Maine Geological Survey
DEPARTMENT OF CONSERVATION
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Title: *Photo-lineament Mapping at 1:40,000 Scale in the Sebago Batholith and Bottle Lake Complex of Mainc*

Author: *Caswell, Eichler and Hill, Inc.*

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This report is preliminary and has not been edited or reviewed for conformity with Maine Geological Survey standards.

Contents: 10 page report and 3 maps

Special Geological Studies in the Department of Energy's Proposed Candidate High-level Nuclear Waste Sites in Maine

Introduction

In January, 1986, the federal Department of Energy released its Draft Area Recommendation Report which identified two granitic plutons in Maine, the Sebago batholith and the Bottle Lake Complex, as candidate sites for a high-level nuclear waste repository. The Maine State Legislature followed this action in early 1987 with a special appropriation to the Maine Geological Survey for the purpose of conducting studies intent on gathering additional, high quality, detailed geologic information with which to further assess the Department of Energy's designation of these areas. This report is one of a series of reports detailing the results of those studies.

In order to best utilize the funds provided by the Legislature, the Maine Geological Survey designed a research program which concentrated the majority of effort in the Bottle Lake Complex which, to that date, was the poorer studied of the two areas. The funds provided the Maine Geological Survey with the opportunity to contract services from some very well respected geologists and geophysicists working in Maine and elsewhere in the country. Our research program was divided into four parts: (1) Lineament studies of both the Bottle Lake Complex and Sebago batholith; (2) Bedrock mapping in the Bottle Lake Complex; (3) a gravity study of the Bottle Lake Complex; and (4) a seismic reflection analysis of the Bottle Lake Complex. Each of these studies is described more completely in the following sections.

Lineament Study (Open-File Report 90-25a)

The lineament study was conducted by Bradford Caswell of Caswell, Eichler, and Hill, Inc., a geological consulting firm with an extensive record of similar work in Maine. For both the Bottle Lake Complex and Sebago batholith, Maine Geological Survey file aerial photographs at a scale of 1:40,000 were interpreted for lineaments. Individual interpreted aerial photographs were submitted to the Survey where the final compilation from photograph to map was done through use of the Survey's geographic information system. This compilation eliminates the duplication of individual lineaments discussed in this report, which the compilation postdates. The lineament maps at a scale of 1:100,000 are presented as plates at the back of the Caswell, Eichler, and Hill report.

Bedrock Mapping (Open-File Report 90-25b)

Bedrock mapping was conducted in the Bottle Lake Complex during the summer and fall of 1988 by John T. Hopeck, a doctoral candidate at Queens College, New York with considerable experience mapping the complex geology of eastern Maine. The goal of this investigation was detailed mapping of joints and shear zones within the pluton. By combining detailed analysis of shear zones with understanding of the geology of surrounding rock units, a more thorough understanding of the timing of faulting in the Bottle Lake Complex was realized.

Gravity Study (Open-File Report 90-25c)

One of two geophysical studies in the Bottle Lake Complex, a gravity study was conducted by William E. Doll, Colby College, and student Stephen Potts during the summer and fall of 1988. Aimed at augmenting the sparse gravity data base for the region and defining the subsurface geometry and homogeneity of the complex, this work consisted of taking accurate gravity measurements at nearly 200 sites. Various analytical techniques were used to generate contoured gravity anomaly maps and models of the complex's geometry at depth. When combined with the seismic data described in the next section, these data constrained the bottom of the complex within the 3.5 to 4.5 km depth range and showed that the contacts with country rocks dip inward toward the center of the complex.

Seismic Reflection Study (Open-File Report 90-25d)

During October and November 1988, a total of 27 miles of seismic reflection data were collected in the Bottle Lake Complex by Western Geophysical Company, Houston, Texas, under contract with the Maine Geological Survey, using four Vibroseis trucks and a full compliment of recording and processing equipment. The digital records from this study were processed and analyzed by John Costain, Virginia Polytechnic Institute, over the following year and a half. The seismic sections resulting from this investigation, shown as plates in Costain's report, show the base of the Bottle Lake Complex at 1.5 to 2 seconds two-way travel time which corresponds with the depths defined in the gravity study. Perhaps the most prominent feature of the seismic sections is the steeply dipping Norumbega fault zone which is seen to offset the base of the crust at 30-32 km depth. Additional interpretation suggests that the Bottle Lake Complex is heterogeneous and has a series of faults below it.

Acknowledgements

The Maine Geological Survey thanks, in particular, the land owners in the area of the Bottle Lake Complex for their permission to conduct these investigations on private land. These include Georgia-Pacific Corporation, International Paper Company, and the Penobscot Nation. The residents of the town of Lee were most understanding when traffic was disrupted by seismic data acquisition.

Maine Geological Survey
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Photo-lineament Mapping at 1:40,000 Scale in the Sebago Batholith and Bottle Lake Complex of Maine

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INTRODUCTION

Two areas in Maine are identified by the U. S. Department of Energy Crystalline Repository Project as possible high-level radioactive waste repositories. These are the Sebago batholith in southwestern Maine, and the Bottle Lake Complex in east-central Maine depicted on Figure 1.

Migration of radioactive wastes from a repository in saturated bedrock depends almost entirely on ground water movement. In igneous rocks, such as the Sebago batholith and the Bottle Lake Complex, ground water flow is restricted essentially to movement along brittle fractures created by jointing and faulting. The extent and pattern of fracturing in the igneous bedrock is, therefore, critical in determining the suitability of these sites for a high-level nuclear waste repository.

Photo-lineament mapping is a means for examining the geographic distribution and surface expression of bedrock fracturing. It is a remote sensing technique, commonly referred to as "fracture-tracing" that is used successfully in exploration for high-yielding water wells in the crystalline bedrock of Maine, New England, and elsewhere (see for example Caswell, 1985). For ground water exploration, other remotely sensed data such as satellite imagery, side-looking airborne radar (SLAR), and various geophysical techniques are often combined with aerial photograph analysis. Fracture tracing, however, does not duplicate the detailed subsurface information on the orientation, interconnection, and permeability of bedrock fractures that is obtainable from test borings. Furthermore, its use in ground water exploration is typically directed at no more than the upper 1000 feet of bedrock.

Caswell, Eichler and Hill, Inc. (CEH) was employed by the Department of Conservation during 1987 to work with the Maine Geological Survey (MGS) in accomplishing the following specific objectives:

- Prepare photo-lineament overlays of 1:40,000 black & white stereo aerial photographs covering the Sebago batholith and the Bottle Lake Complex.
- Transfer the photo-lineament data to 1:100,000 scale planimetric maps.
- Compare the 1:100,000 scale photo-lineament maps to available bedrock geologic maps of the two study areas.
- Prepare a report commenting on the general distribution and characteristics of the mapped photo-lineaments and on the possible relationships between the photo-lineaments and geologic or hydrologic features.

