PALEOMAGNETISM OF SOME SULFIDE OCCURRENCES FROM THE SOUTH RANGE OF THE SUDBURY BASIN

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ABSTRACT

A magnetic remanence history is established for eight locations of extensive sulfide mineralization from the south range sublayer unit of the Sudbury basin. By comparing the remanence directions characteristic of each site with those found in the main irruptive it is possible to differentiate three phases of sulfide genesis.

Three remanence directions are associated with the presence of sulfide mineralization. The first phase of sulfide genesis is probably of magmatic origin, as it is characterized by a remanence direction (D = 270°, I = +70°) that is directly related to the intrusion of the granophyric micropegmatite. No barren intrusives have been recognized carrying the remanence signature related to the second and third phases of sulfide genesis. Also, these signatures have been found in all units of the Sudbury structure from the Norite to the Onaping Formation. Hence, the preferred model for the genesis of these later mineralization events may be either remobilization of pre-existing sulfide phases, or hydrothermal introduction of new sulfide-rich solutions. That remanence in the third-phase sulfides was probably acquired over an extended period is suggested by the smear of remanence directions associated with this mineral phase. The directional smear observed in the south range sulfides is similar, but not identical, to that in data from the rest of the Sudbury basin area. A small displacement in inclination between these two smears is attributed to post-mineralization fault rotation of the south range.

INTRODUCTION

The origin and emplacement of the copper-nickel sulfide deposits of the Sudbury Basin has long been the subject of much controversy. While it has been generally accepted that spatially the sulfides are intimately associated with the distribution of a unit locally termed as sublayer, the temporal relationships between the sulfides and the sublayer, and between the main mass irruptive and the sublayer, are still the subject of some dispute. Furthermore, although it appears that the main copper-nickel ore deposits are predominantly located in the sublayer, not all the sublayer is equally mineralized. The sulfide content in the sublayer varies from massive ore grade to finely disseminated blebs (Souch *et al.*, 1969). Two possible explanations for this observation are a) more than one phase of sublayer is present, one of which is preferentially mineralized, or alternatively b) some as yet undefined mechanism has imposed a specific distribution pattern on the mineral deposits.

In essence these two alternatives present the two extreme endogenic models for genesis of the Sudbury sulfides: magmatic segregation and hydrothermal origin. As proposed initially, the magmatic segregation model considered that the ores were derived from a differentiating norite-micropegmatite body — the Sudbury Irruptive (Coleman, 1926; Collins, 1937). Recognizing that this model was not chemically viable, Naldrett and Kullerud (1967), later followed by Souch *et al.* (1969) modified the magmatic segregation model to one that related the sulfides to magmatic segregation from a later intrusion of a sulfide- and inclusion-rich sublayer magma along the base of the earlier main irrup-

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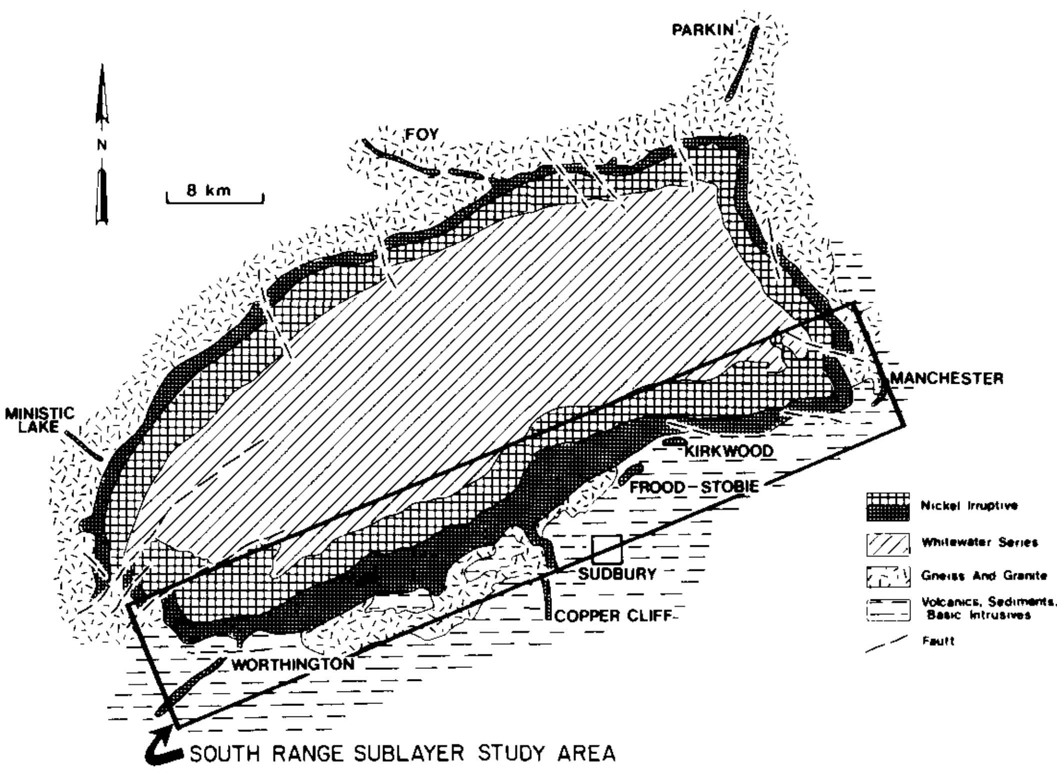
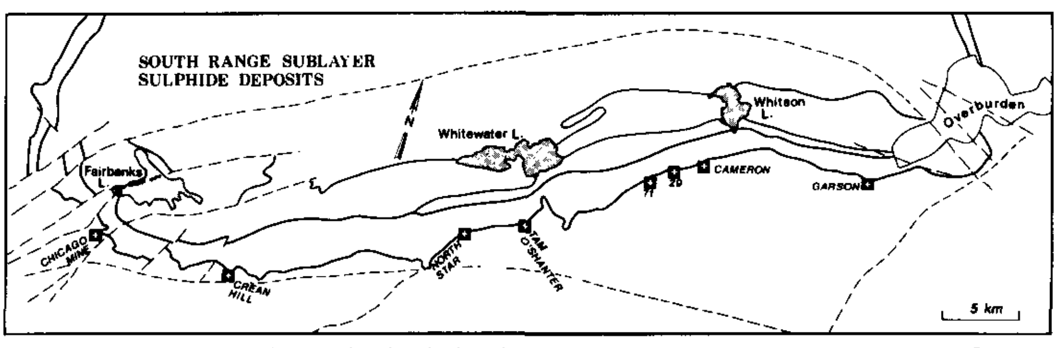
tive. However, noting that certain types of mineral alteration occurred around the ore deposits, Phemister (1925) and Yates (1938, 1948) favoured a hydrothermal origin for the ores. Support for this latter hypothesis has recently been given by Fleet (1977) who, describing the chemical heterogeneity of sulfide blebs in a disseminated sulfide deposit, found that it was incompatible with the magmatic segregation model. (It would be remiss not to mention Dietz's [1972] exogenic meteorite impact model, in which he considered the ores of cosmogenic origin being emplaced by splash as a result of impact melt. His model will not be discussed further in this paper.)

