MAGNETIC FABRIC OF THE EXETER PLUTON, NEW HAMPSHIRE

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Abstract: Although it is massive in outcrop and compositionally variable, the Exeter pluton in southeastern New Hampshire has a systematic, penetrative magnetic fabric. The direction of maximum susceptibility is parallel to the long axis of the pluton and to the axial trace of the anticline into which the pluton was emplaced. The direction of minimum susceptibility is normal to the fold surface of the anticline and to the contacts of the pluton. Magnetic foliation is most intense near the margins. The magnetic fabric is due to secondary magnetite and may mimic a petrofabric caused by magma flow or postemplacement strain.

Introduction

Magnetic susceptibility anisotropy of oriented rock samples was measured to determine if the Exeter pluton, lacking visible foliation, has a subtle magnetic foliation. Magnetic lineations might indicate magma flow patterns in this compositionally complex body.

The Exeter pluton, 7 by 32 km, crops out along the crest of the Exeter anticline (Figure 1). General descriptions and discussions of structural, petrological, and chronological relations are given in three major references [Novotny, 1963, 1969; Billings, 1956]. Although diorite is most widely exposed, rock types ranging from gabbro to granite dominate large portions of the outcrop area (Figure 2). The variations have been attributed to differentiation in situ [Novotny, 1963]. Contacts between the various rock types have never been reported nor were they observed during this study.

Cross-cutting contacts with the country rock, inclusions of metamorphosed and folded country rock, and location of the pluton at the crest of a large anticline indicate late syntectonic or post-tectonic emplacement. Structural attitudes of the surrounding Silurian (?) metasediments suggest that the anticline is overturned to the east (Figure 1). Analyses of a 15 mGal Bouguer gravity anomaly [Bothner, 1974] and of aeromagnetic anomalies (F.S. Birch, unpublished manuscript, 1975) show that the bulk of the pluton, about 3-km thick, lies west of the surface outcrop. A preliminary whole rock Rb-Sr age of 410 my. (H. E. Gaudette, personal communication, 1978) agrees with previous interpretations of a Middle Devonian (?) age based on structural relations.

Many geologic situations in which magnetic susceptibility anisotropy has proved a useful petrofabric guide are reviewed by Bhathal [1971] and Khan and Rees [1967]. Several mechanisms, of which preferred orientation of non-equant magnetite grains is most common, produce different susceptibilities in different directions. The susceptibility can frequently be described by an ellipsoid with three orthogonal principal axes: k-max, highest susceptibility from parallel orientation of long axes of magnetite grains; k-int, intermediate susceptibility, and k-min, lowest susceptibility from parallel orientation of short dimensions of magnetite grains. Previous studies show that, in general, k-max, or magnetic lineation, lies parallel to, or occasionally transverse to, flow directions of magmas, lavas, tills, and streams. In these situations k-min, normal to magnetic foliation, tends to be either nearly vertical or normal to a confining boundary. In folded rocks, k-max tends to be parallel to the fold axes; k-min, perpendicular to fold surfaces. (In this paper 'fold surface' means a mathematical surface, originally planar, that has been arched into a fold. In stratified rocks the fold surface is the bedding itself. In massive igneous rocks the fold surface is not directly observable.)

Unlike other Acadian plutons in southeastern New Hampshire and southern Maine the Exeter pluton is not visibly foliated, with one minor local exception [Sundeen, 1971]. As this casts a shadow of doubt on its presumed age and emplacement history, magnetic fabric measurements were made to search for a more subtle foliation. Alternatively, if the fabric is due to magma flow rather than postemplacement strain within the pluton, these measurements might determine if the pluton is composed of separate magmatic intrusions or if the magma differentiated in place. In the case of separate intrusions the flow directions (or k-max) might radiate from several centers; differentiation in situ might produce a weak cumulate texture (vertical k-min).

Sampling, Measurement, and Data Reduction

Over 300 cores were drilled at 52 sites (Figure 3); at most sites, six cores were taken from outcrops 1-50 m in length (a few outcrops may be large glacial erratics). The cores were oriented by magnetic compass and inclinometer with an estimated accuracy in trend and plunge of $\pm 5°$. The diameter of the cores is 1.9 cm; length is 1.8 ± 0.1 cm.