PHOTO-LINEAMENT MAPPING

U.S. Department of Agriculture, black & white vertical aerial photographs at the scale of 1:40,000 were obtained from the Maine Geological Survey in Augusta. These are 1984 photographs in 9-inch by 9-inch format with full stereo coverage. The Sebago batholith was covered by 173 photographs, while the Bottle Lake Complex was covered by 108 photographs.

The stereo aerial photographs overlap one another by about half in the direction of the flight lines (north/south), and by about one-fourth between flight lines (east/west). This overlap provided two slightly different views of most parts of the study areas, and four slightly different views of numerous smaller areas where the corners of four photographs overlap.

Photography for the Sebago batholith area was largely for the spring, or "leaf off" part of the year, while that for the Bottle Lake Complex was largely for the summer, or "leaf on" part of the year. Consequently, the Bottle Lake Complex photographs are high sun-angle with full vegetation cover that tends to obscure topographic and surface bedrock geologic information from view. The Sebago batholith photographs, in contrast, are low sun-angle with minimal vegetation cover such that the land-surface topography and surface geologic features are enhanced for viewing.

Individual photographs were covered with clear mylar that was secured with drafting tape, and then viewed at various angles

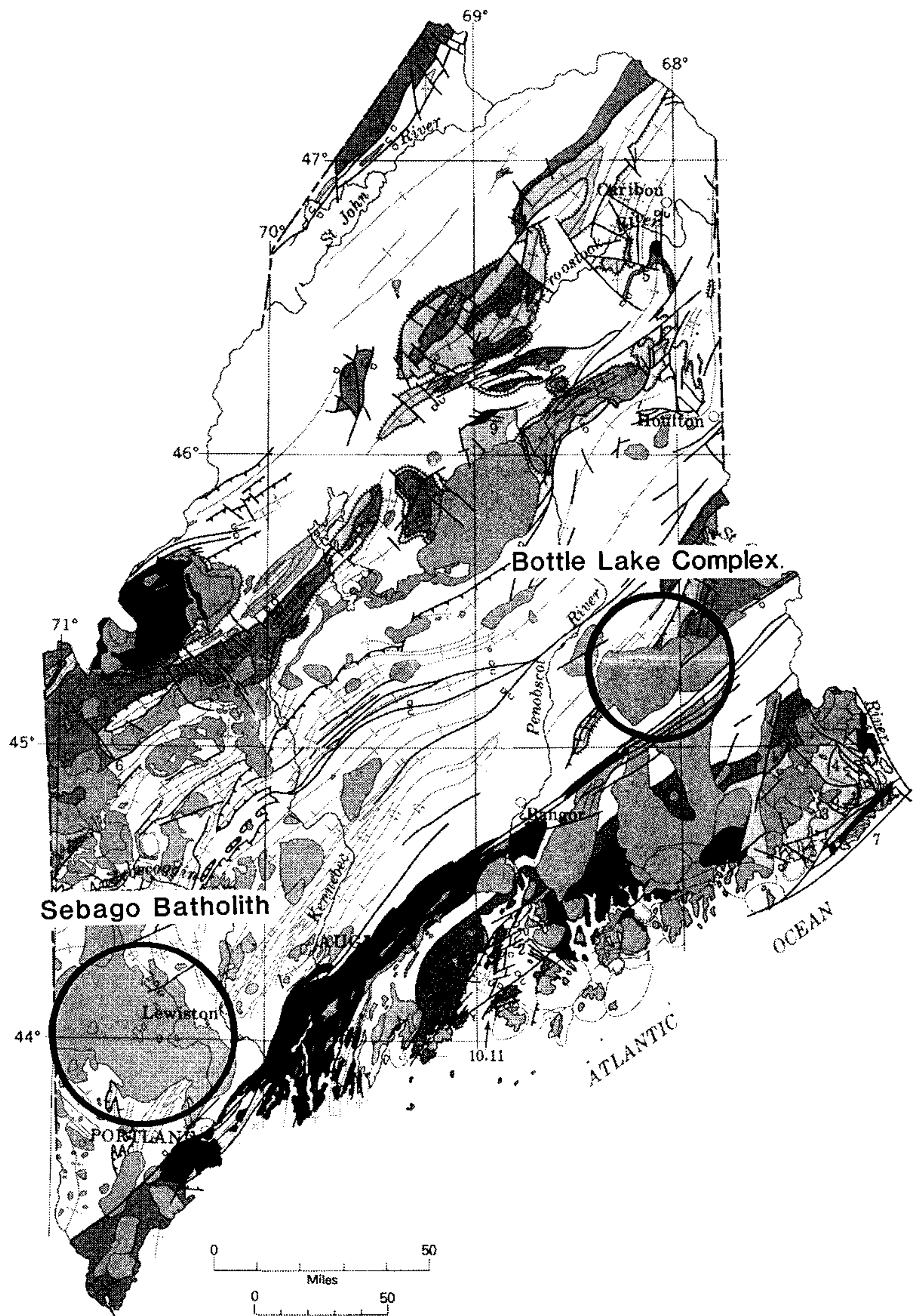

Figure 1. Location of Sebago batholith and Bottle Lake Complex areas (Tectonic Map of Maine from Osberg, et al., 1985).

and with different intensities of illumination. Straight-line features (lineaments) were marked on the mylar overlay using a fine-line, permanent ink pen. Care was taken to avoid marking property lines and other man-made features, and only straight-line segments actually observed were marked. Extension and connection of straight-line features, or lineaments, was strictly avoided. Photographs mapped previously were not viewed while mapping each subsequent photograph, that is, each photograph was treated independently of all other photographs. Furthermore, topographic and geologic maps of the study areas were also not studied or viewed during the photo-mapping process. Mapping lineaments in each of the 281 photographs was completed over a period of about five months.

CONVERSION TO PLANIMETRIC DATA SET AND PREPARATION OF MAPS

The 1:40,000 photographs with registered overlays attached were returned to the Maine Geological Survey where the mapped linear features were digitized. Control points common to both the U.S. Geological Survey 1:100,00 scale topographic maps and to each of the 1:40,000 air photographs were digitized and used to transform the linear features to a planimetric base. Following the digitizing process, the end-points of the linear features were converted to Universal Transverse Mercator (UTM) coordinates and stored for later computer analysis.