No one particular model appears to explain all the different deposits. One may adequately explain the genesis of a certain deposit at one particular locality, but then that explanation will be inappropriate at another location. Fur-





Figs. 1a, b. Diagrammatic map showing the location of the sampling sites on the south range of the Sudbury basin.

ther confusion is found on a closer examination of the sulfide textures in the sublayer. Fragmental sulfides are most common in the leucocratic breccia phase of the sublayer, whereas in the adjacent igneous sublayer phase interstitial sulfides predominate (Pattison, 1979). Together with the inadequacy of any one particular model in explaining the genesis of these ore deposits, the textural variations suggest the possibility of more than one sulfide-forming event. If more than one mineralization event is accepted, then it becomes important first, to define how the various events relate to the tectonic evolution of the Sudbury Basin (Morris, 1980, 1981), and second, to identify if any one particular mineralization event is related to economic-grade deposits.

Paleomagnetism provides a method of detecting the relative ages of rock units and their alterations, and also a method for defining the amount of relative rotation an area has undergone since acquisition of a particular remanence signature. This paper reports the results of a paleomagnetic investigation of a number of sulfide occurrences, most of which are located in the south range sublayer (Fig. 1). The exception is the Chicago mine site, which is located not in the sublayer but in a belt of older greenstone outcropping immediately south of the sublayer. The amount of sulfide present at the eight localities varied from massive ore-grade sulfide to occasional bleb sulfide in a noritic matrix. By covering this range of sulfide contents, it was hoped to provide answers to some of the problems related to sulfide genesis as outlined above.

RESULTS

Experimental Techniques

At each locality at least six (and occasionally as many as twelve) cores were drilled. Each core provided two specimens for paleomagnetic analysis. Remanence measurements and both thermal and alternating field treatments of the specimens were all made mainly on Schonstedt instruments (DSM, TSD and GSD). (Some high field a.f. treatments were performed on equipment built by the Earth Physics Branch.) Each specimen was demagnetized by at least eight treatment steps. No bulk cleaning was performed. Alternating field treatments were made in intervals of 1.0 to 10 mT, beginning at 1.0 mT and continuing up to a maximum of 160 mT. Thermal demagnetization steps of from 10°C to 100°C were used, depending on the proximity to any particular thermal unblocking point. Three methods were used (with varying degrees of success) to isolate individual remanence components from the multicomponent demagnetization trajectories of the individual specimens: a) least-squares fitting of linear and planar demagnetization segments on orthogonal projections (Zijderveld, 1967), the acceptance criteria being a minimum of four demagnetization steps and a maximum angular error of 7.5°; b) least-squares fitting of great-circle segments (Halls, 1976), with acceptance criterion being a minimum of five circle segments each having arc lengths greater than 10°; and c) sequential vector subtraction, the acceptance criterion being a minimum of three subtracted vectors with angular differences of less than 10°. From these methods it was possible to define remanence directions that are characteristic of a particular specimen. Summarizing the data from these specimens gives site mean directions that characterize the magnetic history of the area covered by the site.

Individual site mean results based on the statistical analysis of the demagnetized data outlined above are listed in Table 1. Groupings are made on the bases of directional similarity and demagnetization characteristics. Many of these directions are similar to directions previously reported from the Norite, the Micropegmatite and the Foy Offset (Morris, 1980, 1981; Morris and Pay, 1981); characteristic directions are respectively identified by the prefixes N, M and O. For the results reported here from the south range sublayer the prefix S is used. Directions closely similar to those previously reported from the other units of the Sudbury basin are identified by the same numerical designation (*e.g.*, M4 and S4 are directionally similar but are from respectively the micropegmatite and the sublayer). As some remanence acquisition events have different directional signatures in different sections of the basin, it must be remembered that in this paper we are mainly concerned with directions that represent the south range of the basin.

Chicago Mine

Samples at this locality were collected over a distance of 60 m; all were mineralized to some extent, and most came from within 30 m of a zone of massive sulfide. From all specimens at this locality it was possible to identify three distinct directional groupings, S4, S6 and S7 (Tables 1, 2, 3). None of the directional group-

Site	N	R	k	α_{95}	D	I	
N4/M4			S4				
Cameron 1	9	8.754	33	9	313	46	337 43
Chicago	12	11.532	24	9	328	32	321 24
"29"	11	10.478	19	11	321	44	341 45; 299 39
North Star					(312	60)	
Crean Hill 1	14	13.828	76	5	327	49	
Crean Hill 2	11	10.825	57	6	341	36	
N3/M3	$D=204^{\circ} I=+38^{\circ}$		S3				
Tam O'Shanter	4	3.952	62	12	015	-33	
Garson	4	3.980	154	7	226	18	
M8	$D=268^{\circ} I=+63^{\circ}$		S8				
Cameron 1	6	5.947	94	7	270	71	
"71"	6	5.897	48	10	260	72	
North Star	7	6.917	73	7	268	72	
Tam O'Shanter	9	8.936	126	5	79	-43	
Cameron 2	7	6.902	61	8	119	-69	

Notes: N and M prefixes define characteristic remanence directions previously found in the norite and micropegmatite units, N is the number of specimens retaining that particular remanence direction, R, k and α_{95} are the standard Fisher (1953) paleomagnetic statistics. Directions in brackets are the mean of three (or less) specimen determinations.

Table 1. Mineralization magnetizations.

ings has any diagnostic rock magnetic characteristics. The median destructive field (m.d.f.) is usually around 4 to 5 mT, although in some instances the direction may be retained up to fields as high as 50 to 70 mT. For most specimens meaningful directions are removed by 20 mT, and further treatment produced wild intensity and directional oscillations. These effects are almost certainly related to the acquisition of spurious magnetic components during the demagnetization process, the rate of decay of the alternating field being particularly important. Upon thermal treatment all specimens exhibit little directional coherence beyond 350°C, although some do show intensity decays of minor significance around the Curie point of magnetite.

Intensity decay during demagnetization up to 350°C is variable: some specimens show minor but gradual decay up to 340°C and then a large decay at 350°C; others exhibit a continuous gradual decay to 300°C, retain the same direction up to 350°C and then show no meaningful direction thereafter. All gradations between these two extremes are seen. Specimens with the S7 direction, which have the highest NRM intensities, tend to be demagnetized at slightly lower unblocking temperatures (T_{ub}). Purely on the basis of remanence characteristics, therefore, it is not possible to erect any definite acquisition chronology for these three remanence directions.

The three directions (S4, S6, S7) exhibit a crude zonation relative to the main mineralized zone. S7 is found nearest the mineral vein, S4 in the adjacent zone of disseminated mineralization, and S6 in the least mineralized part. S4 does not show a simple Fisherian distribu-