Magnetic susceptibility anisotropy for samples cut from the cores was measured on a spinner magnetometer (Princeton Applied Research model SM-2) following the general procedure of Noltimier [1971]. Absolute susceptibility along the cylinder axis was determined by using a susceptibility bridge (Minntech model MS-3) with an accuracy of $\pm 10\%$. Directions and magnitudes of the principal susceptibilities were calculated by using a

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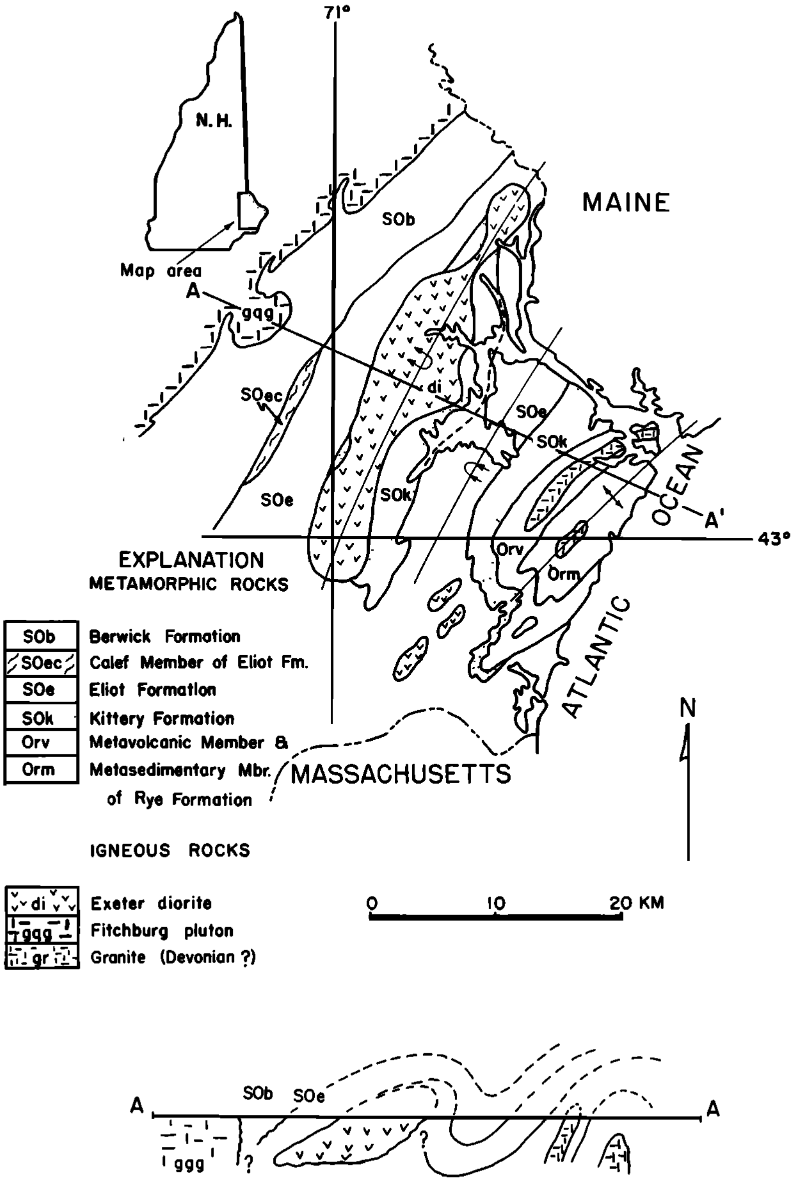

Fig. 1. Generalized geologic map and cross section adapted from Billings [1956], Bothner [1974], and Novotny [1969].

standard matrix diagonalization subroutine; the computer program (KPAR, F. S. Birch, unpublished manuscript, 1975) also rotates the axes into geographical coordinates and calculates various descriptive shape parameters of the susceptibility ellipsoid. Comparative measurements, on two different torque meters for four representative samples, indicate that the directions of the principal axes are accurate to within 15°.

Because some experiments indicate that spinner magnetometers can give erroneous results for specimens of nonideal length/diameter ratios [Kent and Lowrie, 1975] it is important to demonstrate that the results here are not seriously influenced by the specimen shape effect. The four comparative samples have length/diameter ratios ranging from 0.89 to 1.02, mean susceptibilities ranging from 64 x 10^{-6} to 4600 x 10^{-6} emu/cm^3, and percentage anisotropies of 14-19. The axial directions for these test samples, representative of the complete collection, differ from the spinner results by an average of only 10° (all samples, all axes) with a maximum difference of 24°. The angle between the direction of maximum susceptibility and the cylinder axis of all the samples shows no correlation with sample length for individual sites or for the complete data set. Neither do various susceptibility shape parameters. Another argument against a serious shape effect error is that the principal susceptibility axes at a given site generally are more closely grouped than the directions of the core axes (these were deliberately drilled in random directions whenever possible). Another argument is that mapped shape parameters are commonly similar at nearby sites. Finally, the shape effect for spinner magnetometer measurements is expected to be significant only for specimens of low anisotropy. For these reasons the results are considered acceptable.