As a result of overlap among stereo aerial photographs, some linear features were mapped on more than one photograph. The extent of the multiple mapping was evaluated for the Bottle Lake Complex by plotting the digitized data from each photograph in a different color on 1:62,500 scale topographic quadrangle maps. This revealed a few overlying lineaments and some closely spaced and parallel lineaments. The latter are likely duplicates because each overlapping photograph gives a slightly different view of the same area, hence slight differences in where a linear featured is mapped, and because distortion along the edges of the photographs results in some offset during digitizing from true geographic position. No effort was made during digitizing or in subsequent analysis to remove these presumed duplicate linear features. Duplicate lineaments were subsequently eliminated by marking features as duplicates on the 1:62,500 scale maps and removing them from the digital map datasets. Thus, the 1:100,000 scale maps included with this report do not have duplicate lineaments.

In a very few cases, parts of town lines were mistaken for natural linear features and were mapped as lineaments. These errors were recognized once the lineament data were plotted on topographic maps and were deleted from the data file. Individual data files for each of the black & white air photos were combined into single files and plotted on U.S. Geological Survey, 1:100,000 scale, 30 x 60 minute quadrangle maps. For the Sebago batholith, the information was plotted on the Portland and Lewiston sheets, and for the Bottle Lake Complex the information was plotted on the Lincoln, Calais, and Bangor sheets (see Plates 1-3).

ANALYSIS

Visual Inspection

The Sebago batholith mapping area (Plates 1 and 2) reveals numerous photo-lineaments with a significantly greater density of mapped features in the northwest part of the study area. This greater density of features is unlikely to mean that the bedrock in the northwest part of the area is more fractured than elsewhere. Rather it results from there being a thinner unconsolidated cover in the northwest relative to elsewhere in the study area (see the overburden thickness map in Caswell and Lanctot (1976) for example). The cover is generally thin till in the northwest, while it is generally a thicker, blanketing cover of glaciomarine silt and clay in the southeast part of the area (see Thompson and Borns, 1985). The glaciomarine sediments tend to smooth and mask topographic features that may be bedrock controlled, as well as diffuse, by their relatively greater thickness, soil moisture and vegetational conditions that often reveal underlying bedrock fracture zones by tonal variations on black and white aerial photographs. This phenomenon of apparently greater lineament density in areas of thin unconsolidated cover is very common in the experience of CEH.

Along the eastern margin of the Sebago batholith mapping area there appears to be a change in photo-lineament orientation that is best demonstrated by a nearly continuous and curved set of lineaments that trend north-south just west of Lewiston. This linear feature trends more northerly from south to north.

There also is an apparent shift in trends from the eastern to the western part of the mapped area. East-northeast-trending linear features in the eastern area appear to become northeast-trending in the west, while north-northwest-trending linear features in the east appear to become northwest-trending features in the west.

Some of the mapped photo-lineaments in the Sebago batholith area might be linked together to form linear features of several miles length, for example, the photo-lineaments that trace the east shore of Little Sebago Lake (just east of Sebago Lake) and appear to extend northeastward. Similar lineament mapping of the same area using 1:250,000 scale SLAR imagery (CEH, 1986) suggests this and many other such linear features. Yet overall, the mapping presented here leaves the impression that there are few obviously major geologic features traced by the 1:40,000 scale photo-lineaments. This is in contrast to the number of major linear features reported by Barosh (1986) using LANDSAT satellite imagery in conjunction with aerial photography.

In the Bottle Lake Complex mapping area (Plate 3) the number of mapped linear features is noticeably fewer than for the Sebago batholith area. This difference is most likely the result of having only "leaf on" aerial photographs available for interpretation in the Bottle Lake Complex area as opposed to having "leaf off" photographs for the Sebago batholith area. Summer aerial photographs in the experience of CEH always reveal fewer bedrock lineaments than fall or spring photographs.

It is possible, however, that the masking effect of high sun-angle and summer vegetation results in the mapping of better geologically defined bedrock fracture zones.

Whether it is a result of the "filtered" mapping or a real difference in bedrock geology is not clear, but there appear to be more through-going linear features in the Bottle Lake Complex mapping area than in the Sebago batholith mapping area. For example, in the southwest part of the Bottle Lake Complex mapping area there is an apparent fracture zone trending west-northwest through the towns of Grand Falls and Summit. Similarly, there are several northeast-trending zones that tend to stand out.

In neither study area is there any obvious change in the pattern of bedrock lineaments that would indicate the location of the contacts between the igneous bedrock and surrounding country rock. Barosh (1986) reports the same lack of igneous contact definition in his study of the same areas using LANDSAT satellite imagery as well as other remotely sensed data.

Photo-Lineament Orientation

The digital data sets were processed through a BASIC computer program to generate rose diagrams of the linear orientations. Rose diagrams included as figures in this report show orientations from N 90° W through N 90° E. The photo-lineaments were filtered into 2.5 degree intervals and then the total number of photo-linears falling within each angular interval were plotted as rose diagrams.

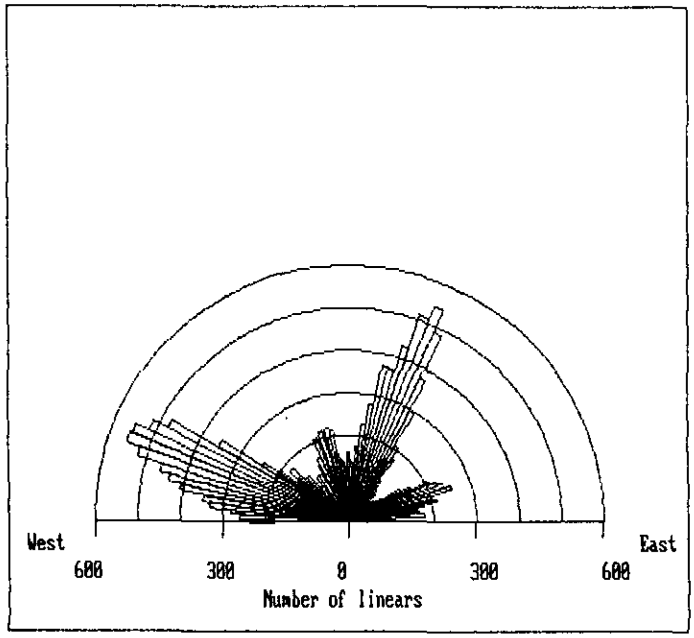

Figure 2. Rose diagram based on 17,025 photo-lineaments mapped in the Sebago batholith area of Maine.

Figure 2 is a computer-generated rose diagram for 17,025 photo-lineaments mapped in the Sebago batholith area that shows two distinct maxima and two distinct minima. The most common lineament directions, the maxima on the rose diagram, are N 60-80° W and N 15-30° E, while the less common trends are N 10-20° W and N 60-70° E. It appears that the maxima represent trends of a primary conjugate joint set, and the minima represent a secondary conjugate joint set. The earlier discussion of a "rotation" in lineament orientation may in reality be map observation of the primary and secondary joint sets. Although no analysis of lineament orientation was completed for selected parts of the mapped area, visual inspection suggests, however, that a given joint set is more prominent in one area than in another.