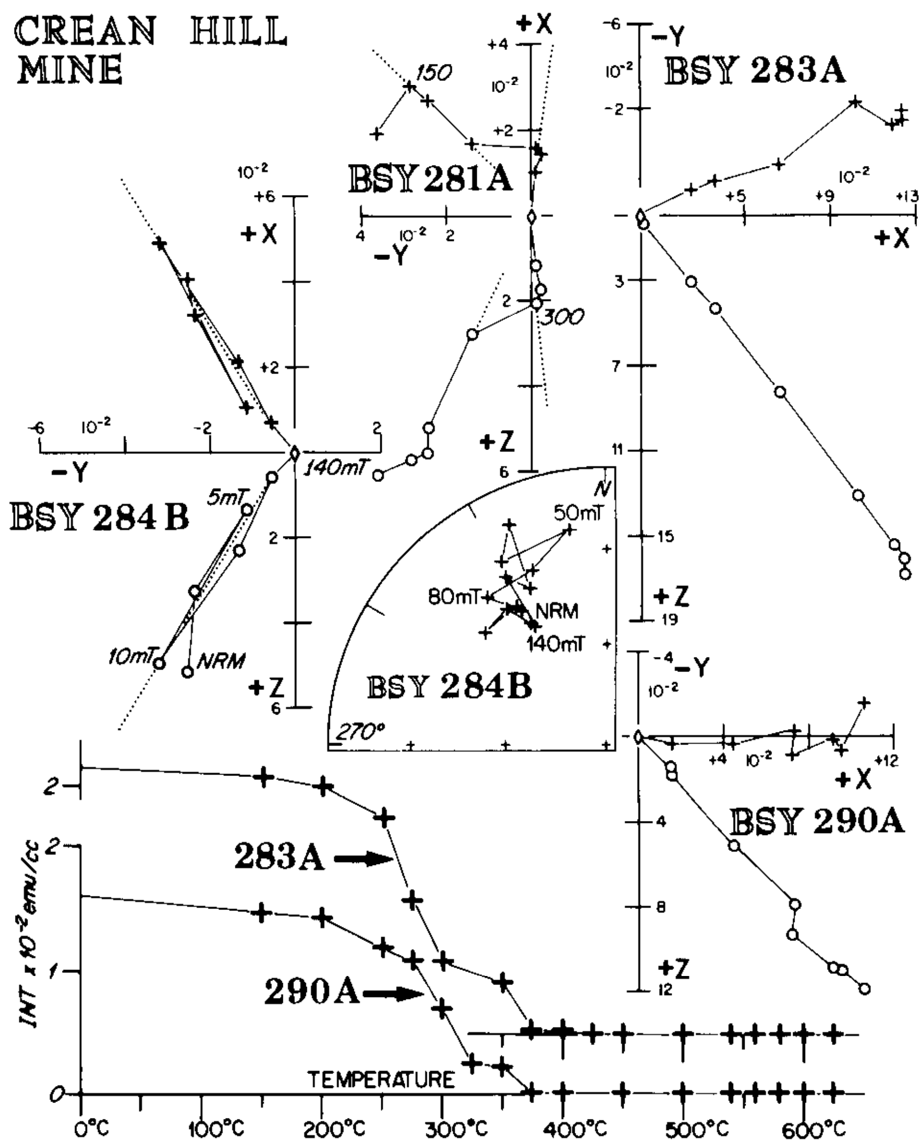


Fig. 2. Typical examples of the specimen demagnetization characteristics from the Crean Hill mine sampling locality. Zijderveld-type orthogonal plots are used in all diagrams. Projections onto the horizontal (xy) plane are indicated by crosses, projections onto either of the two vertical planes (zx, zy) are represented by open dots. The direction convention is + X is North and + Y is East. Individual directional components are identified by dotted lines. BSY284B shows the dual-polarity S4 remanence that survives to 140 mT. BSY281A shows the changes of declination possible in the two phases of S4. BSY283A and BSY290A show the unidirectional S4 remanence with two distinct T_{ub} points.

tion about the calculated mean. Indeed, there may be two distinct populations, with inclinations around 42° and 24°.

Crean Hill Mine

At this locality two sets of seven cores each were collected from highly mineralized sublayer. At each of the two sites, which are approximately 200 m apart, the sublayer has a definite foliation. The remanence signature at these two sites is totally dominated by the S4 remanence direction (Table 1).

Characteristically, the S4 direction at this locality has two unblocking temperatures at approximately 300°-320°C and 340°-360°C (Fig. 2). In most examples there is no significant directional difference between the two portions of demagnetization trajectory. On further thermal treatment above 400°, none of the specimens appears to have any meaningful directional components. Neither is there any evidence for the presence of any other stable remanence in the intensity decay curves. The higher thermal treatments usually reveal erratic direction and intensity fluctuations. The specimens themselves develop an over-all reddish cast related to the removal of sulfur and the generation of hematite. (Upon exposure to the ambient earth's field, this hematite can easily acquire a significant but spurious remanence.)

On a.f. demagnetization again, one observes a single direction that appears to reside in two distinct remanence carrying phases. One phase had a median destructive field between 5 and 7.5 mT (Fig. 2). Often on removal of this phase the remanent intensity exhibits a marked increase during the demagnetization steps immediately following. *On vector diagrams this intensity* decrease-increase with constant direction has the signature characteristic of a dual-polarity remanence (BSY284B — Fig. 2). The second phase, for most specimens, retains the same direction, with demagnetizing fields as high as 140 mT (Fig. 2). The remanent intensity found at these high demagnetizing fields often exceeds 1.0 mAm^{-1}. Superficially, these remanence characteristics may be misconstrued as evidence for significant amounts of hematite residing in these specimens. There is, however, no evidence for this either petrographically or in the thermal demagnetization data. Rather, the explanation is to be found in the petrographically recognized presence of two grain sizes of pyrrhotite, one that demagnetizes with low a.c. field as expected, and another that is shielded from demagnetization by a "skin effect". Essentially, this effect is caused by conduction of the demagnetizing field along the grain boundaries protecting the centres of these grains from demagnetization (Schwarz, 1975).

Site	N	R	k	α_{95}	D	I
<u>M6/N6</u>	D=033°I=+69°			<u>S6</u>		
Chicago	5	4.818	22	17	61	46
"29"	7	6.704	20	14	025	61
Crean Hill 2					(002	51)
<u>M2/N2</u>	D=193°I=+70°			<u>S2</u>		
Cameron 1	8	7.940	117	5	183	70
"29"	10	9.817	49	7	186	76
Tam O'Shanter	9	8.981	413	3	189	72
Cameron 2					(184	75)
<u>N1</u>	D=156°I=+43°			<u>S1</u>		
"71"	4	3.968	93	10	167	51
North Star	13	12.938	192	3	164	49

Table 2. Intrusion magnetizations.