To facilitate presentation of the results on maps, the least squares mean directions of k-max

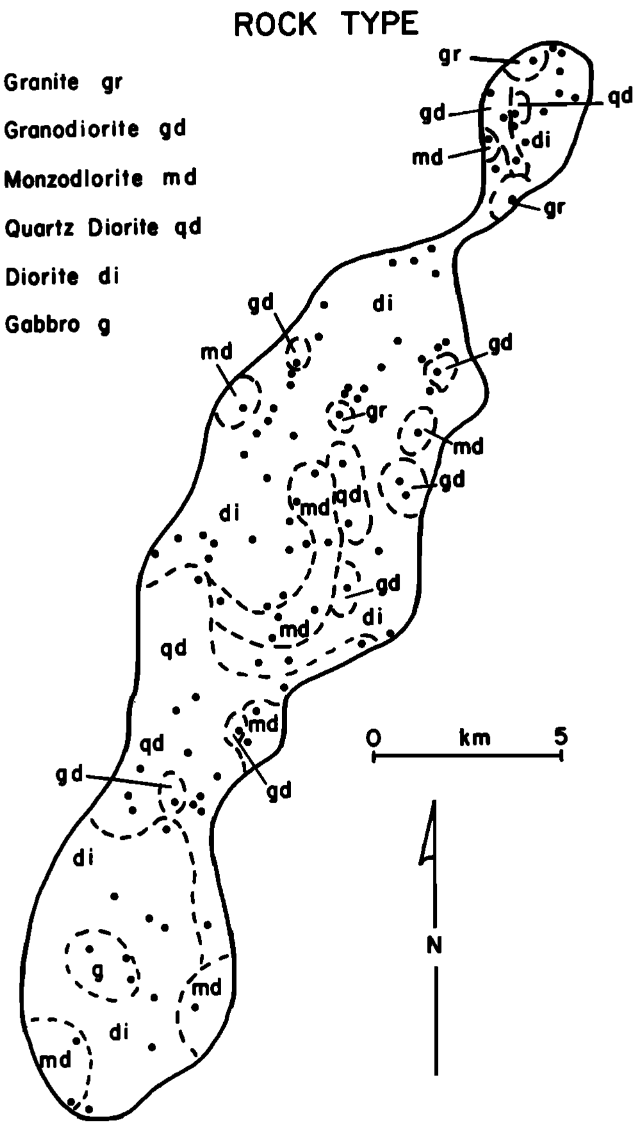

Fig. 2. Rock types from analysis of thin sections from sampling sites (dots). Dashed contacts are illustrative only. Rock types designated as: gr, granite; gd, granodiorite; md, monzodiorite; gd, quartz diorite; d, diorite; and g, gabbro.

and k-min at each site were found iteratively by using a search procedure with a search increment of 5° in both trend and plunge. The root mean square angular deviation of the individual axes from the mean is a measure of closeness of grouping. Since for most sites this deviation is less than 40° (equivalent to a cone subtending only 23% of the area of a sphere), these mean directions are taken to be geologically significant (Table 1). Another test of the significance of the mean directions is the orthogonality of the separately determined mean values of k-max and k-min; the mean angle between them is 90.6° $\pm$ 10.8° standard deviation (52 sites).

An alternative method of describing the dispersion of the principal susceptibility directions is the use of Fisher statistics as is commonly done in paleomagnetism. In the case of the Exeter pluton these have not been calculated because the scatter is large and it is not always clear what sense to assign to each susceptibility axis prior to vector addition. In addition, it is not clear that the principal directions always form unimodal distributions. As detailed statistical treatment is probably premature, all the sample data are shown on equal area stereographic plots (Figure 4).

Methods used by other authors to summarize the shape of the susceptibility ellipsoid generally proved useless in this study. In this case the usual descriptive parameters are so strongly correlated with mean susceptibility that they cannot be used effectively for these rocks of greatly differing susceptibility. The more direct approach used here is to plot the site mean values of k-int/k-max versus k-min/k-int; in other words, a conventional Zingg diagram commonly used in other kinds of shape or fabric studies (Zingg [1935], see Figure 5). As is discussed below, this presentation allows approximate removal of mean susceptibility effects as well as preserving the complete shape data in a simple form. Recently, other authors have used the inverse of the ratios of a Zingg diagram [Hrouda and Janak, 1976; Kligfield et al., 1977]. The author prefers the original Zingg diagram because the ratios are restricted to the range 0-1 and because of greater ease in visualizing the ellipsoid shape.

Determination of the modal mineralogy of the core samples as well as of numerous unoriented samples was done by W. A. Bothner by microscopic analysis of thin sections; classification was according to Streckeisen [1967].