When considering the magnitude of linear features with a northwest trend, it is important to realize that glacial features in the area have the same fabric orientation that may be confused with bedrock linear features. This is particularly true for the northwestern part of the Sebago batholith mapping area where northwest-trending drumlins are prominent (see Thompson and Borns, 1985). Care was taken, however, while mapping the bedrock lineaments to avoid including drumlins and melt-water channels.

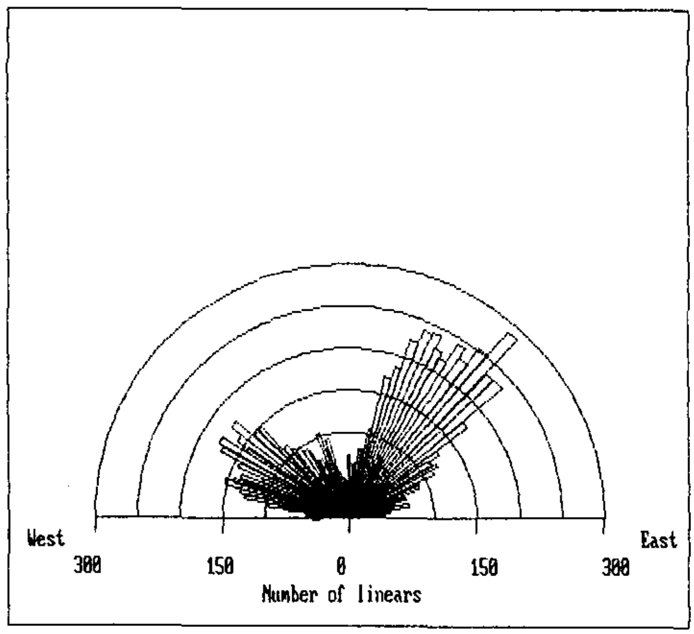

Figure 3. Rose diagram based on 8,480 photo-lineaments mapped in the Bottle Lake Complex area of Maine.

Figure 3 is a computer-generated rose diagram for 8,480 photo-lineaments mapped in the Bottle Lake Complex area that shows maxima at N 30-50° E and N 50-70° W. The orientation of these maxima are in good agreement with the orientations of photo-lineaments mapped by Hopeck (1990) in the Bottle Lake Complex, but the relative magnitudes are reversed. Hopeck found that northwest-trending photo-lineaments are more abundant than northeast-trending photo-lineaments. His LANDSAT satellite imagery, however, showed the same relative magnitude as shown in Figure 3. In addition, the satellite imagery showed a strong north-trending lineament orientation. Hopeck's field-mapped brittle fractures (predominantly joints) show a pattern generally similar to Figure 3, but with clear distinction of fabric elements trending approximately N 5° W, N 45° E, N 40° W, and N 75° W. Hopeck reports that the magnitude of northwest-trending elements in the aerial photograph and satellite imagery analyses are likely exaggerated by inclusion of the northwest-trending glacial fabric.

Correlation with Bedrock Faults

The Nonesuch River fault is a major brittle feature mapped in southern coastal Maine (Hussey, 1985). It lies just on the southeast margin of the Sebago batholith mapping area. Photo-lineament orientations in this part of the study area do not reflect the northeast trend of this structural feature as is illustrated by Figure 4. The mapped northeast trending lineaments appear to be too easterly in orientation to match the mapped trend of the fault. They could, however, be extensional features associated with dextral movement along the fault.

In the northeastern portion of the Sebago batholith mapping area illustrated in Figure 5, there are a series of photo-lineaments with trends approximately parallel to the Ben Barrows fault defined by Creasy (1979). None of the photo-lineaments, however, are coincident with either the trace of the fault or its possible extension to the northeast or southwest.

In a broader sense, the apparent shift in orientation of photo-lineaments from northeast to east-northeast, and from northwest to north-northwest from west to the east across the Sebago batholith could indicate a clockwise rotation related to movement along the major dextral shear faults in the southeast part of the state, including the Nonesuch River fault, the South Portland fault, and the Norumbega fault (refer to Osberg, et al., 1985).

In the southeastern part of the Bottle Lake Complex mapping area, there are a number of photo-lineaments that are either parallel or sub-parallel to the Norumbega fault zone as illustrated by Figure 6. These photo-lineaments, however, are not as prominent as might be expected given the marked topographic expression of the fault zone.

Along the northern border of the Bottle Lake Complex there are three faults mapped by Hopeck (1990) and illustrated by Figure 7. These are the North Bancroft fault, the Stetson Mountain fault, and the Rand Hill fault. There is some parallelism and coincidence of photo-lineaments with at least a southwest extension of the North Bancroft fault, but little or no expression of the sub-parallel Stetson Mountain fault or of the Rand Hill fault to the south.

The Stetson Mountain fault was formed during a compressive event before the pluton emplacement and fracturing associated with it is restricted to the fault proximity (Hopeck, 1990). This may explain the lack of obviously associated photo-lineaments. Evidence for the Rand Hill fault includes a 5-foot wide dike (Hopeck 1990) that suggests an extensional regime. Photo-lineaments oriented more easterly than the fault trend could be related to shear stress associated with this fault.

Photo-lineaments spatially associated with the Stetson Mountain fault appear to increase in density along the Rand Hill fault trace. Planes of weakness could have formed during movement along the Stetson Mountain fault which were later opened under the stress field associated with the Rand Hill fault. The observed photo-lineaments are parallel to the orientation of shear fractures that would be expected with the Rand Hill fault. Another possibility is that later dextral shear along the Rand Hill fault caused previously formed planes of weakness to reopen.

Ludman and Hopeck (1988) describe five classes of faults in an area of eastern Maine that includes most of the Bottle Lake Complex mapping area. These include west-northwest high angle sinistral strike-slip faults, northeast to north-northeast high angle dextral strike-slip faults such as the Norumbega, north to north-northeast high angle normal then strike-slip faults such as the North Bancroft and Stetson Mountain, and northeast thrust and reverse faults. Regional linears with these orientations can be picked out of the photo-lineament area mapped for the Bottle Lake Complex area (Plate 3). Some of these linears that may be selected by observation appear to be major, through-going features. A similar class of linear features for the Bottle Lake Complex is described by Barosh (1986). Recent field work by the Maine Geological Survey (R. Marvinney, pers. commun.) confirms the presence of mylonites associated with northeast trending zones within the area of the Bottle Lake Complex. At least some of the apparent linears may be traces of faults.

