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SULPHUR ISOTOPE STUDY OF THE MUSKOX INTRUSION, DISTRICT OF MACKENZIE (86 J/13, O/3)

(Report, 18 figures and appendix)

Akira Sasaki

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ABSTRACT

Sulphur isotopic ratios (S^{32}/S^{34}) have been determined in more than 300 samples of sulphides, mainly pyrrhotite, chalcopyrite and pyrite, collected from about 260 different localities in the Muskox intrusion and its adjoining rocks. The results are given in δS^{34} per mil values with respect to the Cañon Diablo troilite sulphur, assuming its S^{32}/S^{34} ratio to be 22.220.

All the samples from the intrusion body have isotopic compositions enriched in S^{34} relative to the meteoritic standard. Data for the main structural units of the intrusion are as follows: feeder dyke – +6.4 to +14.4, averaging +10.1; marginal zones – +3.1 to +16.9; layered series – +1.1 to +10.4, averaging +5.1.

In the outermost 200 feet of the marginal zone, the isotopic data correlate with the type of adjacent country rock. δS^{34} for the marginal-zone sulphides is greater than +9.0 in the areas adjacent to metasedimentary rocks, and less than or equal to +9.0 adjacent to granitic rocks. Isotopic data in the inner part of the marginal zone are less variable and somewhat lighter, with δS^{34} values ranging from +3.1 to +7.3 and averaging +5.0. Sulphides in country rocks adjoining the intrusion have δS^{34} values from -4 to +30.

From the composite data it is concluded that the average isotopic composition of sulphur in the intrusion magma was about +5 at the time of emplacement or very shortly afterwards. This average was preserved without much change in the rocks of the layered series and the inner part of the marginal zone, but appears to be significantly modified in the feeder dyke and the outer part of the marginal zone as the result of certain interactions between the magma and the country rock. It is difficult to draw definite conclusions as to the nature of these interactions. Contamination by country rock sulphur is a possible process but there is opposing evidence indicating that little or no foreign sulphur was introduced into the intrusive margin.

As long as the intrusion is considered to be an almost uncontaminated derivative of the upper mantle of the earth, the apparently heavier isotopic value of the sulphur in the intrusion as compared to other mafic and ultramafic intrusions may suggest inhomogeneity in the isotopic composition of the mantle sulphur. However, the average sulphur isotopic value in the emplaced magma (+5 per mil) may have been influenced by sulphur in the country rock and, therefore, may not be representative of either the original Muskox magma or of the mantle.

SULPHUR ISOTOPE STUDY OF THE MUSKOX INTRUSION, DISTRICT OF MACKENZIE (86 J/13, 0/3)

INTRODUCTION

The Muskox intrusion is a layered ultramafic-mafic pluton of Precambrian age situated in the Coppermine River area of the Northwest Territories. One of the remarkable features of this intrusion is that it is continuously exposed from its feeder to roof, and its entire internal form is well preserved. The intrusion has been studied since 1960, as part of the Canadian contribution to the International Upper Mantle Project, and comprehensive geological, geochemical and geophysical studies are now in progress. This paper presents the results of a sulphur isotopic study made by the author at the Geological Survey of Canada between 1962 and 1964. The study involved about 300 determinations of the S^{32}/S^{34} ratio of sulphide sulphur obtained from various parts of the intrusion and its environs. The samples used for the study were collected by members of the Geological Survey of Canada during field investigations from 1959 to 1963 (Smith, 1962; Findlay and Smith, 1964).

It was anticipated that the sulphur isotope data would be important in two respects. First, combined with basic geological and geochemical data, they should aid in interpreting the processes involved in the formation of the intrusion, particularly its sulphides; and secondly, the data may add important information on the isotopic composition of sulphur in the earth's subcrust or mantle where the parental magma of the intrusion was probably derived.

The isotopic trends obtained in this study are in fact very complicated. Amongst the many unusual features, a marked enrichment in the heavier isotope, S^{34}, is perhaps most striking: the average isotopic ratio expressed as a δS^{34} per mil value is about +5 with respect to meteoritic sulphur. This is surprising, because it is considered that the intrusion is derived from the earth's mantle and that its sulphides are magmatic in origin. In other investigated occurrences of probable magmatic sulphide, the sulphur has an isotopic composition close to the meteoritic value (i.e. $\delta S^{34} \sim 0$; e.g. Smitheringale and Jensen, 1963; Shima et al., 1963). Interpretation of the Muskox data therefore forces a choice between the following two major postulates: (1) the sulphur isotopic composition of the mantle, where the parental magma of this intrusion originated, was significantly heavier than that of meteoritic sulphur; or (2) the bulk of the sulphur contained in the present intrusive body is not truly representative of mantle sulphur. A few possibilities for the second case are discussed, but none appears conclusive at the moment.

ACKNOWLEDGMENTS

The study was carried out in the laboratories of the Geological Survey of Canada where the author spent two years as a postdoctorate fellow

Ms. received 6 June, 1968.

of the National Research Council of Canada on temporary leave from the Geological Survey of Japan. The author wishes to express his thanks to the Geological Surveys of Canada and Japan for the opportunity to do this work, and to the National Research Council of Canada for financial assistance.

A number of people at the Geological Survey of Canada assisted the author in various stages of the investigation. The author is particularly indebted to R.K. Wanless for his encouragement, suggestions and criticisms throughout the work. C.H. Smith, J.A. Chamberlain and T.N. Irvine gave much valuable information about the geology, petrology and sulphide mineralogy of the Muskox Intrusion as well as many helpful discussions and criticisms on the work, and the author is grateful for their kindness. The criticisms and suggestions of K. Kanehira and R.D. Stevens are also greatly appreciated. Acknowlegment here, however, does not necessarily imply agreement with all of the ideas expressed.

Assistance in the laboratory work was given, in particular, by J.A. Lowden, R.D. Stevens, C.R. McLeod and D.C. Bradshaw. S. Sasaki aided in preparation of the manuscript.