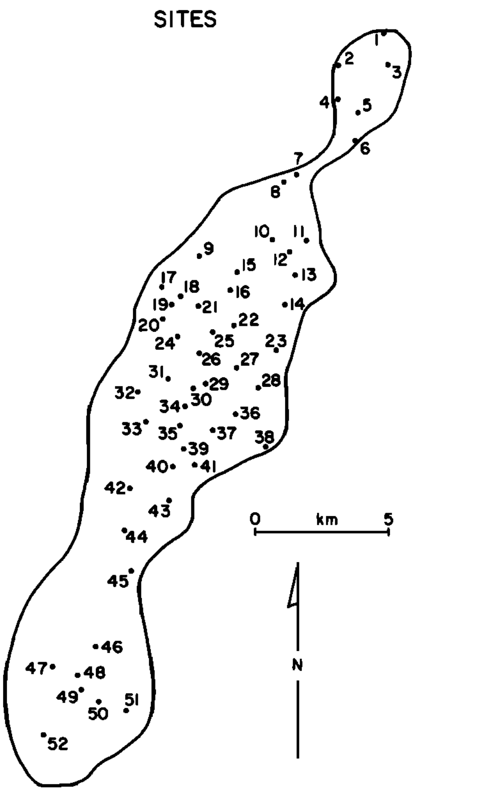

Fig. 3. Sites (dots) where groups of oriented cores were drilled for susceptibility anisotropy measurements. Each site is numbered for reference.

TABLE 1. Site Average Results

Site	k-max/k-int	k-min/k-int	k-int emu/cm^3/Oe x 10^6	number of samples	rms Angular Difference, deg. k-max	rms Angular Difference, deg. k-min
1	1.01	0.97	48	7	46	38
2	1.02	0.97	27	6	37	39
3	1.02	0.98	47	5	37	38
4	1.02	0.92	23	5	15	15
5	1.12	0.95	52	6	44	27
6	1.02	0.97	20	4	35	17
7	1.04	0.95	36	5	29	42
8	1.11	0.96	92	5	33	42
9	1.05	0.93	129	6	47	38
10	1.08	0.85	998	5	39	3
11	1.01	0.96	56	4	21	27
12	1.11	0.93	976	5	25	28
13	1.08	0.85	623	6	42	28
14	1.12	0.92	1545	6	22	42
15	1.05	0.95	456	8	36	46
16	1.04	0.96	68	8	40	34
17	1.10	0.84	382	6	27	11
18	1.06	0.92	1029	6	40	20
19	1.05	0.93	213	6	37	40
20	1.09	0.91	290	6	16	18
21	1.09	0.88	911	6	41	17
22	1.08	0.93	358	6	49	41
23	1.09	0.76	1144	6	32	13
24	1.11	0.91	638	6	40	38
25	1.06	0.93	320	6	41	22
26	1.06	0.89	37	3	39	37
27	1.05	0.92	167	5	33	23
28	1.09	0.86	1717	6	43	27
29	1.04	0.95	113	6	36	46
30	*	*	1227	1	0	0
31	1.10	0.87	1673	5	38	9
32	1.04	0.92	3054	6	25	31
33	1.05	0.93	1880	6	35	32
34	*	*	349	1	0	0
35	1.09	0.88	2650	6	21	28
36	1.10	0.89	580	4	20	36
37	1.09	0.89	2457	5	27	20
38	1.04	0.94	137	7	20	42
39	1.09	0.85	3646	6	22	11
40	1.11	0.92	661	6	37	36
41	1.08	0.88	2084	4	26	37
42	1.05	0.94	149	5	49	33
43	1.06	0.93	259	8	44	38
44	1.04	0.92	95	6	42	24
45	1.03	0.96	54	5	39	44
46	1.02	0.94	180	6	33	19
47	1.14	0.86	1641	4	43	43
48	1.06	0.94	569	4	20	21
49	1.04	0.96	461	6	33	27
50	1.06	0.96	1230	6	44	51
51	1.05	0.97	52	6	29	26
52	1.04	0.90	2922	5	36	27

*Not averaged for single sample.

Results

The site mean directions of k-max and k-min form coherent spatial patterns within the Exeter pluton (Figures 6 and 7). Sample results at each site are shown in Figure 3.

For most sites, k-max trends parallel to the long axis of the pluton and thus to the axial trace of the Exeter anticline (Figure 6). Plunge of k-max is typically low and toward the middle of the pluton. At 13 sites, k-max trends approximately normal to the longitudinal axis; these sites lie on several distinct lines (Figure 8).