Correlation of the mapped photo-lineaments in both the Sebago batholith area and the Bottle Lake Complex area with mapped bedrock faults is not certain. Only with the North Bancroft fault in the Bottle Lake Complex is there clear coincidence of photo-lineaments with the fault trace. Elsewhere there is no clear coincidence of photo-lineaments with known fault traces. There are many linear features, composed of numerous individual photo-lineaments, in the Bottle Lake Complex that appear to have the same orientation as recognized classes of faults, but actual coincidence with fault traces is not known. In some cases for both the Sebago batholith and Bottle Lake Complex areas, there are possible structural explanations for the orientations of photo-lineaments that are spatially associated with mapped faults, but none of this is certain. Overall, the photo-lineaments mapped here are not obviously aligned with bedrock fault as is often assumed and interpreted to occur.

Because of the complicated tectonic history in Maine with several periods of deformation and varying stress-field orientations, it may be difficult to associate photo-lineaments, or selected linear features composed of multiple photo-lineaments, with faults. Lineaments, for example, could have formed during an initial stress, they could be features opened along previously formed planes of weakness during a later stress regime, or they could have formed during that later stress regime. To complicate interpretation, lithologies with varying competencies behave

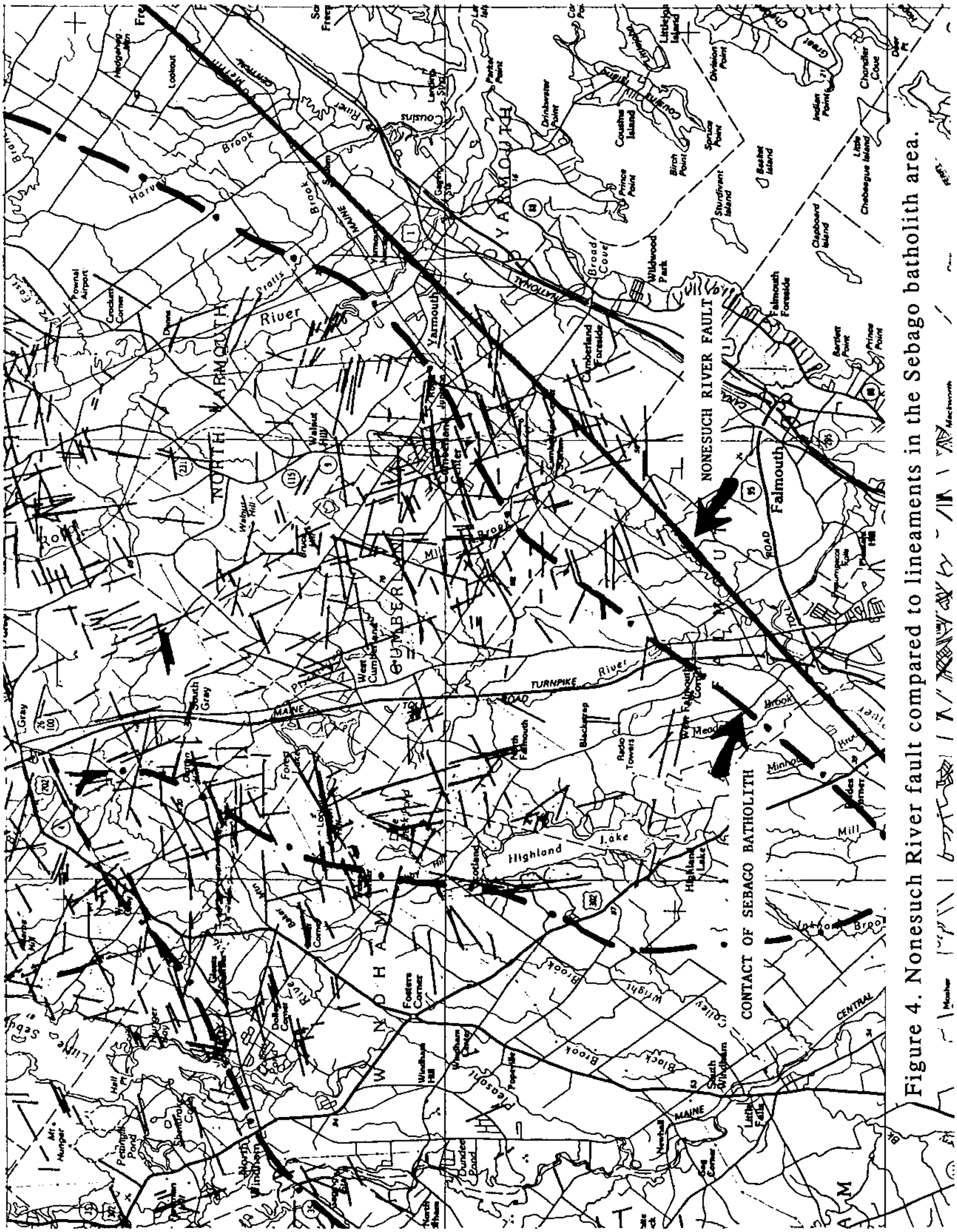

Figure 4. Nonesuch River fault compared to lineaments in the Sebago batholith area.