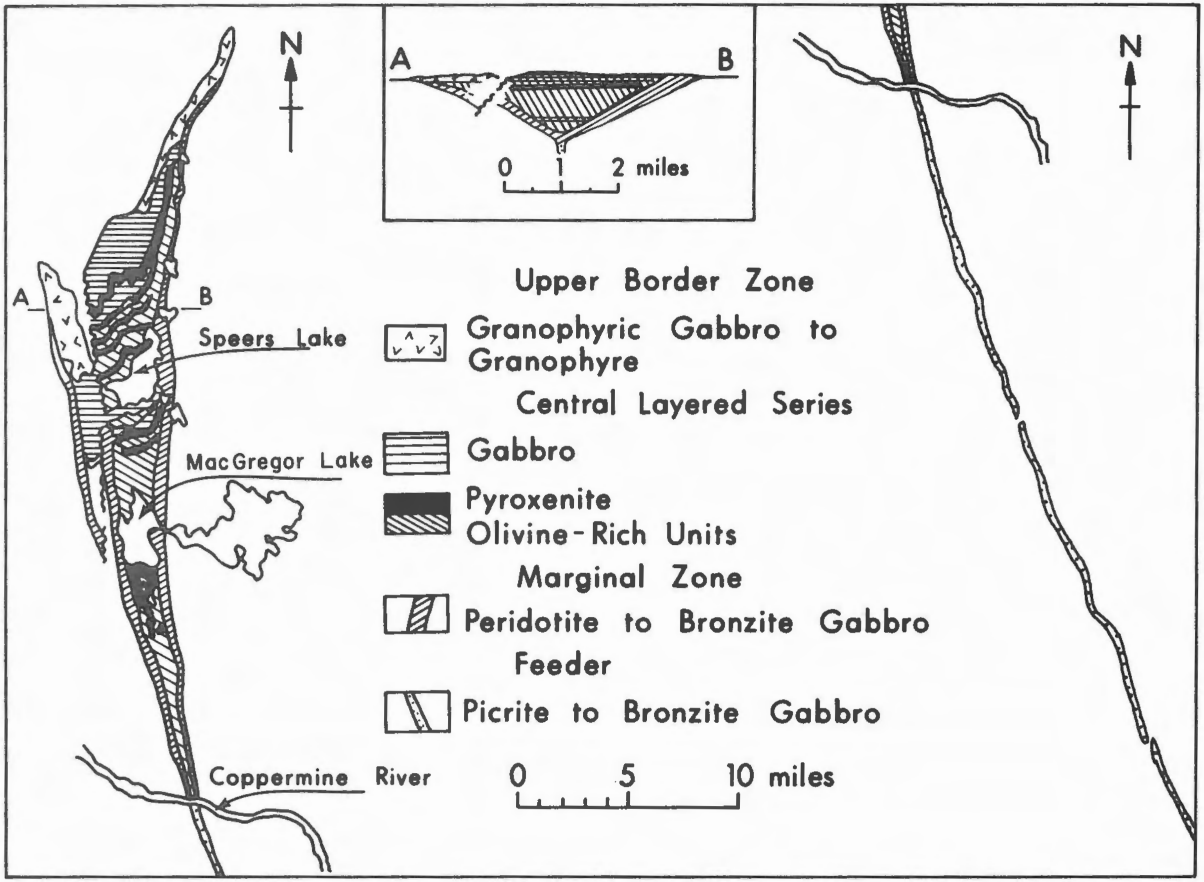
GEOLOGICAL SETTING

The original setting of the Muskox intrusion was outlined by Fraser (1960). The geology of the intrusion was first described by Smith (1962), and a preliminary discussion of its petrological significance, in particular the apparent difference between the bulk composition of the intrusion and its chill facies, was given by Smith and Kapp (1963). A detailed description of a diamond drilling program carried out in 1963 has been published by Findlay and Smith (1964), and coloured geological maps at 1 inch to 1 mile have been published (Geol. Surv. Can. Maps 1213 A and 1214 A). The sulphides associated with the intrusion are described by Chamberlain (1967), and a short account of the geologic history of the intrusion is given by Irvine and Smith (in Wyllie, 1967)

The intrusion is exposed for 74 miles in a Precambrian basement complex of steeply dipping gneiss, metasedimentary and metavolcanic rocks. The age of the basement complex as indicated by a K/Ar age on biotite from granodiorite is 1765 m.y. The intrusion is emplaced beneath a Middle Proterozoic sequence of sandstone, dolomite, and basalt that rests unconformably on the basement rocks and dips gently to the north. Aeromagnetic and gravity data show that the intrusion extends northward beneath these roof rocks for at least another 75 miles, its cross-sectional dimensions becoming larger in that direction. Where exposed, the intrusion is dyke-like in plan and funnel-form in cross-section, so that its shape may be compared to a sailboat, the main body of the intrusion corresponding to the hull, and the feeder dyke, to the keel. The northward plunge of the body at an angle of 4 degrees causes the feeder to be exposed at its southern end. The K/Ar age of the intrusion based on biotite in picrite from the marginal zone is 1155 m.y.

The intrusion is internally divided into three principal structural units: the feeder, the marginal zone, and the layered series, with the layered series having an upper border zone (see Fig. 1).

The feeder consists of bronzite gabbro and picrite in zones parallel to the nearly vertical walls. The bronzite gabbro occurs along the walls,



(after SMITH and KAPP, 1963)

Figure 1. Generalized geology of the Muskox intrusion.

and is chilled against the country rocks but not against the picrite. The chilled margin has the composition of a tholeiitic basalt (Smith and Kapp, 1963). The marginal zones are situated along the inner dipping walls of the main body of the intrusion. They range in thickness from 200 to 1,200 feet, and grade inward from bronzite gabbro at the contact through picrite and feldspathic peridotite to peridotite and, in places, dunite.

The central layered series is approximately 6,500 feet thick at its centre and contains 42 main layers of dunite, peridotite feldspathic peridotite, olivine clinopyroxenite, websterite, orthopyroxenite, melano-gabbro, feldspathic websterite, picritic websterite and gabbro. Individual layers range in thickness from 10 to 1,100 feet. The layers have sharp contacts, in contrast to gradation in the marginal zone, and they are nearly flat lying and so are discordant to the marginal zones. Chromite is concentrated in two thin layers.

The upper border zone is less than 200 feet thick. Its lower boundary is arbitrarily defined by the appearance of abundant interstitial granophyre and quartz in the upper gabbro units Within the upper border zone there is an upward gradation from granophyric gabbro through mafic granophyre to granophyre. This takes place over thicknesses of the order of 100 feet. The top of the intrusion has barely penetrated its sandstone roof, fragments of which are included in the granophyre layer, forming in places a zone of contact breccia.

The history of the intrusion is briefly as follows (T.N. Irvine, and C.H. Smith, personal communication): magmatic liquid of basaltic composition initially rose along a near-vertical fracture (as now represented by the feeder dyke) in the basement rocks and spread along the unconformity beneath the sandstone. Room for the magma was largely made by downwarping of the basement rocks, and it is believed that the much larger, unexposed northern part of the body may occupy a graben or rift-type structure. The original liquid apparently carried some olivine in suspension, this being concentrated in the centre of the feeder dyke by flowage differentiation and eventually frozen in, thus giving the picritic central zone of the dyke (Smith and Kapp, 1963; Bhattacharji and Smith, 1964). Some of the transported olivine may also have settled in the main body of the intrusion, becoming incorporated in the lower marginal zones. Fractional crystallization of the main body of the liquid then commenced, leading to formation of layers of dunite and pyroxenite. However, the crystallization was repeatedly interrupted by movements of magma from north to south in the space between the roof of the intrusion and the accumulated layers. In this way, new liquid was periodically brought in from the north to where the intrusion is now exposed (the old liquid was probably pushed on to the south and errupted through volcanic fissures), with the result that the repeated layers of dunite and pyroxenite were precipitated. Eventually, the overall fractionation of the magma progressed sufficiently so that layers of gabbro were also formed. When the magma chamber was largely filled with crystalline material, and north-south movement of liquid was no longer possible, complete fractionation of the remaining liquid, together with partial melting of the roof-rocks, produced the granophyre.

There has been some contact metamorphism of the country rocks adjacent to the intrusion as indicated by the presence of minerals such as biotite, garnet, cordierite, hypersthene and sanidine, but present knowledge of these rocks is limited and the exact extent of the metamorphic aureole is not established, although it probably has a width of the order of a few hundred feet.

A number of diabase dykes are exposed in the area. They occur in swarms parallel with the Muskox intrusion and generally cut all other rocks of the area. Most are medium grained, and they generally contain free quartz and granophyre.

SULPHIDE DISTRIBUTION IN THE MUSKOX INTRUSION AND ADJACENT ROCKS

The following summary of the sulphide distribution in the Muskox intrusion and adjacent rocks is based on descriptions by Smith (1962), Chamberlain and Delabio (1965), Chamberlain *et al*. (1965) and Chamberlain (1967).