K-min trends transverse to the long axis of

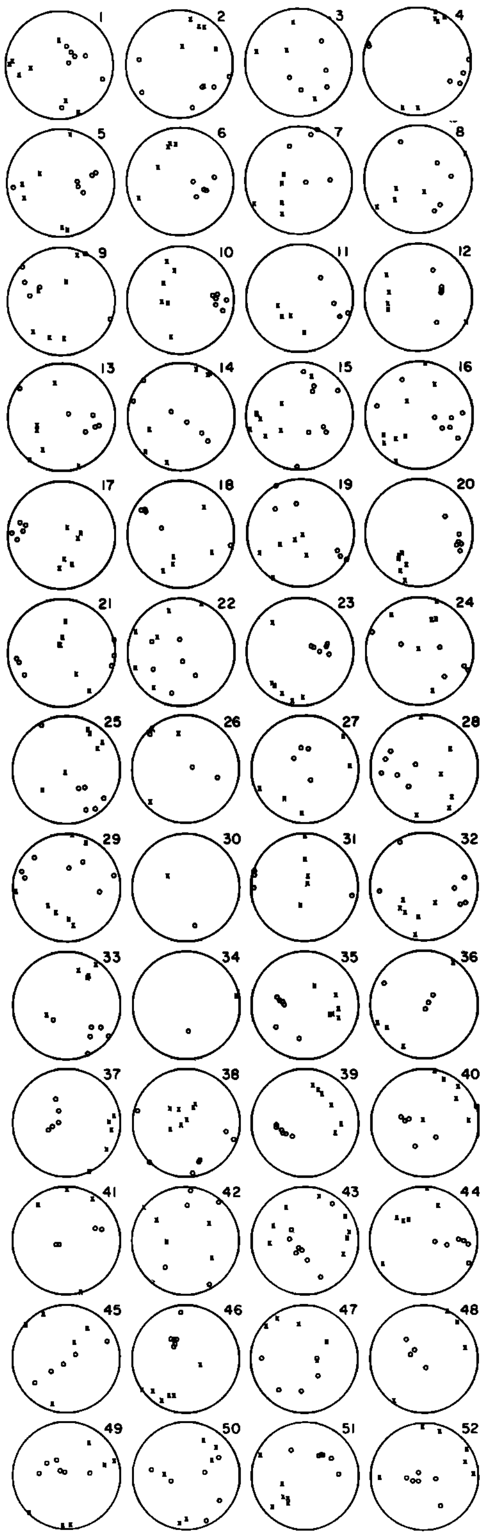

Fig. 4. Equal area stereographic plots (lower hemisphere) of sample data for all sites (numbered as in Figure 3). K-max is indicated by x; k-min by o.

the pluton at most sites (Figure 7). The plunge is very low on the western side of the pluton and steepens to the east. Along the long axis, k-min plunges very steeply, usually to the west. On the eastern margin, k-min plunges moderately to the east.

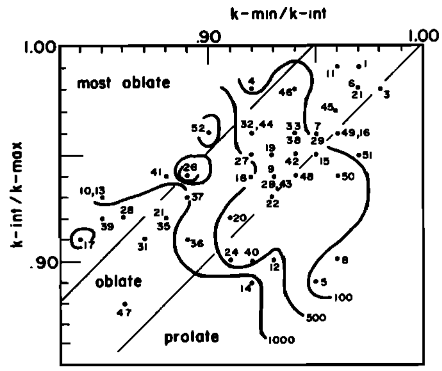

Fig. 5. Zingg diagram of site-averaged ratios of principal susceptibilities. Contours of mean susceptibility labeled in units of 10^{-6} emu/cm^3/Oe. Lines sloping 45° separate fields labeled prolate, oblate and most oblate.

The relative magnitudes of the principal susceptibilities are shown in a Zingg diagram (Figure 5) and listed in Table 1. Contours of mean susceptibility show that as the mean susceptibility increases, the ellipsoid becomes less spherical. Lines roughly normal to the susceptibility contours, or at 45° to the axes of the graph, indicate the degree of oblateness or prolateness of the ellipsoid. Ellipsoids represented by points upward and leftward on the diagram are more oblate or disk shaped; to the right and downward the ellipsoids are more prolate or rod shaped.

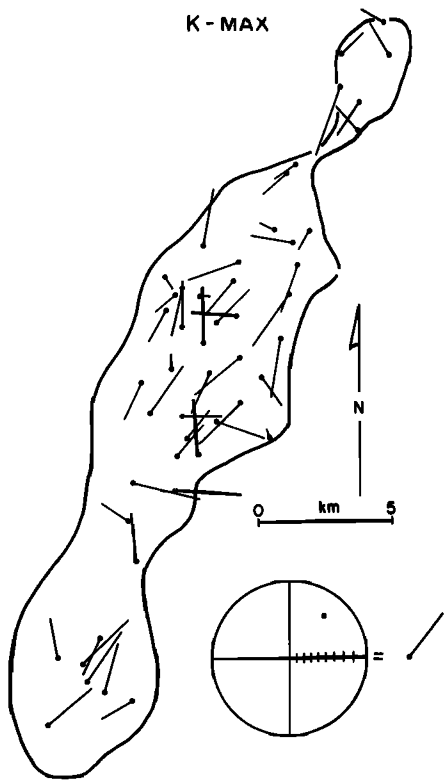

Fig. 6. Equal area stereographic representation of site average k-max directions. Inset shows how a point on the lower hemisphere is represented on the map by a radius drawn from the sampling site (dot).

