized heights above 50 percent (fig. 8). The relation between principal peaks for discrete-measurement and spacing-normalized domain analysis is shown in table 1. Domain-spacing-normalized analysis identified the least number of fracture-correlated lineaments in this study. This analysis also yielded a smaller number of principal peaks with the fracture data than the domain-discrete-measurement analysis. Normalizing for fracture spacing can mask the trends of sets that have large fracture spacings. Domain-discrete-measurement analysis identified peaks that correlate with peaks from open and vug-filled fractures that domain-spacing-normalized analysis did not identify.

High concentrations of fracture-correlated lineaments were identified in areas with many outcrops. Seventy-one percent of fracture-correlated lineaments and 66 percent of all lineaments are found on the west side of the bay, where overburden is thin. The highest density of lineaments and fracture-correlated lineaments (10 and 3 per km^2, respectively) were on the west side of the bay in the Exeter Diorite and Kittery Formation, where the till overburden generally is thin. Sand-and-gravel settings had lineament and fracture correlated-lineament densities of 5 and 1 per km^2, respectively. All of the lineaments mapped with color infrared air photography beneath the surface of the bay water were fracture correlated. Bedrock type and contacts also appear to affect fracture-correlated lineament density and trends.

Approximately east-west trending fracture-correlated lineaments near the shore of Great Bay are dominant in the northwestern part of the study area, between Durham Point and just south of Adams Point. The geology of this area is mapped as the Kittery Formation, and the trends of the lineaments roughly are parallel to the trend of the bedding and of open and vug-filled fractures. Just inland and westward from this area and to the south along the western shore, fracture-correlated lineaments trend roughly north, from north-northwest to north-northeast. These lineaments are identified in the Exeter Diorite, and strike roughly parallel to its contact with the Kittery Formation. To the southwest in Newmarket, fracture-correlated lineaments switch direction from north-northeast to northeast, parallel to the shift at the Exeter Diortite and Kittery Formation contact.

The Kittery Formation on the northwestern side of the bay may represent an area of increased hydraulic connection to Great Bay for the following reasons: (1) there is a high density of relatively open fracture-correlated lineaments oriented perpendicular to the bay, and (2) the Kittery Formation has been identified by Moore and others (in press) as having an increased probability for high-yielding [greater than or equal to 151 L/min (40 gal/min)] bedrock. However, the upland (recharge) area immediately west of this zone has no stratified drift and is Exeter Diorite, which has a much lower probability for high-yielding bedrock (Moore and others, in press) than the Kittery Formation. Additionally, the fracture-correlated