INTRUSION

Sulphides in the Muskox intrusion are most abundant along its basal margin. Disseminated to massive sulphides occur along and adjacent to the main intrusive contact, in general within a zone 10 to 20 feet wide, although, in places, minor disseminated sulphides may extend both outward into the country rocks and inward into the marginal zone of the intrusion for some 100 feet. Along the contact is breccia ore consisting of intrusive and country rock fragments in a sulphide matrix. Pyrrhotite is the principal mineral in the sulphides, accompanied by chalcopyrite, cubanite and pentlandite. Minor amounts of sphalerite and galena occur in places, associated with other sulphides or forming separate, late-stage veinlets cutting the contact zone. The massive sulphides tend to be extremely coarse grained: single crystals of pyrrhotite having edges more than 5 cm are not rare, and one crystal was found to measure over 30 cm. Disseminated sulphides are fine to coarse grained, and in places are poikilitic in texture. Near-surface weathering conditions have resulted in the development of secondary sulphide minerals such as marcasite, pyrite and siegenite.

Within the marginal zone of the intrusion, the sulphides occur as fine disseminations, their grain size normally being less than 1 mm. The sulphide mineral assemblage is similar to that observed in the main contact zone, as given above, but the copper-bearing minerals seem to decrease inward. The average sulphide content in the marginal zone, excluding the contact sulphides, is of the order of 0.1 per cent of the volume of the host rock.

Sulphides are common minor constituents in the feeder dyke of the intrusion, especially in the bronzite gabbro. The same four-phase sulphide assemblage, pyrrhotite-pentlandite-cubanite-chalcopyrite, is observed, but chalcopyrite predominates, especially toward the southern end of the dyke. The grain size of the sulphide minerals is variable, but the average is well below 1 mm. In contrast with the basal contacts of the marginal zones, no concentration of sulphide minerals has been observed along the contacts of the feeder dyke. The average sulphide content in the feeder rocks is estimated at about 0.05 to 0.1 per cent by volume.

In the central layered series of the intrusion, sulphides are thinly disseminated as small (mostly less than 0.5 mm across) specks and blebs. There is a vertical zoning in the sulphide mineral assemblages sympathetic with variations in the host silicates (Chamberlain, 1967). A nickel-iron sulphide zone that contains pyrrhotite and pentlandite occurs in the lower dunite-rich layers. In the middle horizons of the central layered series, where olivine-rich rocks such as dunite and peridotite alternate with various pyroxenites, a nickel-iron-copper sulphide zone is recognized; the sulphide minerals are pyrrhotite, pentlandite, cubanite and chalcopyrite, but pentlandite is less abundant compared to the underlying nickel-iron sulphide zone. The upper part of the central layered series, which consists mainly of gabbroic rocks, comprises a copper-iron sulphide zone of chalcopyrite, cubanite, pyrrhotite and pyrite. Chalcopyrite occurs rather consistently throughout the zone, whereas cubanite, pyrrhotite, and pyrite are predominant in its lower, intermediate, and upper portions, respectively. The sulphide content in rocks of the central layered series tends to increase upward. The average value (by volume) is estimated as 0.005 per cent for the nickel-iron zone, 0.005 to 0.05 per cent for the nickel-iron-copper zone, and 0.5 to 0.1 per cent for the copper-iron zone.

A few chromite-rich horizons in the upper part of the central layered series contain higher concentrations of sulphides (up to 2 per cent across 5 to 10 feet). Small concentrations of pyrrhotite and chalcopyrite in the two thin chromite-rich layers are strikingly similar to sulphides in the Merensky Reef of the Bushveld Complex of South Africa. Cubanite and pentlandite are common minor constituents in these sulphides. The disseminated grains are commonly 2 mm in diameter but range up to 2 cm or more locally.

Sulphides in the upper border zone of the intrusion are mainly pyrite associated with some chalcopyrite, and occur as fine disseminations through the host granophyric rocks. The mineral assemblage and the mode of occurrence of the sulphides are, therefore, similar or gradational to those of the upper part of the central layered series. However, the sulphide content of this zone appears to be considerably higher than that of the central layered series; the average value may be as high as 1 per cent by volume. Along the intrusive contact between the upper border zone and the roof-rocks, pyrite and chalcopyrite are commonly concentrated within a width of a few inches. The same sulphide assemblage extends into the roof-rocks for a few more tens of feet.

The zoning of the sulphide mineral assemblages in the central layered series and upper border zone of the intrusion is schematically shown in Figure 2. The relative sulphur content in each zone is given according to the results of microscopic modal analysis made by Chamberlain (1967). It is remarkable that the sulphur in the upper border zone comprises nearly 80 per cent of all the sulphur in the layered rocks.

The majority of the sulphides in the central layered series appear to have formed interstitially against early formed silicate and oxide grains such as olivine, pyroxene and chromite; they are not texturally distinguishable from 'intercumulus' silicates such as pyroxene and feldspar. This, together with the systematic variation in the sulphide mineral assemblages outlined above, indicates that these sulphides crystallized directly from the magma in equilibrium with their host silicates. Similar textural relationships between sulphides and silicates can generally be seen in the

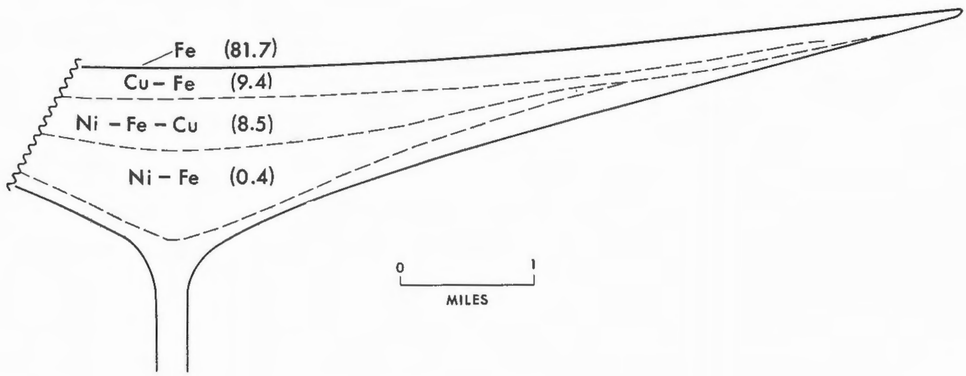


Figure 2. Distribution of sulphide zones in the layered series of the Muskox intrusion. Figure in parenthesis shows the abundance (in per cent) of sulphide in each zone to total sulphides in the layered series (after Chamberlain, 1967).

feeder, and in those parts of the marginal zone where sulphides are relatively sparse. The high concentration of sulphides along the intrusive contact, especially along its basal margin, cannot be explained by simple magmatic segregation in situ. It requires the introduction of sulphide-forming materials. Available mineralogical data indicate that the sulphide concentration was developed by a desulphidization of the Muskox magma during its primary cooling cycle and that the sulphide transfer in these locations was controlled primarily by the temperature gradient in the magma rather than by gravity settling of a separate sulphide fluid (Chamberlain, 1967).