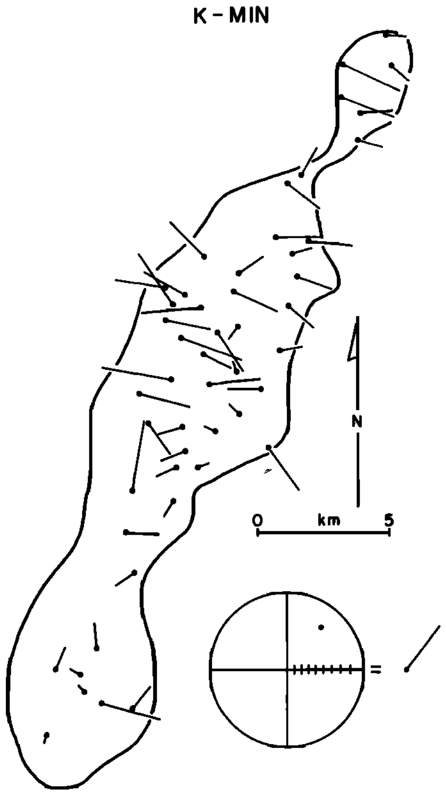

Fig. 7. Equal area stereographic representation of site average k-min directions. Inset shows how a point on the lower hemisphere is represented by a radius drawn from the sampling site (dot).

At most sites the ellipsoid is oblate with k-int/k-max greater than 0.9; only eight ellipsoids are prolate. A map of the shape of susceptibility ellipsoid, expressed as location of ellipsoid axial ratios on the Zingg diagram, shows two systematic relationships (Figure 9). The highly oblate ellipsoids occur at the borders of the pluton. The prolate ellipsoids lie along the axial strip of steeply plunging k-min. Thus in magnetic fabric terms, the pluton is most strongly foliated at its margins and most strongly lineated at its center. The magnetic foliation plane (normal to k-min) is vertical on the western margin, dips slightly eastward along the axis and steeply westward along the eastern margin.

The directions of the principal susceptibility axes and the shapes of the susceptibility ellipsoid are independent of rock type. Comparisons of the rock type map (Figure 2) with maps of axial directions (Figures 6 and 7) and of ellipsoid shape (Figure 9) shows that the results depend on location within the pluton, not on rock type.

Discussion

What components of the samples are responsible for the magnetic fabric? What does the fabric tell about the emplacement of the pluton?

The only high susceptibility mineral in these rocks is magnetite (the exact nature of this phase has not been investigated). The anisotropy could be caused by three mechanisms. One is preferred orientation of nonequant magnetite grains or shape anisotropy. The strength of the anisotropy favors this explanation [Uyeda et al., 1963; M. D. Fuller, personal communication, 1978]. Another possible mechanism, called textural anisotropy, found in metamorphic and foliated igneous rocks is grouping of grains into lines or planes [Heller, 1973]. A final possible mechanism is that there might be a preferred orientation of the [111] crystallographic direction (higher susceptibility) of the magnetite grains; this gives magnetocrystalline anisotropy. Petrographic inspection of thin sections (W. A. Bothner, personal communication, 1975) and observation of samples and outcrops have not resolved this important question. The similarity of the magnetic fabric to a visible petrofabric is supported by the only mapped fabric in the Exeter pluton [Sundeen, 1971]. At this exceptional site (number 52) at the southern end of the pluton, k-min is roughly normal to the visible foliation and k-max lies in the plane of foliation.

Petrographic examination (W. A. Bothner, personal communication, 1975) including use of the universal stage, has provided useful information on the second question, the history of the pluton. The fabric of the rocks, as shown by rare biotite flakes and c axes of quartz, shows no apparent preferred crystallographic orientations. Much of the magnetite is a secondary alteration product of ferromagnesian minerals; this is consistent with the observations of Novotny [1963]. Thus the magnetic fabric is secondary with respect to time of emplacement of the magma. Possibly it is an amplified reflection of weak undetected original orientations of the altered minerals. Such a mimetic magnetic fabric was found in the granodiorite Cista pluton of Czechoslovakia [Hrouda et al., 1971]. In that case, magnetite replacing biotite preserved and even intensified the original biotite fabric. In the case of the Exeter pluton, however, petrographic study also reveals some evidence for postcrystallization deformation. This includes bent and fractured plagioclase twin lamellae and strain shadows in quartz (W. A. Bothner, personal communications, 1975). Thus the secondary magnetite may have grown under conditions of differential stress.