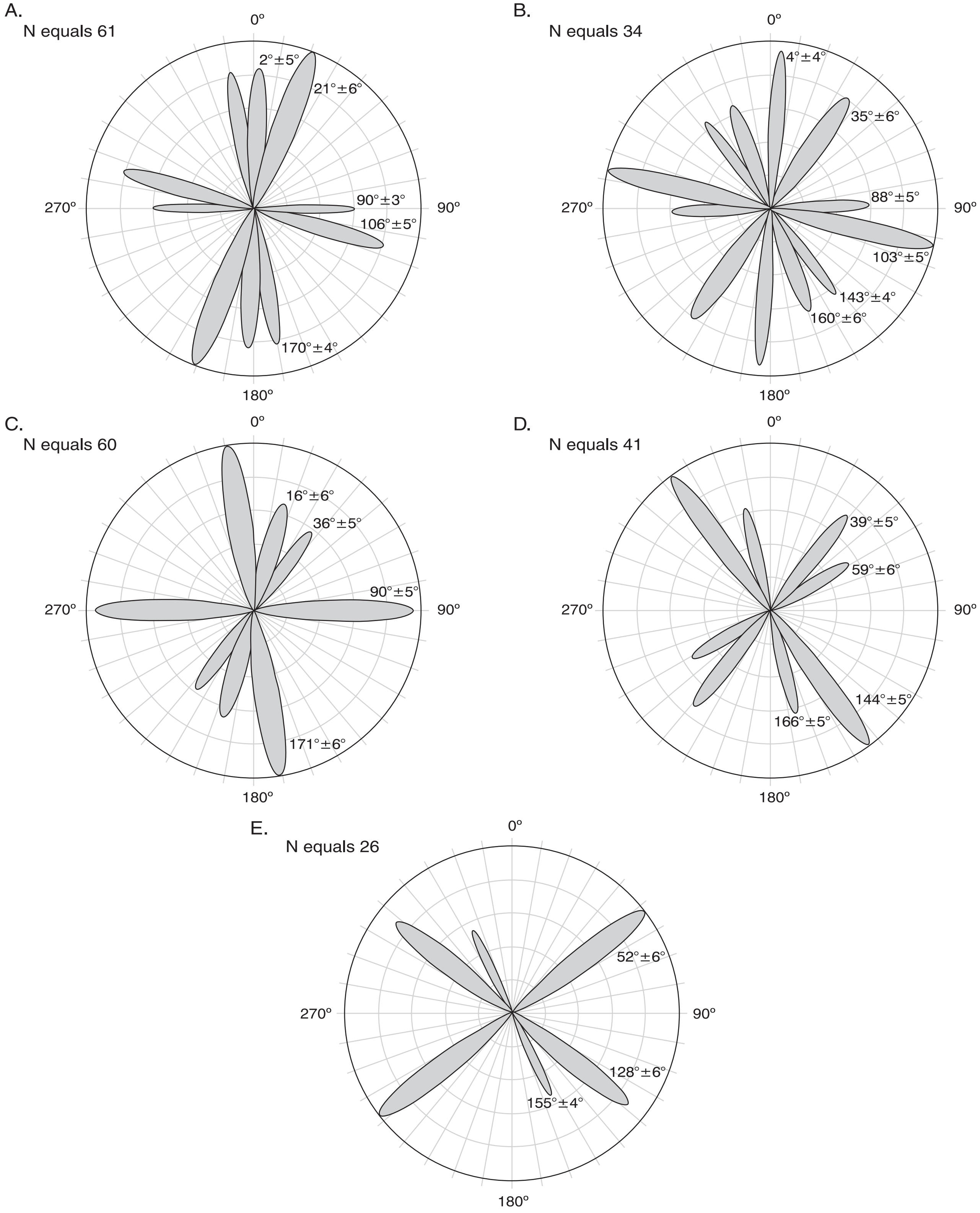


Figure 7. Azimuth-frequency plots of discrete-measurement analysis of fracture data from domain cells, Great Bay, N.H. The length of the family peaks on the plots indicates the normalized height. Circle interval equals 20 percent, increasing outward. The width of the peak represents the standard deviation, or range, of orientation for each family. Principle peaks with normalized concentrations greater than 50 percent are plotted. Letters (A-E) correspond to letters in domain cell locations in figure 2.