All olivine-rich units of the central layered series show some alteration to serpentine, this having occurred well after freezing of the intrusion. The serpentinization has modified the original sulphide mineral assemblages causing the formation of minerals such as secondary pyrrhotite, mackinawite, chalcocite, native copper, and native alloys of iron and nickel or cobalt, from the primary pentlandite, pyrrhotite, cubanite and chalcopyrite. The native metals occur mainly in the central part of the layered series, whereas secondary sulphides predominate near its peripheries. It therefore seems probable that the sulphur distribution in the layered series as illustrated in Figure 2 has also been disturbed to some degree by the serpentinization, although it is difficult to make a quantitative estimation of the effect (Chamberlain and Delabio, 1965; Chamberlain et al., 1965; Chamberlain, 1967).

COUNTRY ROCKS

As stated, the contact country rocks of the main intrusive body have some disseminated sulphides for distances of a few tens to some one hundred feet from the contact. The mineral assemblages of these sulphides are similar to those in the adjacent intrusive rocks, indicating that the majority of sulphides were derived from the intrusion. In the country rocks well away from the intrusive contact, pyrite and chalcopyrite are sparsely distributed; these sulphides are probably unrelated in origin to the Muskox intrusion.

DIABASE DYKES

Pyrite and chalcopyrite are common minor accessories in the diabase dykes, whereas pyrrhotite is only rarely present. Like the sulphides in the Muskox feeder, these minerals occur as sparsely disseminated grains, normally with grain size less than 0.5 or 1 mm. However, the sulphide content of the dykes appears to be generally lower than that of the Muskox feeder; it is estimated at less than 0.05 per cent by volume.

EXPERIMENTAL PROCEDURE

SAMPLE

Sulphur isotope data were obtained from sulphide minerals only, because other forms of sulphur, such as sulphate, are considered to be negligible. It is known that, in general, only a few per cent of the sulphur in mafic intrusive rocks may exist as sulphate, the remainder being present as sulphide (Ricke, 1960). Some sulphur could exist in the form of sulphate in the country rocks, especially in metasedimentary and metavolcanic rocks, although to date none has been observed.

Sample localities are given in Figure 3. Brief descriptions of each specimen are given in the data tables. A total of 262 samples from different environments were used for the study, and in 51 cases the possible isotope fractionation between coexisting sulphide species was investigated. Thus the study is based on a total of 313 analyses.

SULPHIDE EXTRACTION

In general, sulphide-bearing samples were crushed to -100 mesh and separated using a superpanner, hand magnet and isodynamic separator. In some instances they were directly collected from hand specimens by a small vibrating chisel. Very fine grained (0.1-0.3 mm) sulphides were extracted from a few of the almost sulphide-free rocks using a laboratory flotation cell as well as magnetic and gravimetric techniques. As far as possible, at least 100 mg of sulphides were concentrated for SO_2 gas preparation, although in several instances it was impossible to collect more than 20 to 50 mg because of limited size of the available rock specimens and/or their low sulphide content. The final sulphide concentrates were generally better than 70 per cent pure according to polished section observation. Non-sulphide impurities consisted of oxides and silicates such as magnetite, ilmenite, chromite, olivine, pyroxene and plagioclase, but no carbonate.

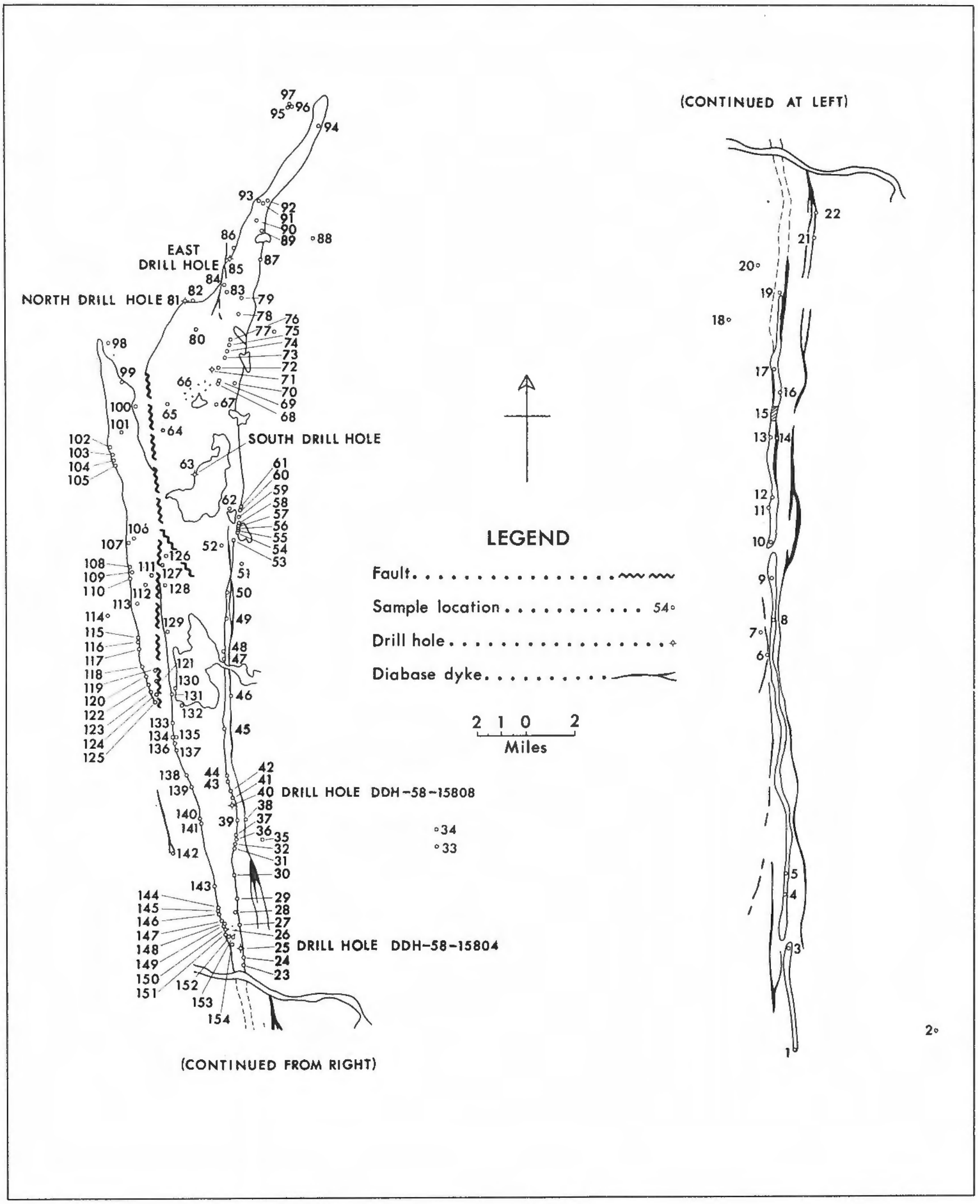


Figure 3. Location of sulphide samples for the sulphur isotope study of the Muskox intrusion and adjacent area.

SULPHUR DIOXIDE PREPARATION

Sulphur dioxide gases were prepared by direct combustion of sulphides employing the method described by Wanless et al. (1960). The combustion furnace was operated at a temperature of 1500 ± 50° C in order to reduce the possible isotopic fractionation of sulphur due to the formation of SO_3 to negligible proportions (Thode et al., 1961). A single constant source of oxygen with a known isotopic composition was used for the combustion of all samples.