Besides this petrographic evidence of postemplacement strain and mineral alteration, the simple geometrical relationship of the principal susceptibility axes to folding of the country rock supports the hypothesis that the magnetic fabric in the Exeter pluton is due to tectonic stress. Alignment of k-max parallel to fold axes and k-min normal to fold surfaces is common in folded sedimentary rocks [Henry, 1973], basalts [Fujiwara and Schwartz, 1975], and gneissic intrusives [Balsley and Buddington, 1960]. In these instances it may be assumed that k-max corresponds to the extensional strain axis, at the appropriate time, and that k-min corresponds to the greatest compressional strain axis.

Similar magnetic fabrics related to folding have not been found in unfoliated plutonic rocks, although very similar results were found for the slightly foliated tonalite-granodiorite Riesenferner Massif in the Alps [Henry, 1975]. In that

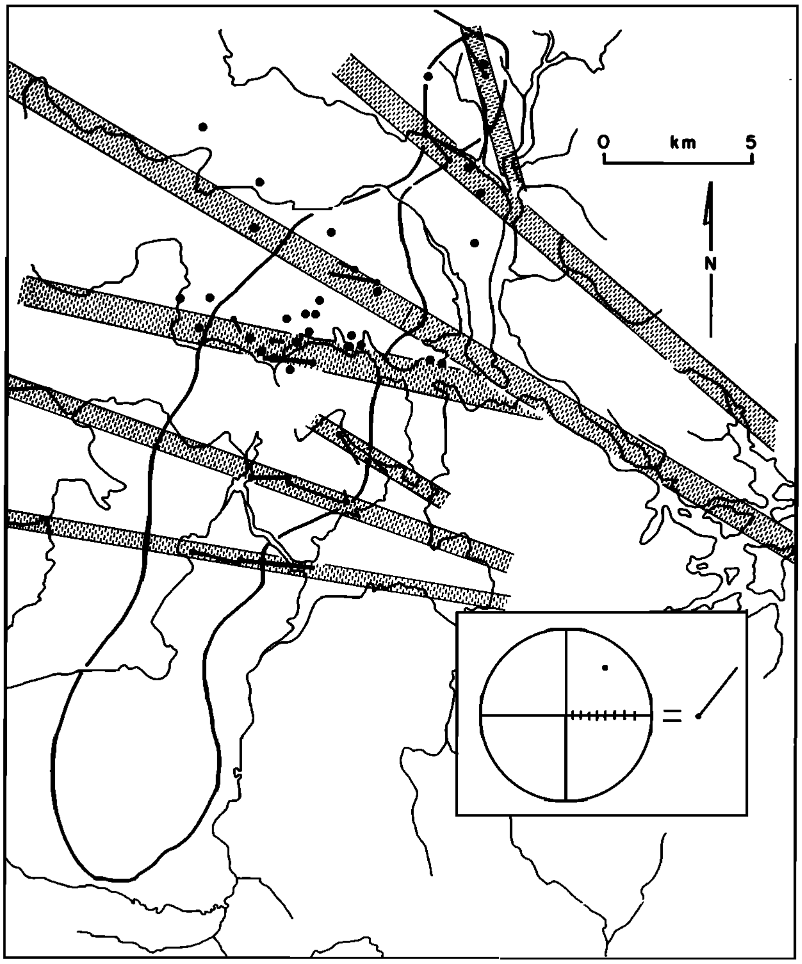

Fig. 8. Map of Exeter pluton showing speculative relationship between anomalous k-max directions (inset shows stereographic plotting convention), streams, high-yield water wells (large dots) and hypothetical fault zones (patterned stripes). No well data have been compiled for the southern half of the pluton [Stewart, 1971].

pluton, k-max parallels fold axes of the country rock. K-min appears to be normal to the fold surface, although complex folding and irregular site distributions somewhat obscure this relationship. The magnetic fabric is secondary relative to emplacement of the pluton and is attributed to late stages of Alpine deformation.

Additional but inconclusive evidence for a postemplacement origin of the magnetic fabric is the well-developed foliation in nearby plutons. Examples are foliation in small diorite satellite plutons, similar to the Exeter, at Bride Hill and Great Hill and foliation and lineation of the Breakfast Hill granite [Novotny, 1963]. In southeastern Maine the nearby younger Biddeford pluton and somewhat older Lyman and Webhannet plutons show similar lineation and foliation [Hussey, 1962; Gaudette et al., 1975]. However, because these plutons are elongated relative to structural trends of the country rock, it is not altogether clear how much of the foliation is parallel to contacts, thus primary, and how much is parallel to the fold surfaces and thus secondary. No magnetic fabric measurements have been made on these plutons.