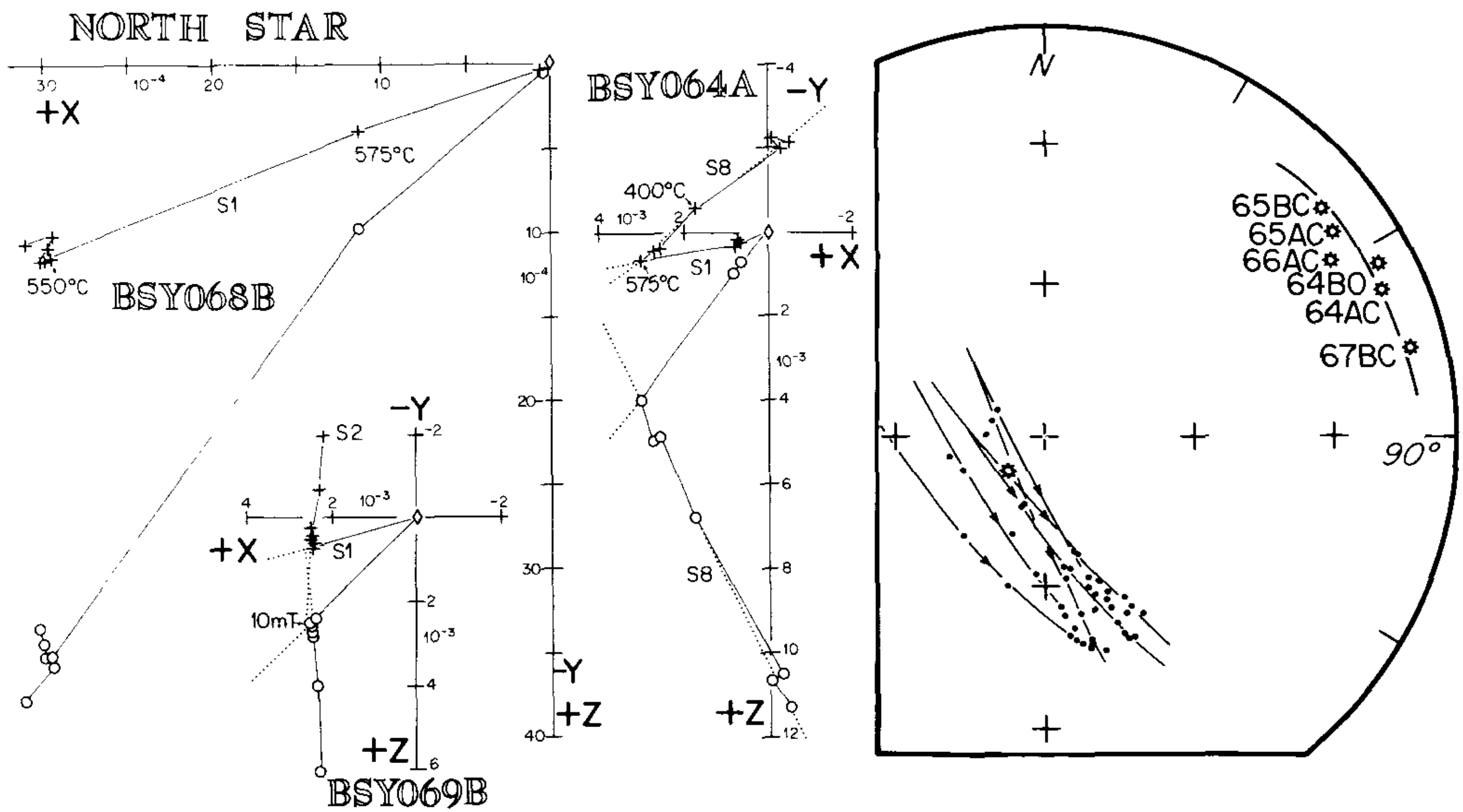


Fig. 3. Typical examples of the specimen demagnetization characteristics from the North Star mine sampling locality. At right, great-circle demagnetization segments are plotted on an equal angle stereonet. Individual specimen directions are identified by solid dots. Poles to the specimen great-circle segments are identified by asterisks, and an estimate of the mean vector being removed is also identified by an asterisk. BSY068B shows unidirectional S1 remanence in magnetite and hematite. BSY069B shows partial overprint of S2 on an S1 remanence. BSY064A shows separation of S8 and S1 remanences.

Directions found at these two sites do not show a simple symmetrical cluster about a mean; rather they show a smear from a northerly direction round to a more westerly direction. Inclination varies much less, with bounds of approximately +30° to +50°. Three specimens on thermal demagnetization have a direction that more closely resembles an S6 direction (steep down to NNE) than the more commonly observed northwesterly S4 direction. Where found, these directions apparently reside in phases with remanence characteristics similar to those carrying the S4 direction.

North Star Mine

Samples at this locality were collected from a region of disseminated sulfide mineralization in the sublayer very close to the basal contact with the main irruptive. From these samples three remanence directions were resolved (Tables 1, 2).

By far the most common direction found at this locality is that typical of the unaltered south range norite N1 = S1. Both thermal and alternating field demagnetization indicate that the dominant remanence carrier of this direction is a relatively low titanium magnetite which unblocks in the ranges 570° to 575°C and 60 to 80 mT. Further demagnetization reveals that this same direction is also found in hematite (Fig. 3).

The other two directions found at this site exist as low blocking temperature and coercivity components relative to the dominant S1 direction. Characteristic of this group are unblocking temperatures around 275° to 300°C and m.d.f. in the range 4 to 6 mT. No unblocking temperatures are observed in the range 300° to 400°C. There are no remanence characteristics by which it is possible to distinguish these two directions. Most often observed is a steep westerly direction — S8 (Table 1). As illustrated in Figure 3 (right-hand diagram), many specimens show evidence of the removal of this component during the first few demagnetization steps. Least-squares line-fitting estimates and a great-circle analysis estimate of this direction are identical.

The separate identity of the last direction (S4) quoted for this site is uncertain. Although the direction reported in Table 1 is distinct from the S8 direction discussed above, the errors in the estimates of individual S4 and S8 directional components are such that the two components are not statistically distinct.

Tam O'Shanter

One site was sampled from the disseminated sulfide zone around the Tam O'Shanter property. At this locality there is a sharp boundary between the mineralized sublayer and the overlying, essentially nonmineralized, basal quartz-rich norite. Three remanence directions were resolved from the specimens at this locality (Tables 1, 2).

The dominant magnetization S2 is most similar to the norite N2 direction of the south range. Throughout the locality this direction is characterized by distinctive magnetite unblocking temperatures between 575° and 580°C. Most specimens show almost no intensity decay between 300°C (after removal of other components) and the 580°C point; *i.e.*, the unblocking interval is very discrete. The dominant remanence phase must be magnetite with little or no titanium, with fairly uniform grain size. No trace of this direction is found above the magnetite Curie point.

Again the two overprints found at this locality have somewhat similar remanence characteristics. The apparently lower blocking temperature phase unblocks between 200° and 250°C and has a direction that is negatively inclined to the northeast (S3 reversed). (This direction is found only by thermal analysis.) The second overprint unblocks at slightly higher temperatures, usually in the range 300° to 320°C. In occasional specimens (Fig. 4) it is possible to see the sequential removal of these overprint directions giving rise finally to the dominant, steep, southerly inclined S2 direction. The second overprint has a direction that is negatively inclined to the east. It is uncertain with which direction it should be correlated. It vaguely resembles a reversed S8 direction.

"29" and "71"

Two sites were sampled from an area of mineralized sublayer along the northern margin of the Murray granite (Fig. 1b). Both sites, which are approximately 400 m apart, have disseminated sulfide phases. At site "29", which is closer to the highly mineralized zone adjacent to the easterly margin of the Murray granite, two specimens were also collected from xenoliths in the granite. Although these two sites are from apparently similar localities and lithological units, they have no remanence direction signatures in common. Yet both have three distinct remanence directions (Tables 1-3).