ISOTOPIC ANALYSIS

The sulphur isotope ratio in the prepared SO_2 gas was determined by simultaneous collection techniques (Wanless and Thode, 1953), using a 90 degree, 10 inch radius, Nier-type mass spectrometer. The troilite from the Cañon Diablo meteorite was used as the comparison standard, assuming that it has S^{32}/S^{34} ratio of 22.220 (Thode et al., 1961; Ault and Jensen, 1962; Jensen and Nakai, 1962; Jensen, 1962). Samples were routinely compared to a substandard SO_2 gas prepared from 3 gm of pure pyrite obtained from a massive pyrite ore of the Giant Mine, Yellowknife, Northwest Territories.

The results of the isotopic analyses are given in δS^{34} per mil values defined as follows:

$$\delta S^{34}\ ^{o}/_{oo} = \frac{(S^{34}/S^{32})_{\text{sample}} - (S^{34}/S^{32})_{\text{standard}}}{(S^{34}/S^{32})_{\text{standard}}} \times 1000$$

where $(S^{34}/S^{32})_{\text{standard}}$ is the ratio for the Cañon Diablo troilite.

The reproducibility of analyses will be seen in Table 1 where the analytical results for five samples of the Cañon Diablo troilite are given with the dates of sample preparation and isotope analysis. Since these check analyses were made throughout the entire period of the experiments, the overall analytical precision for sample preparation and isotope analysis has been calculated from the data. The standard deviation has been found to be ± 0.2 per mil.

ANALYTICAL RESULTS; THE MUSKOX INTRUSION AND ITS ENVIRONS

The experimental results are listed in Tables 2 to 20 and are plotted in Figures 4 to 18. In describing and discussing the sulphur isotope distribution in the various parts of the intrusion and the adjacent rocks, the isotope ratio for the most predominant sulphide in each specimen was assumed to represent the value at that location. This could lead to errors, since it has been shown that, in some instances, considerable isotopic differences can exist between coexisting sulphide species (e.g. Smitheringale and Jensen, 1963). However, data to be presented for 53 sulphide pairs, indicate that the fractionation between coexisting sulphide minerals rarely exceeds 1 per mil (Tables 17 to 19 and Fig. 18).

All the analyzed sulphides in the Muskox intrusion contain more S^{34} than meteoritic troilite, their δS^{34} values ranging from +1 to +17 per mil. Sulphides occurring in the country rocks adjacent to the intrusion have an even wider variation, from -4 to +30 per mil. The data are described below in relation to the known structural units of the intrusion.

SULPHUR IN THE FEEDER

The sulphides from the bronzite gabbro and picrite of the Muskox feeder have isotopic values ranging from +6.4 to +14.4 per mil; the average for fourteen individual samples is +10.1 per mil (Table 2). Although the analyzed specimens were obtained from both the chilled margin and inner parts of the feeder dyke, the isotopic values do not appear to correlate with distance from the edge of the dyke or with differences in rock type.

If the values obtained represent the original sulphur isotope ratios of the feeder rocks – or, in other words, the original ratios in the source magma of the intrusion – they are surprisingly heavy. In other investigations of mafic and ultramafic intrusive rocks, the average isotopic composition of sulphur has consistently been found to be nearly the meteoritic value (e.g. Shima et al., 1963; Smitheringale and Jensen, 1963).

As the result of their study on sulphur isotopic composition in the Triassic igneous rocks of eastern United States, Smitheringale and Jensen (1963) made the following comment about the sulphide in mafic igneous rocks (ibid., p. 1185): "Sulphides in most mafic igneous rocks are extremely fine grained and sparsely disseminated. Indeed, they are commonly invisible to the naked eye. Sulphide grains of several mm in diameter or sulphides in noticeable concentrations infer some degree of abnormality in the conditions under which they formed." According to this criterion they considered that many previously reported sulphur isotope values for sulphides in, or associated with, mafic igneous rocks had been obtained which were not properly representative of those igneous bodies.

In some specimens listed in Table 2, sulphides are rather coarse grained or are present in fairly high concentrations. In the remainder, sulphides are thinly distributed and fine grained, but their grain size in places is over 1 or 2 mm in diameter. In this respect it appeared important to analyze the much finer grained (generally between 5 and 100 microns in diameter) sulphides that are sparsely distributed in the feeder rocks. Five picrite and three bronzite gabbro specimens (59-952 to 59-969 in Table 2) which appeared free of visible sulphide were crushed to make a ten-pound sample which was then treated using a laboratory flotation cell as well as ordinary gravimetric techniques. The δS^{34} value obtained for a 15 mg concentrate consisting of pyrrhotite, cubanite, chalcopyrite and a little pentlandite was +9.6 per mil, that is, almost identical with the average value for the feeder dyke. Thus it appears that the sulphur isotopic composition in the exposed part of the feeder is considerably heavier than that of the meteoritic sulphur.

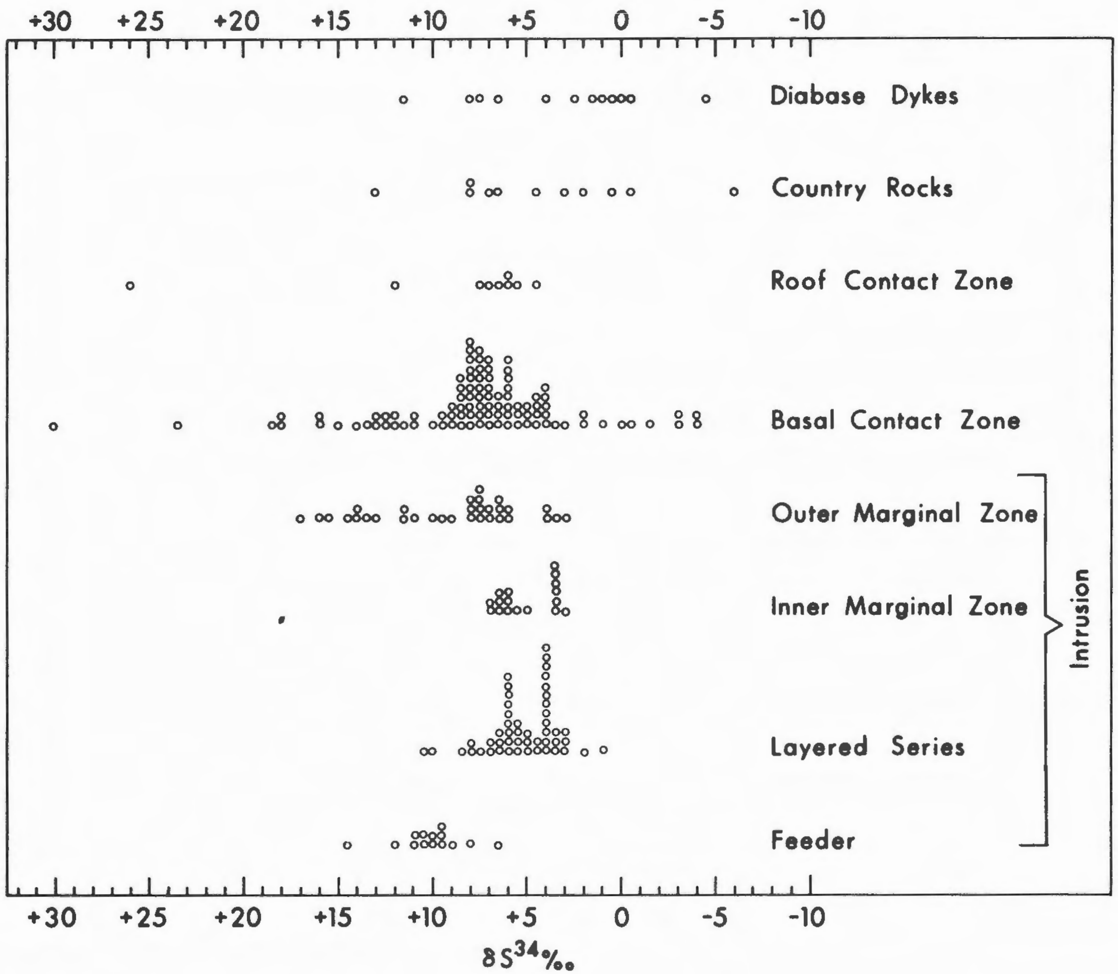


Figure 4. Distribution of sulphur isotope data from the Muskox intrusion and adjacent area.