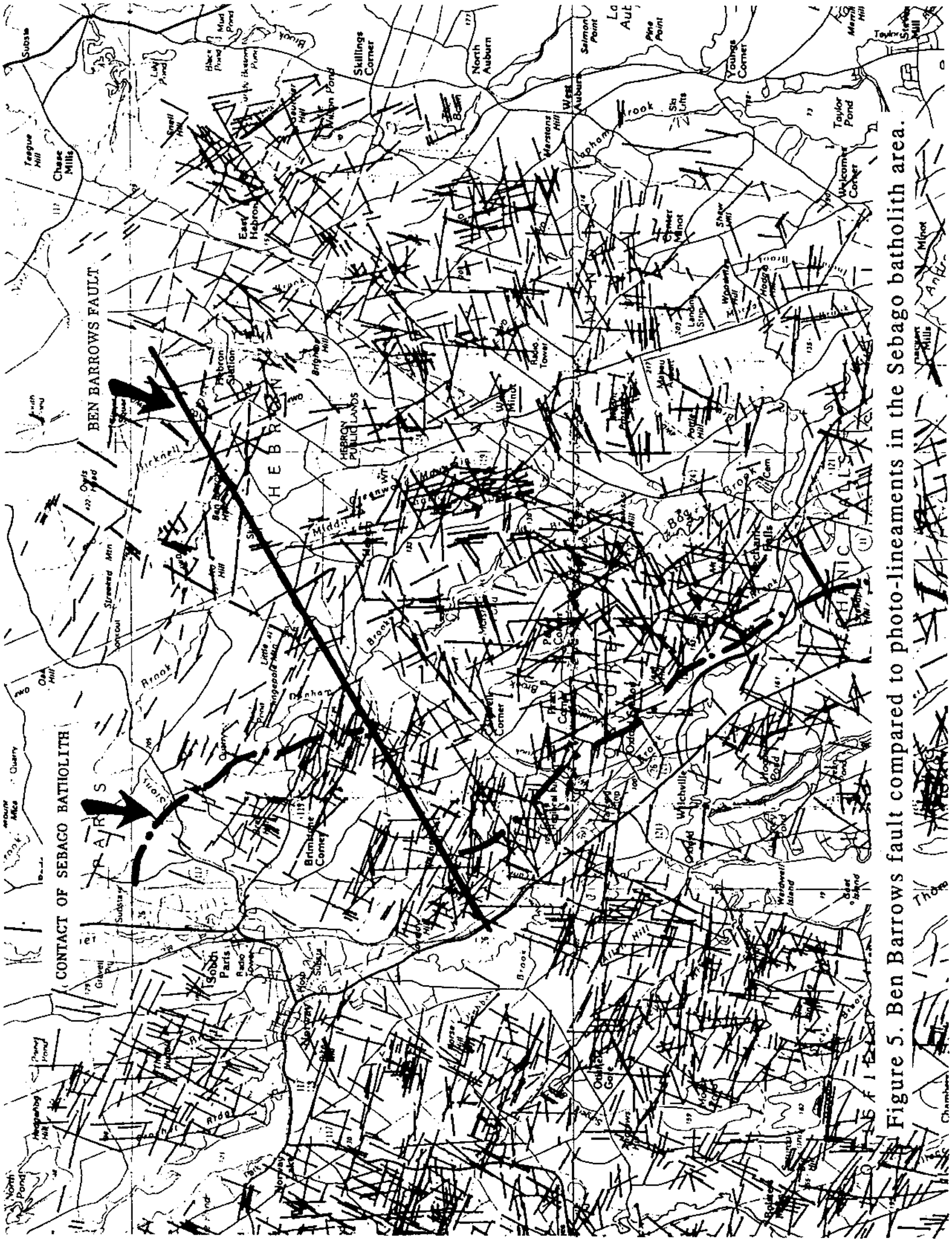

Figure 5. Ben Barrows fault compared to photo-lineaments in the Sebago batholith area.

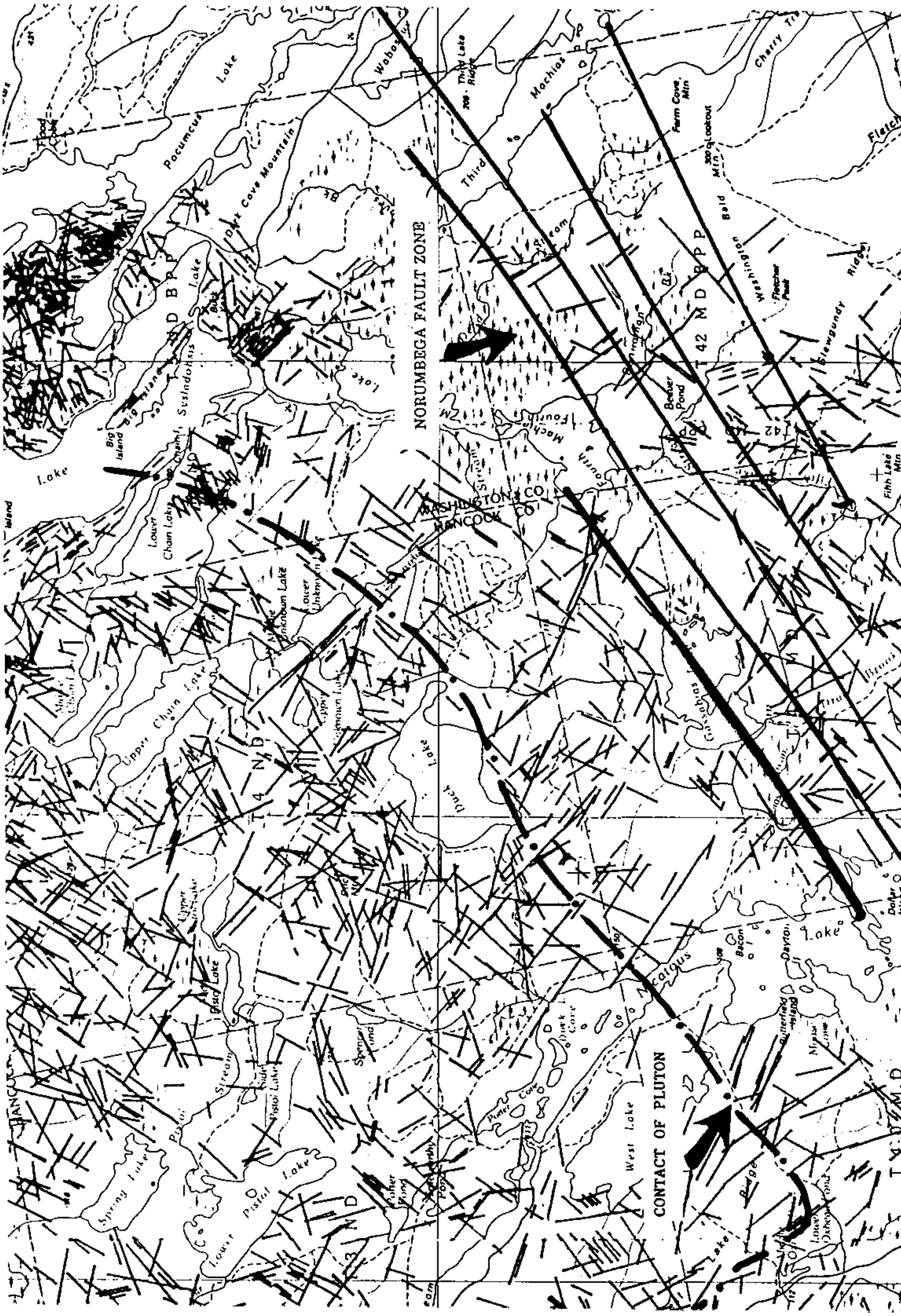

Figure 6. Norumbega fault zone compared to photo-lineaments in the Bottle Lake Complex area.