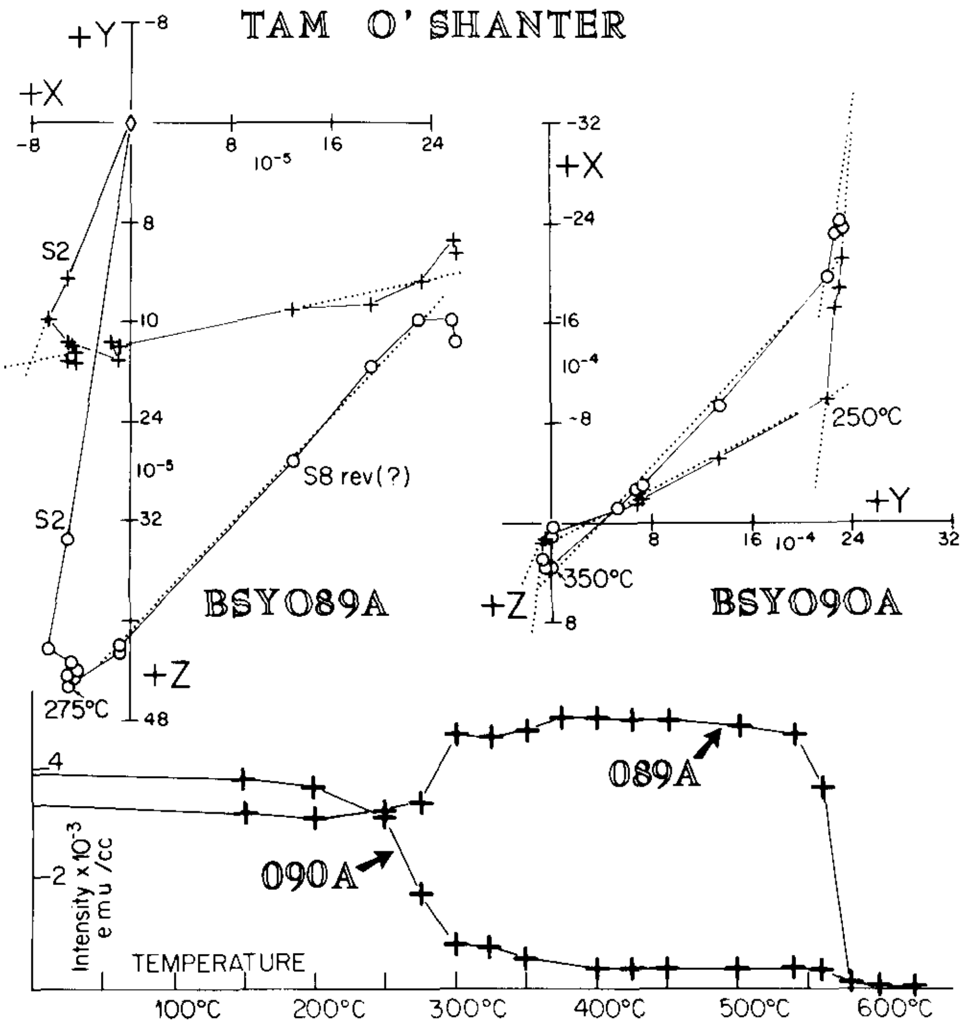


Fig. 4. Typical examples of the specimen demagnetization characteristics from the Tam O'Shanter sampling locality BSY89A and BSY90A show the two-phase nature of the remanence at this site. In both examples the two directions are S8 reversed (?) followed by S2. BSY90A also shows a third overprint that is removed by 250°C. Examples of the intensity change with thermal treatment are shown.

The specimens collected at Site "71" locality can be subdivided into two groups. One group retains only a single remanence direction around D = 260°, I = +72° (S8). The remanence phase carrying this direction has unblocking temperatures in the range 340° to 370° and m.d.f. around 6.0 to 6.5 mT. Further demagnetization beyond these limits does not provide any useful remanence data. The other group of specimens from this locality consistently has two component remanence directions. The less stable phase is characterized by unblocking temperatures around 320° to 340°C and very low m.d.f. ranging from 1.0 to 2.0 mT, and a mean direction that is D = 290°, I = -52° (S7). Further treatment of these specimens always reveals a second component (S1) residing in magnetite (unblocking temperatures 570° to 580°C, and m.d.f. between 50 and 80 mT).

At site "29" a two-component magnetization history is characteristic of most specimens. The

Site	N	R	k	α_{95}	D	I
M7/N7	$D=103^{\circ}$ $I=+30^{\circ}$		S7			
Cameron 1					(101	25)
Chicago	6	5.854	34	12	110	45
"71"	6	5.976	210	5	290	-52
Carson					(126	11)

Table 3. Late overprint magnetization.

first component, which has a mean direction of D = 321°, I = +44° (α_{95} = 11°), usually has unblocking temperatures in the range 300° to 325°C, although occasionally it is still found at temperatures up to 350°C. Upon a.f. treatment this phase is completely erased by 12.5 mT, and the m.d.f. is commonly between 4 and 6 mT. As at other localities where this direction is observed, the individual specimen directions define a smear from a northerly direction to a more westerly direction. At this particular locality, as shown in Table 1, the directions appear to cluster into two distinct groups. The second direction (S2) found in these specimens (Table 2) begins to decay with thermal treatment around 550°C and is totally removed by 580°C (Fig. 5). Upon a.f. treatment this direction is retained in fields up to 40 mT.

A third component at site "29" is of uncertain significance. In the sublayer it is seen only during the first two or three demagnetization treatments (to 2 mT and to 200°C). It is also the only consistent direction that is observed in the xenoliths in the adjacent granite mass. The mean direction of these estimates (D = 025°, I = +61°) agrees very closely with directions referred to as M6/N6 in the neighbouring micropegmatite and norite units. It is also very similar to the local ambient field direction. Recognizing that the phases examined here all have low thermal and coercivity stabilities, it is not possible to distinguish whether these directions are of recent viscous origin, or ancient thermal (?) origin. Because of the dubious significance of these data, they will not be considered further in this analysis.

Cameron Property

The heavily mineralized sublayer area known as the Cameron property, located at the eastern margin of the Murray granite, is close to the presently active Little Stobie mine. Two collections were made from this locality, one from the central, highly mineralized portion of the sublayer and the other from a marginal zone where the sublayer is in contact with the Murray granite. At this latter area mineralization is of the minor bleb occurrence type.

From the site in the central part of the sublayer (Cameron 1) it is possible to resolve three separate remanence directions (Tables 1 - 3), each having distinct unblocking temperature and coercivity characteristics. On treatment by either method the same sequence of magnetic components is always observed. An S4 direction (mean D = 313°, I = +46°, α_{95} = 9°) is associated with unblocking temperatures in the range 300° to 320°C, and m.d.f. between 2.5 mT and 6 mT (Table 1). At this locality all but one of the S4s are clustered toward the westerly direction. The second direction found on further treatment is an S8 (mean D = 270°, I = +71°, α_{95} = 7°), which unblocks thermally in the range 400° to 500°C (Fig. 6) and has m.d.f.s ranging from 10 to 40 mT (Table 1). Good estimates of this direction can be derived by all three analysis methods. As shown in Figure 6, the three methods yield statistically identical directional estimates.

The final component (S2) found at this (Cameron 1) locality unblocks around the Curie point of magnetite, and has m.d.f. in the range 25 to 50 mT (Table 2). Few of the specimen treatments above 580°C give any useful remanence information. In the odd example it is possible to tentatively identify this same S2 direction. However, the demagnetization trajectories are so poorly defined that these directions do not pass the stated minimum acceptance criteria.