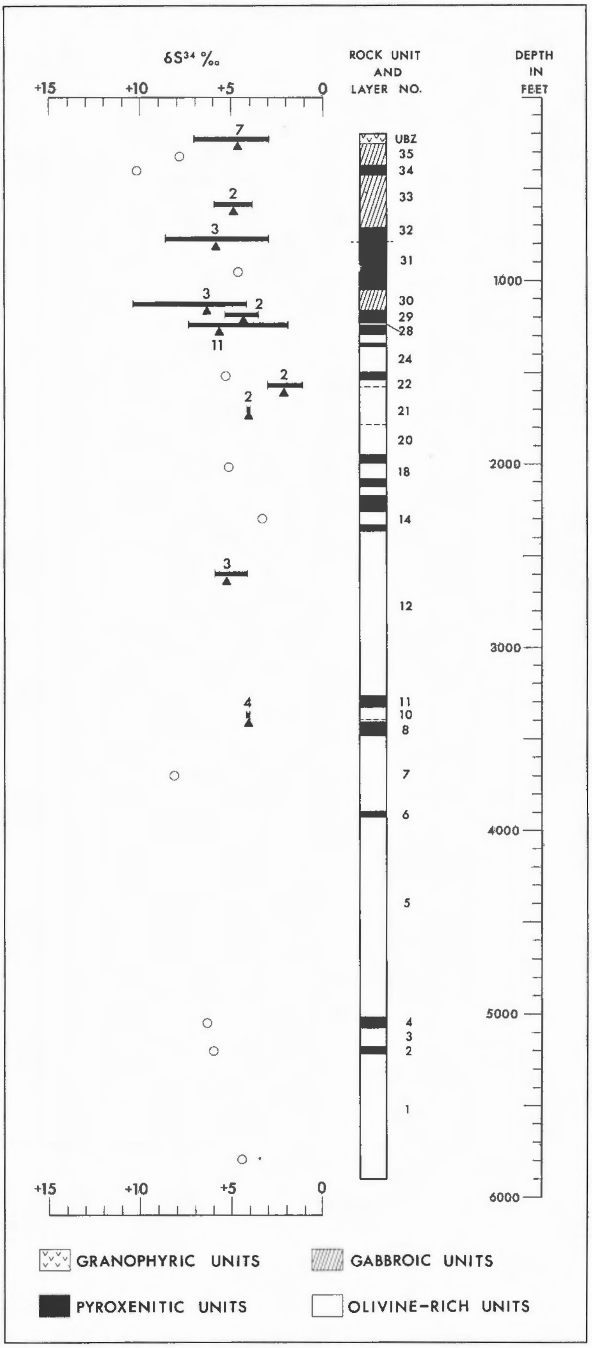


Figure 5. Stratigraphic presentation of sulphur isotope data from the layered series of the Muskox intrusion. Thickness of each layer is presented according to the data from the North and South drillholes (Findlay and Smith, 1964). Average isotopic value in single layer is represented by triangle, with the number of analyses and the variation range of data. Circle represents a single isotopic result.

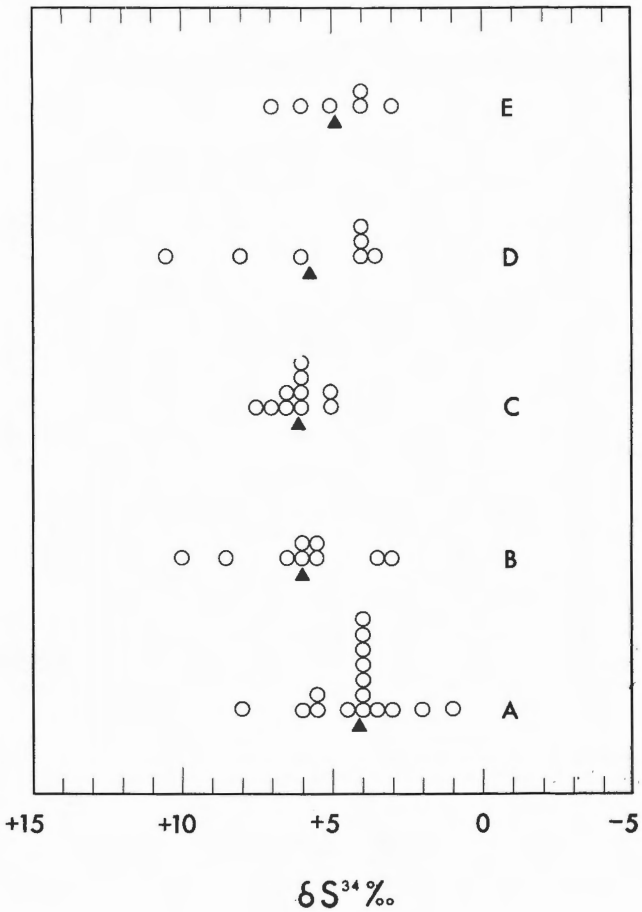


Figure 6. Distribution of sulphur isotope data in major rock units in the layered series of the Muskox intrusion. A, Olivine-rich units (originally dunite, peridotite and feldspathic peridotite, now accompanied with varying degrees of serpentinization); B, Pyroxenitic units; C, Chromititic layer; D, Gabbroic units; E, Granophyric units (including intrusive breccia). Triangles represent the average value for each group.

SULPHUR IN THE LAYERED SERIES

The central layered series consists of forty-two separate layered units ranging from dunite at the base to granophyre-bearing gabbro at the top (Findlay and Smith, 1964). The scarcity of sulphides in many of these layers made it impossible to obtain sulphur isotope data for the whole series.

Analyses were carried out on forty-two samples from nineteen different layers, and on seven sulphide samples taken from granophyric gabbro, granophyre and intrusive breccia of the upper border zone (Table 3).

The measured isotopic compositions range from +1.1 to +10.4 per mil, but the majority fall between +3 to +7 per mil (Fig. 4). In Figure 5 the data are presented with respect to stratigraphic position, and in Figure 6 they are plotted according to major rock units. The average isotopic compositions obtained for five major rock groups, that is, olivine-rich units (originally dunite, peridotite and feldspathic peridotite, all now serpentinized in varying degrees), pyroxenitic units (olivine clinopyroxenite, orthopyroxenite, websterite, feldspathic websterite and picritic websterite), the chromite layers, gabbroic units (gabbro, granophyre-bearing gabbro and granophyric gabbro), and granophyric units (granophyre and intrusive breccia), are +4.2, +6.0, +6.1, +5.7 and +4.9 per mil, respectively, and the average of a total of forty-nine specimens for the layered series is +5.2 per mil.