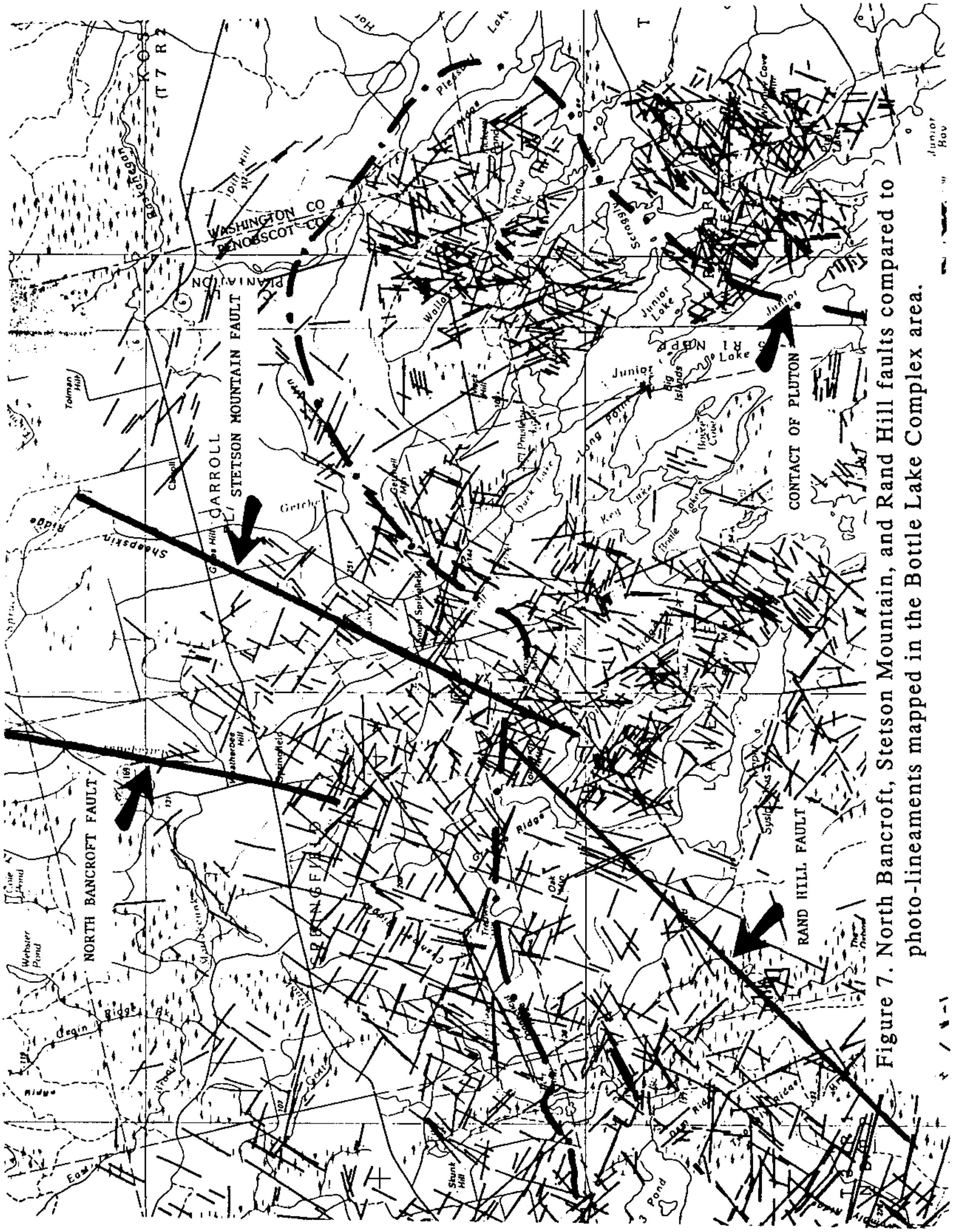

Figure 7. North Bancroft, Stetson Mountain, and Rand Hill faults compared to photo-lineaments mapped in the Bottle Lake Complex area.

differently under stress fields and thereby result in different surface expressions.

SUMMARY

Mapping of photo-lineaments at the scale of 1:40,000 reveals numerous linear features in the area of the Sebago batholith and the Bottle Lake Complex of Maine. Plotting the compass direction and number of photo-lineaments on rose diagrams shows that the orientation of the mapped features is relatively consistent, that is, not random. For the Sebago batholith, there is a distinct primary and secondary set of conjugate linear features, while for the Bottle Lake Complex there appears to be one set of conjugate linear features. The Figure 3 plot, however, may mask less obvious secondary photo-linear orientations. Lineament analysis of LANDSAT imagery and aerial photography, and field observations of fractures by others tends to agree with at least the principal photo-lineament orientations presented here.

Direct correlation of the photo-lineaments with the trace of mapped faults is not found, yet apparent linear features in at least the Bottle Lake Complex area have the same general orientation as various classes of faults recognized by others on the basis of field mapping. At this time, there does not appear to be a direct application of 1:40,000 scale photo-lineament mapping to the broader perspectives of bedrock geologic mapping in the two subject areas. It is clear, however, that the mapped photo-lineaments are surface expressions of numerous and systematic bedrock structural elements, in most cases apparently joints, but in some cases possibly faults.

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Photo-linear analysis by Caswell, Eichler, and Hill, Inc. from 1:40,000 scale aerial photographs. Computer compilation and redundancy reduction by R. Marvinney, Maine Geological Survey.