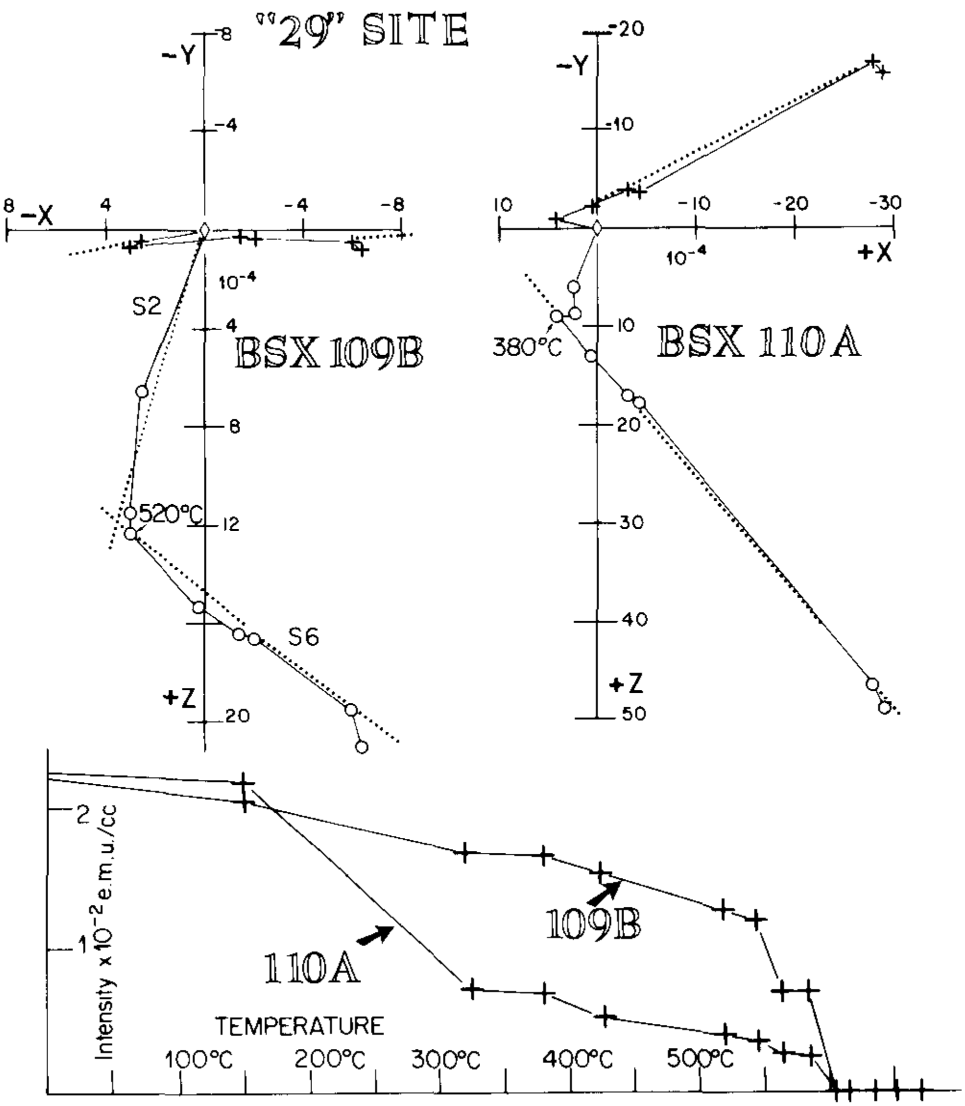


Fig. 5. Typical examples of the specimen demagnetization characteristics from the "29" site sampling locality. See the text for details of the individual examples.

The second site occupied at the Cameron property is approximately 60 m from the site described above, yet at this locality the remanence directions have a totally different signature. One direction ($D = 119°$, $I = +69°$, $\alpha_{95} = 8°$) dominates all the specimens, and only in one specimen is any other remanence direction found. The dominant remanence direction resides in a mineral phase with the following characteristics: unblocking temperatures in the range 300° to 340°C, and m.d.f. in the range 4.0 to 5.0 mT. The mean direction of this component is comparable to a reverse S8 direction (Table 1) which, as noted earlier, has hitherto not been described from this region.

With only one exception, further treatment of these specimens did not reveal any further

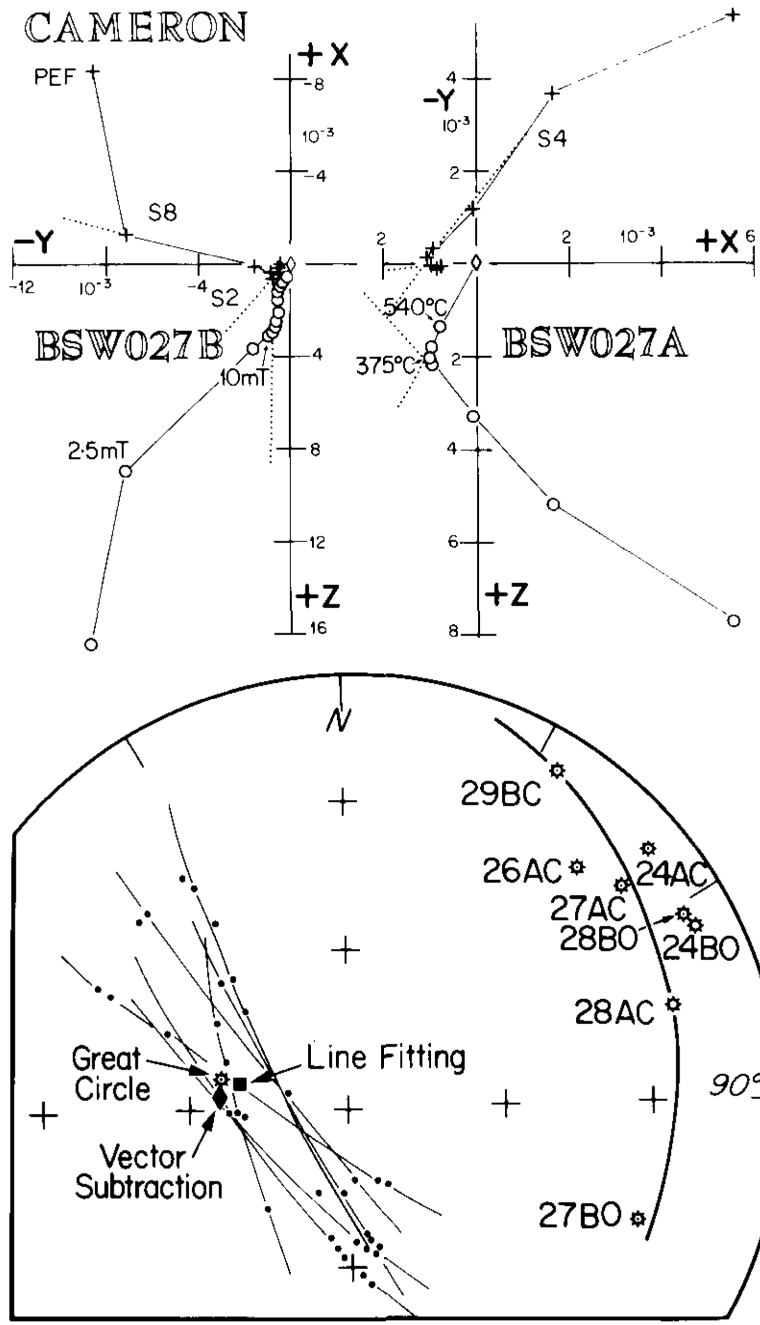


Fig. 6. Typical examples of the specimen demagnetization characteristics from the Cameron 1 locality, and a great-circle analysis of the first component removed. BSW027B shows an S8 direction overprinted on an S2 direction. The other half of the same specimen (BSW027A) has an S4 direction overprinted on an S2 direction. Great-circle analysis, vector subtraction, and least-squares line-fitting all yield identical estimates of the S8 direction as shown in the stereonet plot.

useful remanence record. The exception (specimen 26AC) carries a direction (closely approximating S2) that survives treatment up to approximately 580°C.

Garson Mine

A short section (20 m long) across a zone of gradually decreasing mineral content was examined close to Garson Mine. Three specimens were taken in each of three levels of mineralization. Unfortunately, because of extensive weathering of the least heavily mineralized specimens it was not possible to derive any coherent magnetic signature typical of this zone.

The adjacent zone has a uniform directional signature that is similar to the S3 direction previously reported from the south range norite (Table 1). On thermal treatment these directions show two separate unblocking temperatures, one in the range 250° to 300°C and the other in the range 360° to 370°C. Beyond this 370°C temperature no other information is found. This same two-phase remanence characteristic is also obvious in the data obtained by a.f. treatment. One phase is removed by 5 mT, while the other survives fields up to 150 mT. Throughout, these two phases have identical remanence directions.