As stated, serpentinization of the olivine-rich units has caused some changes in the original sulphide assemblages as well as sulphur content of Muskox rocks (Chamberlain and Delabio, 1965; Chamberlain et al., 1965 ; Chamberlain, 1967). It is probable that the original sulphur isotopic composition has also been affected to some extent by this process. Secondary sulphides produced by the serpentinization are usually very fine grained and intimately associated with primary sulphides. This mode of occurrence made it difficult to separate these secondary sulphides from primary ones in sufficient quantity for isotopic study. However, in the specimens used for the present investigation, more than 80 per cent of primary sulphides appear to have been free of this secondary effect, therefore it is reasonable to expect that the original isotopic composition was unaltered in these specimens.

Previous investigators (e.g. Vinogradov, 1958; Thode et al., 1962; Smitheringale and Jensen, 1963), have reported that there seems to be a tendency for the sulphides in early stage magmatic products (i.e. in the more mafic igneous rocks) to be enriched in S^{32} as compared to those in later stage magmatic products (the more silicic igneous rocks). As shown in Figure 6, the averaged isotopic value for the olivine-rich units in the Muskox layered series is slightly lighter (by about 1 to 2 per mil) than the values for other more silicic rock groups. In addition, a few of the lightest isotopic values in the layered series are from olivine-rich units. These differences are consistent with the tendency noted above. By contrast, however, several values for the olivine-rich units show fairly high contents of S^{34}, giving a range of about 7 per mil for the total isotopic fluctuation in the group, which nearly covers the range of variation determined for the more silicic rock groups. Thus, while the isotopic composition ranges widely (up to 7 per mil) in a single rock group, the average value differs rather little (less than 2 per mil) among the different groups. This wide range of isotopic variation in a single group may be partly due to the complex history of formation of the layered series. As stated, the layered series was not formed by simple gravitative differentiation, but rather, represents a combination of successive injections of new magma and crystal settling. Each group in Figure 6 therefore contains several layers formed at different stages. However, as may be seen in Figure 5, similar ranges of isotopic variation exist in single layers. This would be an indication that the isotopic variation observed in the layered series was largely produced by processes other than the magmatic differentiation which produced the various rock types in this part of the intrusion.

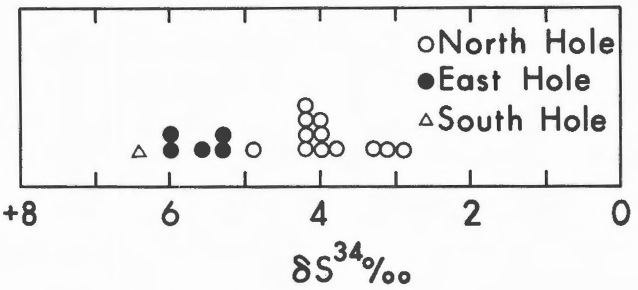


Figure 7. Distribution of sulphur isotope data in samples from the North, East and South drillholes in the layered series of the Muskox intrusion.

An interesting feature can be seen in the drill-core data given in Table 3. In the North drillhole, twelve specimens from ten different layers show isotopic values falling in a fairly narrow range from +2.9 to +4.9 per mil despite the wide variation in the type of host rock. A similar constancy in the isotopic data is also observable in the east drillhole, but with higher S^{34} contents than in the North drillhole. δS^{34} varies from +5.3 to +6.0 per mil in five specimens from four different layers. Thus, although the samples from the two drillholes are not all taken from comparable rock units, there appears to be a distinct difference between the isotopic data from the two drillholes (Fig. 7). The apparently bimodal distribution of the isotopic data from the layered series evident in Figure 4 largely depends on this distinction.

The North drillhole is near the central axis of the intrusion, whereas the East drillhole is closer to its margin. Therefore the data obtained from the two drillholes might indicate the presence of a systematic lateral variation in the sulphur isotopic composition in the layered series. In Figure 8 the data from drillhole and surface samples are all projected on a single cross-section of the intrusion. In general, sulphides from the outer parts of the layered series appear to contain more S^{34} than those from the parts near its central axis. It also seems probable that the general trend of the isotopic distribution follows a pattern similar to the 'contour' shown for $\delta S^{34} = 4$ per mil, although the number of analyses is insufficient to permit a definite conclusion. However, regardless of the details of the final pattern, it seems clear that contours of sulphur isotopic composition would be discordant with respect to the layering. This could be one of the reasons why the isotopic data in the layered series show little correlation with the type of host rock or the course of magmatic differentiation, although the cause of such isotopic pattern remains unsolved.

The sulphide content in the rocks of the layered series increases toward the peripheral areas, and this is attributed to diffusion of sulphur (or sulphides) in response to temperature gradients in the cooling intrusive body, and to slight redistribution of sulphides during serpentinization in olivine-rich rocks (Chamberlain, 1967). The observed isotopic pattern in the layered series may also be related to these diffusion processes. However, if this was the case, the resulting isotopic trend would be expected to be the reverse of