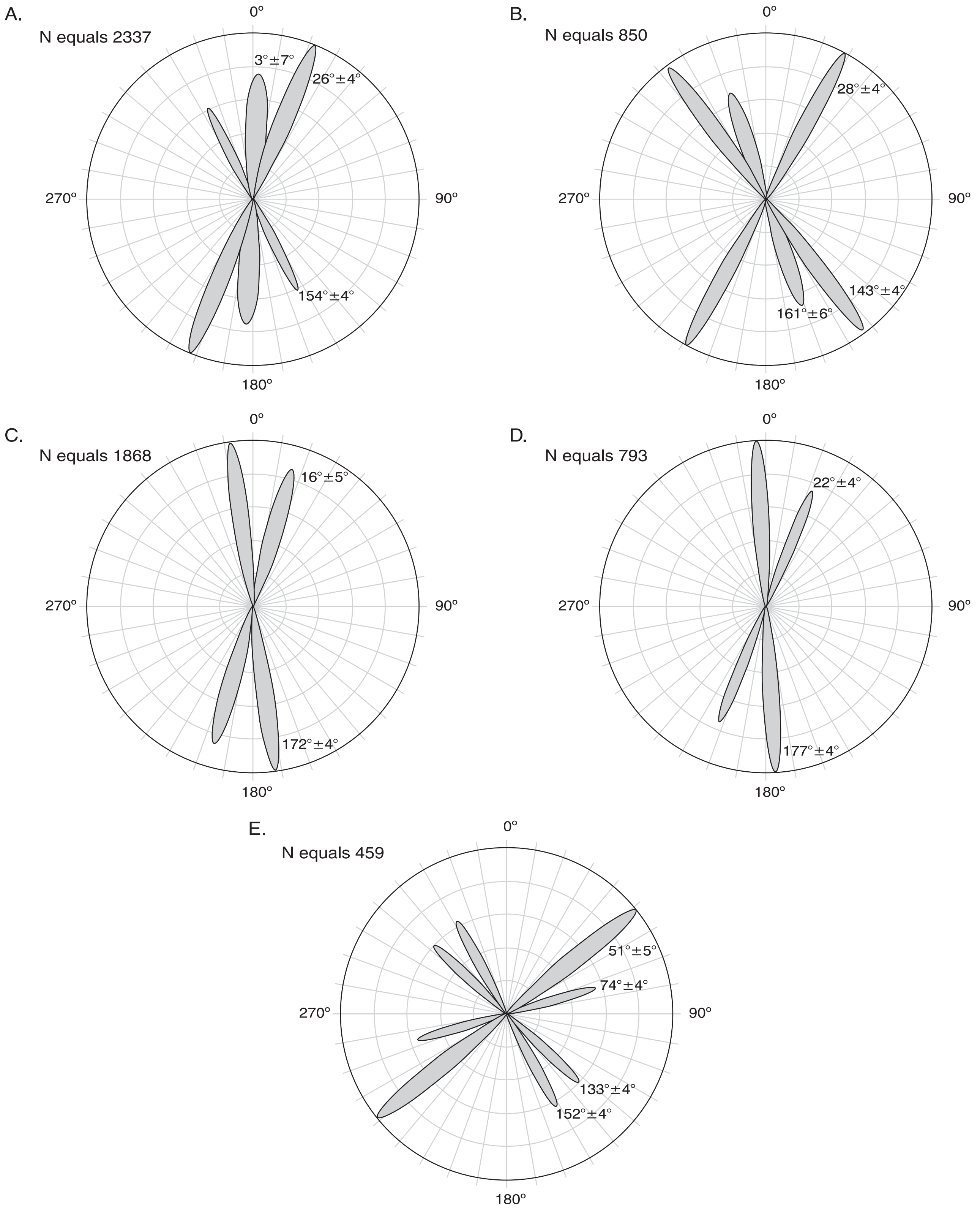


Figure 8. Azimuth-frequency plots of spacing-normalized analysis of fracture data from domain cells, Great Bay, N.H. The length of the family peaks on the plots indicates the normalized height. The width of the peak represents the standard deviation, or range, of orientation for each family. Principle peaks with normalized concentrations greater than 50 percent are plotted. Circle interval equals 20 percent, increasing outward. Letters (A-E) correspond to letters in domain locations in figure 2.

Table 1. Azimuths of principal peaks as determined by discrete-measurement and spacing-normalized domain analyses, Great Bay, N.H.

[All values are in degrees; --, no data]

Domain cell (fig. 2)	Domain	
	Discrete-measurement analysis	Spacing-normalized analysis
A	2	3
	21	22
	270	--
	286	--
	350	334
B	4	--
	35	28
	88	--
	283	--
	323	323
	340	341
C	16	16
	36	--
	90	--
	351	352
D	39	22
	59	--
	324	--
	346	357
E	52	51
	--	74
	308	313
	335	332

lineaments in the Exeter Diorite west of the bay, although fairly dense, are oriented parallel to the bay (north-south) and not directly towards it. Therefore, although bedrock on the western shore of the bay may have an increased hydraulic connection to the bay, this particular area may discharge relatively little ground water considering a lack of inland storage and hydraulic connection.

North-northeast trending fracture-correlated lineaments are identified east of the bay, which parallel the trends of the foliation and bedding in the Eliot Formation and are parallel to the contact between the Kittery and Eliot Formations on the east side of Little Bay. On the south shore of Great Bay, most of the fracture-correlated lineaments identified in the Eliot Formation roughly parallel the contact with the Kittery Formation, mapped at the bay.

Although there are fewer lineaments on the east side of the bay, and they pass through rock with a lower probability of high yield than the west side of the bay (Moore and others, in press), some of the fracture-correlated lineaments on the east side are oriented towards, and may represent fracture zones connected to, large upland stratified-drift deposits. Hydraulic connection to upland stratified-drift deposits may provide a source of recharge, with a large head gradient forming localized springs or appreciable sources of ground-water discharge on the east side. A few fracture-correlated lineaments on the south side of the bay may be fracture zones that could serve as hydraulic conduits to upland stratified-drift-recharge sources, and result in points of concentrated fresh ground-water discharge to the bay.