Specimens from the most mineralized zone, while retaining exactly the same demagnetization characteristics as those described above, have a direction that is very different. In these specimens the only identifiable remanence vector is shallowly inclined to the east (Table 3). The only other distinguishing characteristic is the higher level of the NRM intensity in this zone.

Discussion

In all, seven remanence directions have been isolated from the eight sites of mineralized sublayer examined in this study. As shown in Tables 1, 2 and 3, all of them have direction equivalents in the norite and micropegmatite of the south range (Morris, 1980, 1981). By examining the character of the remanence-carrying phases associated with each of these directions, and the distribution of the correlative directions in the adjacent norite/micropegmatite of the south range, it is possible to deduce the regional significance of each remanence direction in the tectonic and mineralization evolution of this portion of the Sudbury basin.

Both the S2 and S1 directions reside in magnetite, and both are very common in the adjacent irruptive of the south range. Only the S1 direction, however, is found in hematite as well as magnetite. The S1 direction is restricted to the norite, where it is found intimately associated with the distribution of unaltered norite. And it is this direction that is considered representative of the initial intrusive signature of the south range norite (Morris, 1980). This suggests that part of the material here designated as sublayer may in reality be part of the norite unit or, alternatively, was intruded before the norite and then remagnetized by the norite intrusion later.

The S2 direction is found in both the norite and the lower parts of the micropegmatite. In the norite its distribution is directly related to the extent of metamorphic alteration (Morris, 1980). Also, the remanence-carrying phase in the norite has exactly the same characteristics as those described above for this portion of sublayer (unblocking temperatures indicative of pure magnetite, and the absence of the hematite signatures). As discussed before, one possible interpretation of this remanence characteristic is that the magnetite was formed during metamorphism, the remanence being blocked once the grains pass through a critical size threshold; *i.e.*, this is the record of a chemical remanence acquisition event. In the micropegmatite the equivalent M2 direction is known to be recording a separate intrusive event, as evidenced by a positive contact test.

Most other directions found in this study have unblocking temperatures in the range 200° to 350°C. This temperature range is typical for the thermal decay of the mineral pyrrhotite, which in this area is a major constituent of most of the ore deposits. Of the five remaining remanence directions, only three (S3, S4, S8) provide any definite information on ore genesis in the Sudbury area. Directions S6 and S7 can be discounted for the following reasons: Of the three estimates of S6 in this study, only one can be identified with any degree of certainty as a separate directional vector. The data from Crean Hill may, in fact, be recording the extreme end of the S4 data smear, while the directions found at site "29" all have extremely low stability and therefore may be of viscous origin. The S7 direction is identical to the Grenville front overprint direction (N7) reported by Palmer *et al.* (1977) from the Sudbury dykes, and by Morris

(1980, 1981) in the norite and micropegmatite. This remanence direction, dating from around 900 MA, postdates all other remanence acquisition events related to mineralization in the basin.

The recognition of three remanence directions, all intimately associated with the presence of sulfide phases and with remanence residing in pyrrhotite, could be interpreted in two ways. Either there have been three separate periods of mineralization whose origins may be a combination of magmatic and hydrothermal processes, or there has been but one mineralization event which acquired remanence at different periods. In a simple cooling model remanence is acquired only when the phase under consideration cools below its particular Curie temperature. As in this example the Curie temperature is only about 300°C, it is quite possible for regions in which the sulfide is residing to be maintained above this temperature for long periods. At some point later in time the region is uplifted and cooled, and acquires remanence. It may be possible to differentiate between these two models by examining the distribution of the various remanence directions at a particular outcrop. If a direction was acquired by uplift cooling, it should be recorded over an extensive area; that is, until some distinct discontinuity (fault boundary, for example) is recognized. The hydrothermal model could affect regions over a very limited extent.

Equivalents of the S3 and S8 directions have been observed in direct association with significant amounts of sulfide mineralization in the Hess township segment of the Foy offset portion of the Sudbury structure (Morris and Pay, 1981). From the study of a complete section across the offset at this locality, it was possible to identify two periods of mineralization. Part of the mineralization has a direction (S8 equivalent) identical to that observed in the immediately adjacent barren diabase. The identity of remanence directions in the completely barren and heavily mineralised portions of offset may be interpreted in two ways. Either this phase of sulfides is of magmatic origin related to the intrusion of the offset or, alternatively, the whole offset (with T_{ub} of 580°C) was reset when the sulfides were introduced at a later date. The first alternative is preferred, because the S8 direction is found at many other localities in the absence of sulfides, and this same direction has been correlated to the intrusion of the second phase of micropegmatite. The S3-carrying sulfides in this offset are separated from the S8-carrying sulfides by a narrow dyke (≈.5 m). Both remanence directions reside in minerals with similar remanence characteristics (*i.e.*, T_{ub} 300°-350°C). This proximity precludes the interpretation of just one phase of sulfide genesis, because any reasonable burial model would require that all the sulfide in this offset have the same direction. Therefore, the S3 direction must represent either a local remobilization or a later hydrothermal introduction of sulfides.

In the south range sublayer examples examined in this study, these two directions (S3 and S8) are most commonly associated with disseminated sulfide phases. Only at Garson Mine is the S3 direction observed to occur with more significant quantities of sulfide ore. This new data set does not provide any further constraints on the genesis of the the S3- and S8-related mineralization phases.

Like the S3 magnetization, the S4 direction is always found closely associated with mineralization. No barren intrusives containing this remanence direction have been found. This observation, together with the following features, suggests that S4 also records a period of secondary sulfide deposition (be it remobilization or hydrothermal deposition).

First, the S4 direction is found to exist in areas of very limited extent, with adjacent low T_{ub} components having different directions. At the two Cameron property localities the heavily mineralized site (Cameron 1) is dominated by the low blocking temperature phase S4 direction, while just 60 m away no trace of S4 is observed, and the equivalent low blocking temperature components are dominated by S8.

Second, within individual sites there are distinct variations in the directional estimates of S4 (Table 1). This may be indicative of differences in the time of remanence blocking even over relatively small distances (10 m). A plot of all the S4 determinations defined by this study shows broad directional variations in this component. Plotting individual site mean directions shows that this broad smear may actually be a section of directional track. (The smear in the individual data points may be partly real; that is, arising from slightly different blocking times related to secular variation, and partly false, arising from the biasing effects of the anisotropy of remanence-carrying pyrrhotite.)

Third, the S4 remanence acquisition event has regional significance: it is seen overprinting magnetizations in the norite, the micropegmatite, the offsets *and* the Onaping Formation. The individual S4-equivalent data points from all units of the north range are broadly similar to the south range sublayer data described above. The site mean directions outline a possible directional track that is quite similar, but displaced to the south of, the south range sublayer data. (The significance of this displacement is discussed later.)

Fourth, the position of the site mean direction on the possible directional track is location-dependent for both north and south ranges. S4-equivalent directions from the more easterly portion of the north range preferentially have a more northerly direction, while those from the more westerly portion have a more westerly declination. In the south range data there is a suggestion that the more easterly sites have the more westerly declinations, which is opposite to the north range data. However, the more heavily mineralised northwest and southeast corners of the Sudbury Basin both appear to have a predominance of westerly declination S4 directions.

Fifth and finally, the demagnetization characteristics, especially of the data from the two Crean Hill Mine sites, suggest that S4 is secondary origin. Consistently, the thermal demagnetization of these specimens gave two unblocking temperatures at 300° to 320°C and 340° to 360°C. According to Brodskaya *et al.* (1976), this higher Curie point is typical of monoclinic pyrrhotite, while the lower temperature, which represents the more commonly accepted Curie point for pyrrhotite, characterizes hexagonal pyrrhotite. The presence of this monoclinic pyrrhotite reinforces the suggestion that this S4 direction arose as a result of a regional hydrothermal or remobilization event.