The fold or tectonic stress model does not explain 13 sites where k-max trends normal to the inferred fold axis. Several kinds of evidence might suggest that these sites lie on zones of intense jointing or faulting or cross folding (Figure 8). One kind is the observation that faulting in an andesite in Japan changed the directions of the principal susceptibilities [Ozima and Kinosita, 1964]. In the case of the Exeter pluton, the topography, stream patterns, and water well yields [Stewart, 1971] provide additional evidence for zones of intense fracturing. Although the correspondence is remarkable, two problems remain. One objection is that the shape of the susceptibility ellipsoid is apparently unaffected by the faults (Figures 8 and 9). Another is that the geologic map [Novotny, 1968] does not show displacement of the contacts along the proposed faults, although this may well be a consequence of very poor exposures at the margins. Of course the anomalous k-max

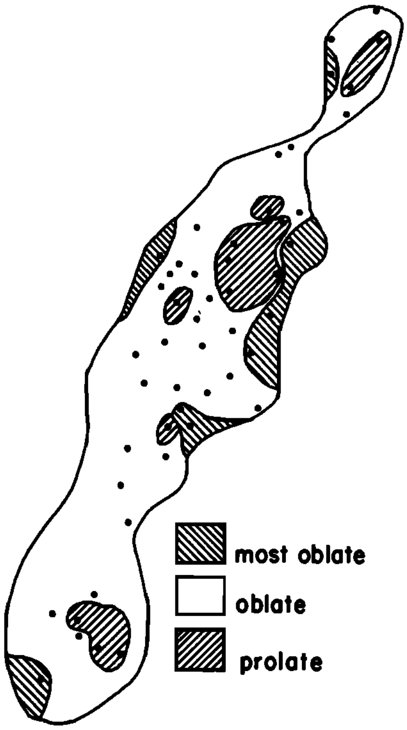

Fig. 9. Map of the shape of the site average susceptibility ellipsoids in terms of the Zingg diagram fields defined in Figure 5.

directions may simply reflect the generally oblate ellipsoid shape throughout the pluton.

If the evidence for faulting is ignored as insignificant, the magnetic fabric can be explained as a consequence of slight transverse compression of the pluton. Can the magnetic fabric be explained in any other way?

An alternative explanation attributes the fabric to magma flow. Following the results of King [1966] on granites in Ireland, the direction of k-int is taken as the flow direction for fluid magma. Examination of Figures 6 and 7 then indicates that flow was upward along the margins of the body (i.e., normal to k-max and k-min). K-min is interpreted as normal to the enclosing margins; these are steeply dipping on the sides and might have been flat at the top of the pluton. The westward-dipping magnetic foliation on the east side is consistent with published cross sections [Bothner, 1974; Novotny, 1969] showing a vertical or westward dipping margin (Figure 1). Essentially vertical magma flow with associated domelike foliation is described for many large plutons [Balk, 1937; Buddington, 1959). The anomalous k-max directions may perhaps by disregarded in light of the oblateness of the susceptibility ellipsoid at those sites. Strongly in favor of the flow model is the relatively strong magnetic foliation at the margins; this is a common feature of many plutons [Balk, 1937; Billings, 1972]. In the center of the Exeter pluton the susceptibility ellipsoid is characteristically only weakly oblate or prolate. This can be interpreted as a result of crystallization in a quiet body of magma; a random orientation of crystals is produced. The only serious argument against the flow model is the similarity of fabric for all rock types. This implies that the fabric postdates magma intrusion if the pluton is composite (i.e., made of separate intrusive units). However, recent maps of chemical and mineralogical trends throughout the pluton (W. A. Bothner, personal communication, 1975) show continuous gradation rather than the possibly artificial discontinuities introduced by indiscriminate use of lithologic names. The absence of any known internal contacts also argues against separate intrusive episodes. Thus the flow model may be correct.

Both the flow and the tectonic compression model can account for the directions of the principal susceptibilities. The flow model better explains the shapes of susceptibility ellipsoids and is more consistent with present slight knowledge of the internal structure of the Exeter pluton and with numerous examples of more obviously foliated plutons. Present evidence favors the flow model, but these models should be viewed as end members of a continuum. In both models the geometry of the pluton and the fold produces very similar fabrics: in one case, through control of magma flow; in the other, through its relationship to strain. A clear choice between the two models requires detailed mapping of the pluton; because of limited exposures this would be a difficult and uncertain task.

Conclusions

The Exeter pluton has a geometrically regular magnetic fabric characterized by k-max roughly horizontal and parallel to the long axis of the pluton. K-min is generally nearly horizontal near the western margins, almost vertical along the long axis, and plunges moderately eastward on the eastern margin. Magnetic foliation is strongly developed at the margins; in the interior it is weak or a weak lineation is developed. These patterns may be explained either by ascent of magma along the margins of the body or by post emplacement strain. The bulk of the data favor the former explanation, although present knowledge of the internal structure and lithology of the pluton is inadequate to permit a clear choice; perhaps both mechanisms have influenced the fabric. Mineralogically, the fabric is apparently mimetic from secondary magnetite formed at the expense of ferromagnesian silicates.

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