Of the 927 lineaments in the study area (plate 1), 406 lineaments are within 305 m of an outcrop or intersect a domain cell. Of the 406 lineaments, 190 (or 47 percent) of the lineaments were classified as fracture correlated by at least one of the three analysis techniques described in the section “Fracture-correlation techniques.” Only 15 percent of lineaments (60 of 399 lineaments) were identified as fracture correlated by more than one technique. Fracture-correlated lineaments sometimes are parallel to other geologic features such as lithologic contacts, and bedding and foliation trends.

SUMMARY AND CONCLUSIONS

Lineaments are remotely sensed linear features on the Earth’s surface that may or may not have a geological basis. Three analytical techniques are described in this report to identify those lineaments that may represent fracture-related features. Fracture-correlated lineaments may indicate the locations of zones of fractured bedrock that could serve as ground-water conduits to Great Bay, N.H. The U.S. Geological Survey, in cooperation with the Civil Engineering Department at the University of New Hampshire, the Cooperative Institute for Coastal and Estuarine Environmental Technology, and the U.S. Environmental Protection Agency, is assessing ground-water flow to Great Bay.

Techniques of fracture correlation include the buffer analysis, domain analysis by discrete-measurement analysis, and spacing-normalized analysis. The buffer-analysis technique was used to identify lineaments that have a coincident trends with nearby bedrock fractures. Buffer-correlated lineaments are related spatially to specific neighboring outcrops. Domain-analyses techniques were used to identify lineaments that coincided with fracture families in different regions of the bay.

Analyses results of these techniques indicate that (1) the buffer technique identified the smallest number of fracture-correlated lineaments (53) but the largest percentage (37 percent) of those analyzed by a given technique, which included lineaments within 305 m of an outcrop; (2) domain discrete-measurement analysis identified more fracture families and fracture-correlated lineaments (120 lineaments) than domain spacing-normalized analysis; and (3) domain spacing-normalized analysis identified the lowest percent of fracture-correlated lineaments (identifying 19 percent, or 77 lineaments) with these bedrock data. Almost half (47 percent) of the lineaments mapped in the Great Bay study area that fall within a domain cell or near an outcrop were fracture correlated by one or more of the techniques. Only 15 percent of lineaments analyzed for fracture correlation were fracture correlated by more than one technique.

Principal fracture-peak trends were identified through domain-discrete-measurement analysis that are coincident with the principal trends of open and vug-filled fractures. These principal trends also are coincident with bedding in the Kittery Formation. Spacing-normalized analysis identified principal fracture-peak trends that are coincident with the trends of closely spaced fracture sets. Principal fracture-peak trends were identified in most of the domains that are coincident with the principal trends and fracture trends of diabase dikes.

High concentrations of fracture-correlated lineaments are identified in areas with many outcrops. Fracture-correlated-lineament density and orientations also vary with bedrock type and contacts. In the northwestern part of the study area, approximately east-west trending fracture-correlated lineaments in the Kittery Formation are parallel to the trend of the bedding, and the strike of open and vug-filled fractures. In the Exeter Diorite, just inland and to the south along the western shore, fracture-correlated lineaments trend roughly north, from north-northwest to north-northeast, and trend roughly parallel to its contact with the Kittery Formation. North-northeast trending fracture-correlated lineaments are identified in the area east of the bay, which parallel the trends of the foliation and bedding in the Eliot Formation and the contact between the Kittery and Eliot Formations. On the south shore of the bay, most of the fracture-correlated lineaments identified in the Eliot Formation roughly parallel the contact with the Kittery Formation and the peak trends of diabase dikes and sills mapped at the bay.

Fracture-correlated lineaments on the west side of the bay, in the relatively high-yielding Kittery Formation, may represent fracture zones that could have an increased hydraulic connection with Great Bay. Fracture zones on the west side of the bay, however, are not likely to be connected to major sources of recharge. Fracture-correlated lineaments on the east side and possibly the south side, which may represent fracture zones, are more likely to represent hydraulic connections to large sources of recharge in stratified-drift aquifers, and result in points of concentrated fresh ground-water discharge to the Great Bay.

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