In comparison to the S8 and S3 sulfide-related magnetizations, the S4 direction is generally associated with the massive concentrations of ore. In particular, three of the areas examined in this study — Chicago, Crean Hill, and Cameron property — are the locations of past mining activity. On the north range the S4-equivalent magnetizations have been found in such well-known mining areas as the Levack region and the Nickel Offsets mine. When all occurrences of this component are separated from all the other sites that have been studied paleomagnetically, it is suggested that there may be a broad regional pattern of mineral occurrences (Fig. 8). Clearly, many more sampling localities are required to either verify or reject this pattern but, if found valid, the presence of this remanence signature could become an important exploration tool.

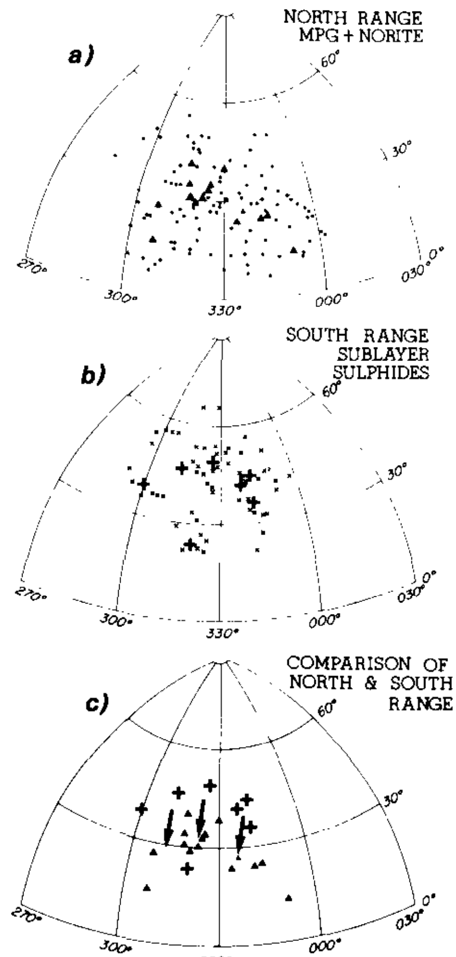


Fig. 7. Equatorial equal-angle stereographic projection of all the individual S4 directions observed in a) the north range norite and micropegmatite (dots) and their site mean directions (triangles), and b) the south range sublayer sulfides (small crosses) and their site mean directions (large crosses), c) comparisons of site mean directions between the south and north range data. The arrows indicate the preferred sense of fault rotation that explains the observed discrepancy in inclination between the two ranges.

There is a consistent inclination difference between the north and south range data for all except one site from the Chicago Mine locality (Fig. 7). This discrepancy may result from the fault rotation of the south range relative to the north range after this remanence direction was acquired. A best estimate of the rotation derived by comparing the modes of the north and south range data suggests that the south range has been rotated by approximately 15° to the northwest about a strike approximately parallel to the major faults that crosscut the southern margin of the basin. This rotation, although of the same magnitude as that defined by the S3 remanence direction in the norite (Morris, 1980), is about a strike at right angles to that defined here by S4 remanence directions. These faults therefore appear to have undergone multiple rotations, and the complexities of their motions are as yet only partially understood.

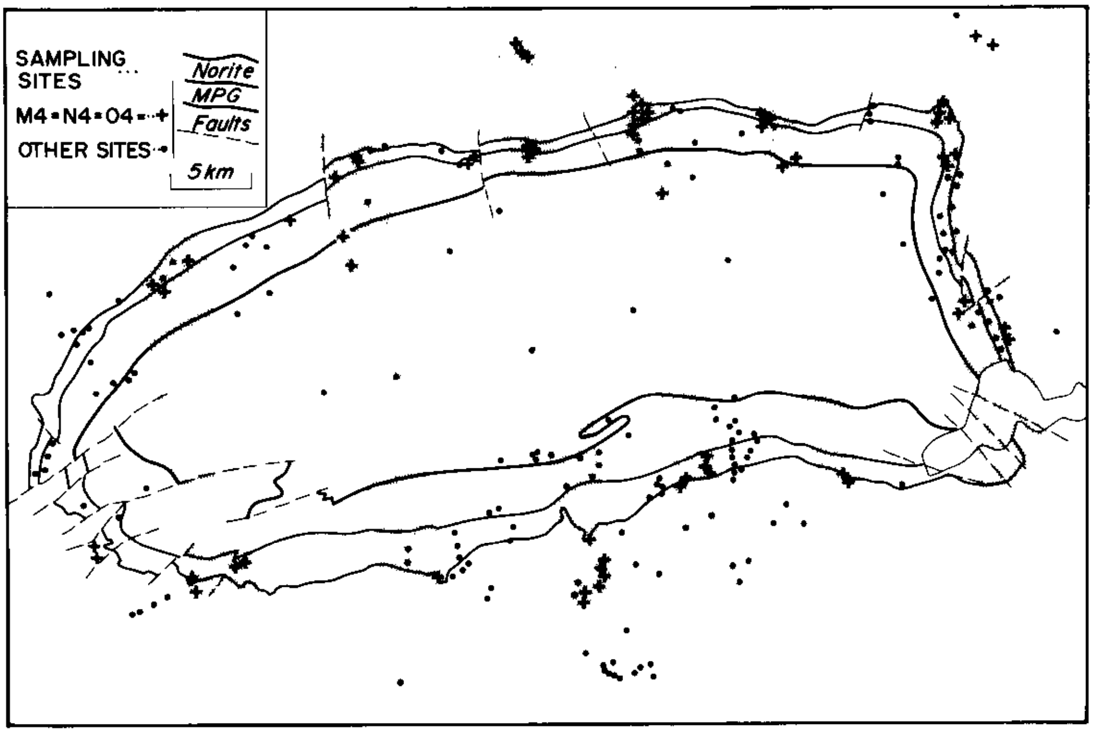


Fig. 8. Plot of all sampling localities occupied during this survey of the Sudbury basin. Sites that contain evidence of the S4 = M4 = N4 = O4 remanence direction are identified by crosses. Sites where the S4-equivalent magnetization is absent are identified by solid dots. The shaded areas appear with the present data set to be the preferred loci of the S4-equivalent magnetizations.

Conclusions

Paleomagnetic data from eight mineralized localities, most of which are located in the south range sublayer, provide evidence that this unit has evolved with the rest of the Sudbury basin through many remanence-recording events. Specific conclusions with respect to the temporal relationship between the sublayer and the irruptive, and on the distribution of sulfide mineralization, are:

1) At least some parts of the sublayer were formed contemporaneously with portions of the main irruptive.
2) Three distinct phases of sulfide genesis can be recognized in the sublayer.
3) The first phase of mineralization recorded by the S8 remanence direction is probably of magmatic origin and was introduced with the second phase of micropegmatite intrusion.

4) The second and third phases of mineralization are probably of secondary remobilization or hydrothermal origin. The paleomagnetic data cannot distinguish between these two possibilities.

5) The third phase of mineralization, which is generally associated with many of the more economic deposits in the Sudbury Basin, appears to have a systematic distribution as defined by the observation of S4 remanence directions.

6) After the formation of the S4-remanence carrying mineral phase, the south range was fault-rotated in relation to the rest of the basin. This fault rotation, although of similar magnitude to one recognized in a study of the Sudbury norite, is about a different axis. It is the first indication that many of the faults may have a multiple-rotation history.

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