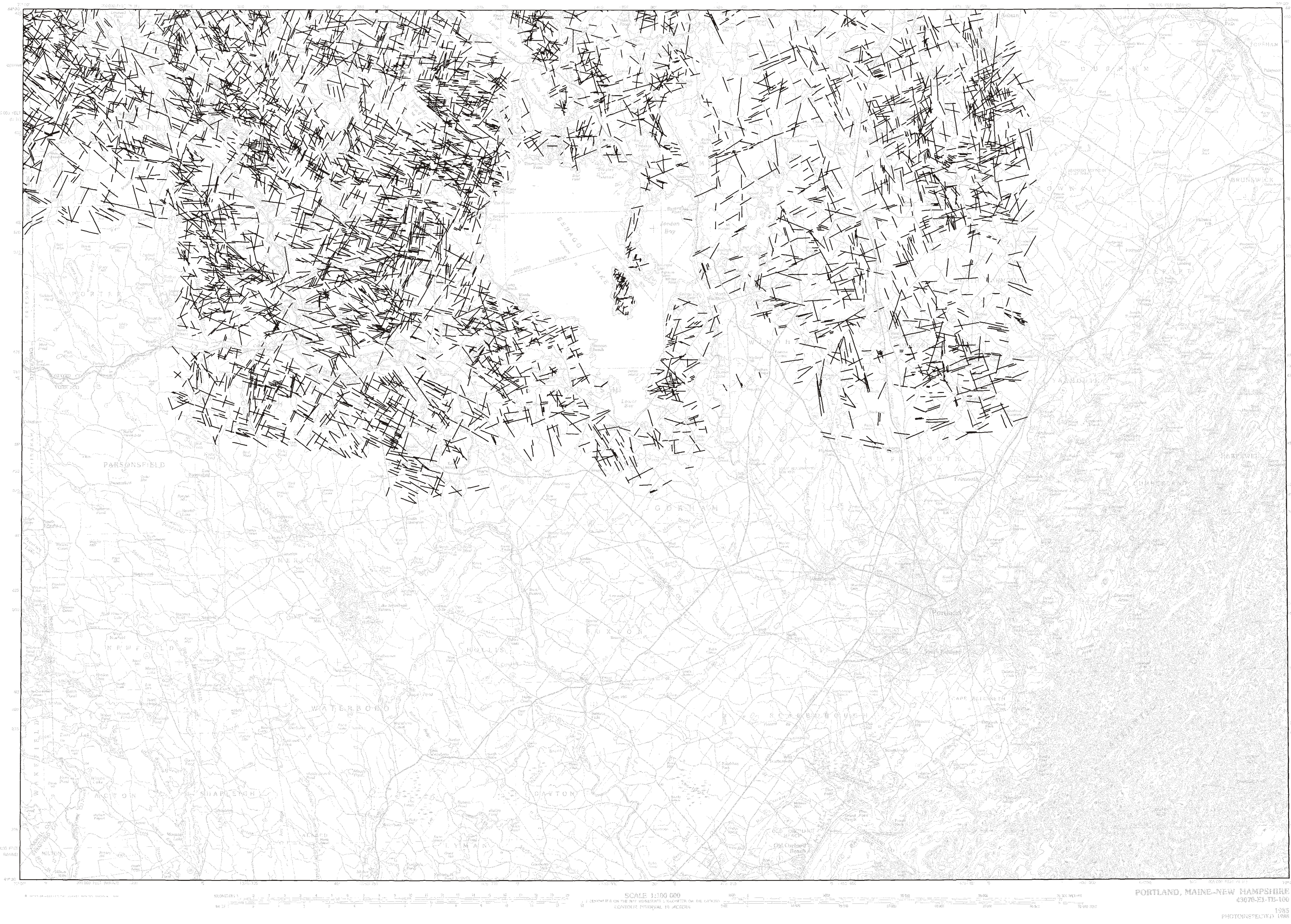

Plate 1

PHOTO-LINEAR SUMMARY, SEBAGO BATHOLITH - PORTLAND SHEET

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Photo-linear analysis by Caswell, Eichler, and Hill, Inc. from 1:40,000 scale aerial photographs. Computer compilation and redundancy reduction by R. Marvinney, Maine Geological Survey.

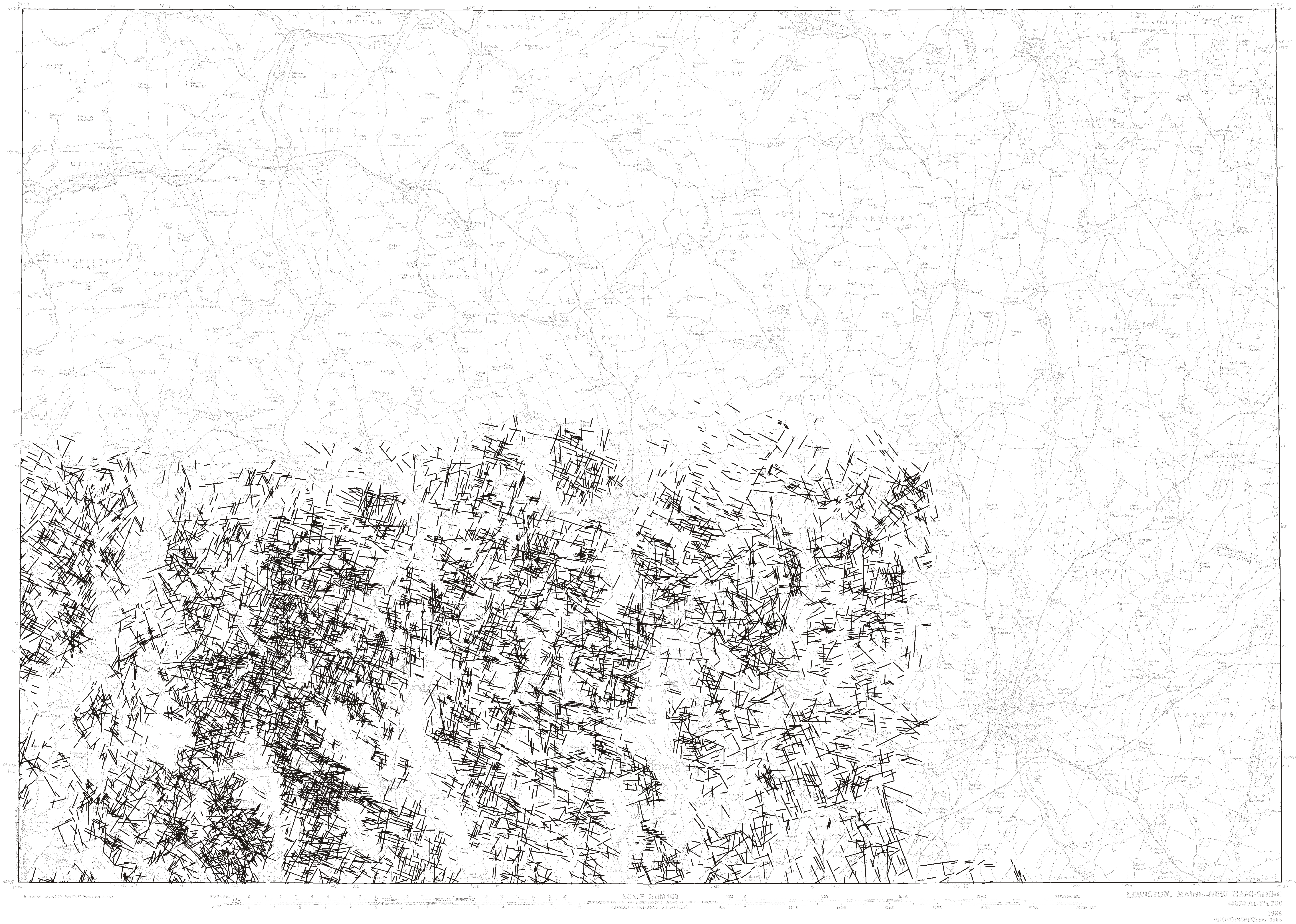

PHOTO-LINEAR SUMMARY, SEBAGO BATHOLITH - LEWISTON SHEET

Plate 2

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Photo-linear analysis by Caswell, Eichler, and Hill, Inc. from 1:40,000 scale aerial photographs. Computer compilation and redundancy reduction by R. Marvinney, Maine Geological Survey.

PHOTO-LINEAR SUMMARY, BOTTLE LAKE COMPLEX

Plate 3