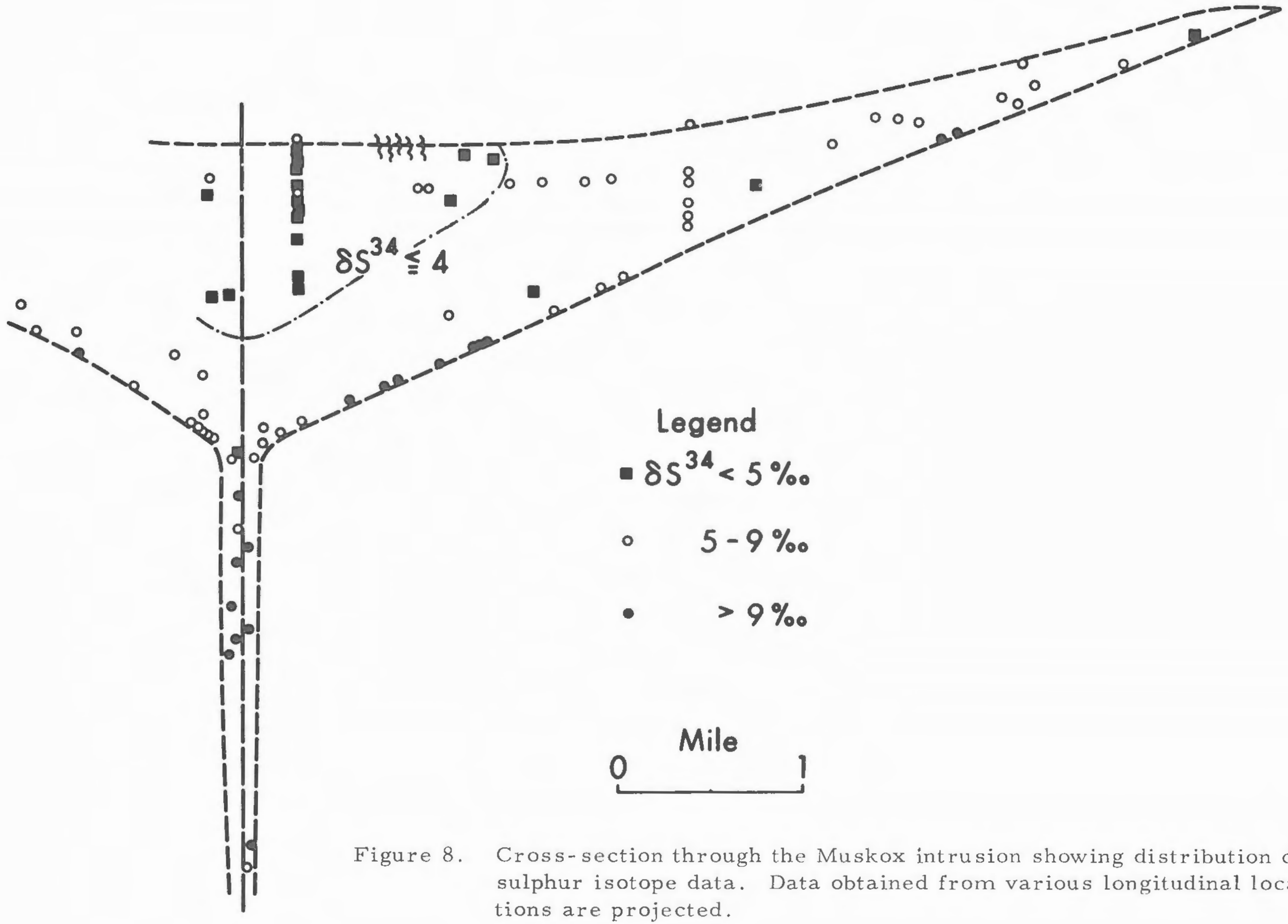


Figure 8. Cross-section through the Muskox intrusion showing distribution of sulphur isotope data. Data obtained from various longitudinal locations are projected.

that observed. If the lighter isotope migrates faster than the heavier one, as is commonly believed, then the central portion of the layered series should be depleted in S^{32} as compared to the peripheral areas.

The specimens projected in Figure 8 are from widely spaced localities in terms of the length of the Muskox intrusion. The question therefore arises as to whether the isotopic composition in the layered series also varies systematically in the longitudinal direction. However, to determine this requires specimens from widely separated longitudinal locations within a single layer, and these were not available in sufficient quantity to permit enough data to be obtained to draw any definite conclusions.

While the arithmetic mean of the data on the layered series is +5.2 per mil, a more exact average may be calculated on the basis of the spatial distribution of isotopic composition and sulphur abundance data within the whole of the series. Although both types of data are still limited, an estimate has been made using the assumptions given in Table 4. Here, the four sulphide zones indicated in the table are the same as in Figure 2. The average isotopic value, weighted according to the sulphur content in the four zones, is +4.8 per mil. Since the uppermost Fe-zone has more than 80 per cent of the total sulphur in the whole layered series, its isotopic trend largely controls the result. Chamberlain (1967) considered that there was little evidence to support the possibility that the majority of sulphur in the upper part of the intrusion was derived from the country rock (Chamberlain, 1967). However, the presence of abundant country rock fragments in the top of the upper border zone (Smith, 1962) may indicate that some of the sulphur in this part of the intrusion is from the country rocks. However, even if the Fe-zone is excluded in the above calculation, the weighted average of the isotopic composition of sulphur in the layered series is still +5.6 per mil. Thus, despite the uncertainty in the final value, it is concluded that, on the average, the sulphur in the present layered series rocks is fairly heavy as compared with the sulphur in meteoritic troilite and probably has a δS^{34} value in the range +5 $\pm$0.5 per mil. As the sulphur in the bottom dunite layers is also isotopically heavy (+4.4 per mil), and as the sulphides in the layers are considered to have crystallized from the cooling magma, it is concluded that the sulphur in the layered series magma was heavy even at the very first stage of the magmatic crystallization.

SULPHUR IN THE MARGINAL ZONE AND IMMEDIATELY ADJACENT COUNTRY ROCK

In the marginal zone of the intrusion sulphides are markedly concentrated along the intrusion wall as rather coarse-grained disseminations and massive aggregates. There are sparse, finer grained disseminations of sulphides in the inner parts of the marginal zone. In general, sulphides from the inner parts of the marginal zone appear to have somewhat lower, and less variable, δS^{34} values compared to the sulphides along the intrusion wall. In order to show this contrast an arbitrary spatial boundary, 200 feet inside the contact of the intrusion and parallel to the intrusion wall, will be used to separate the analytical data into two groups. Massive and coarse-grained disseminated sulphides are rarely found inside this 200-foot limit.

The δS^{34} values obtained for fine-grained disseminated sulphides from the inner part of the marginal zone range from +3.1 to +7.1 per mil, the average for seventeen samples being +5.0 per mil (Table 5). It may be noted that the isotopic results are very similar to those for the layered series described above. The data appear to have a bimodal distribution with peaks at about +3 to +4 and +6 to +7 per mil (Fig. 4). The isotopic values show no apparent correlation with known petrological or mineralogical data.

In the outer zone - that is, near the intrusion wall - the δS^{34} values range widely from +3.1 to +16.9 per mil (Table 6). Although this covers the range shown by sulphides in the inner zone, it is evident that sulphides near the intrusion wall generally contain more S^{34} than the inner zone (Fig. 4). Again, it is difficult to correlate the variation with any mineralogical or petrological feature of the intrusion, but a remarkable regularity can be seen in the spatial distribution of the isotopic data. In Figure 9 the isotopic values are divided into two numerical groups, namely $\delta S^{34} > +9.0$ and $\delta S^{34} \leq +9.0$ per mil, and are plotted on a location map. With a single exception, sulphides having $\delta S^{34} > +9.0$ per mil are confined to the east contact of the intrusion, whereas sulphides with $\delta S^{34} \leq +9.0$ per mil occur along the west contact and the southern part of the east contact. It is seen that the distribution of these two groups of sulphides correlates with the type of country rock adjacent to the intrusion. Along the east contact, where the heavy sulphur occurs, the country rocks consist mainly of rather low grade metasedimentary rocks such as quartz-mica schist, quartzite and slate with occasional intercalations of paragneiss; granitic material is rare. By contrast, the country rocks along the southern part of the east contact and most of the west contact, are either paragneisses with many granitic bands or almost entirely granitic gneisses.

The concentrations of sulphides along the basal contact of the intrusion may occur on either the intrusive or the country rock sides. The isotopic data for the sulphides in the country rocks (these sulphides are disseminated to massive and, in general, are within a few tens of feet of the intrusion contact) are given in Table 7. These data are compared with the data for the sulphides from the intrusive side - that is, from the outer part of the marginal zone - in Figure 10. In general there seems to be little isotopic difference between the sulphides from the intrusion and those in adjacent country rock, and the correlation with type of country rock illustrated in Figure 9 holds with few exceptions for the intrusive sulphides as well as for the sulphides in the country rock.

It must be noted, however, that all specimens represented in Figure 10 were taken from surface exposures, the majority of the sulphides occurring as rather coarse-grained disseminations or massive aggregates as described in Table 7. As will be discussed later (pp. 22-28), a detailed study of drill-cores taken across the intrusion wall reveals remarkable isotopic variations in the sulphides in the country rocks adjacent to the basal contact of the intrusion. If these results are included, then the isotopic values for the contact country rock sulphides range widely from about -4 to +30 per mil, which is twice the range observed for sulphides in the intrusion margin (Fig. 4). Because the sulphides with the exceptionally high or low δS^{34} values are usually very fine grained and/or minor in amount, it is highly probable that they were overlooked in the surface exposures when these were being sampled. This would explain the narrower range of the isotopic compositions found in the surface samples. However, a few specimens in Table 7 (60-40A, 62-4027A(c) and 62-4004C), showing exceptionally or relatively low δS^{34} values compared to other specimens from the same areas are considered to

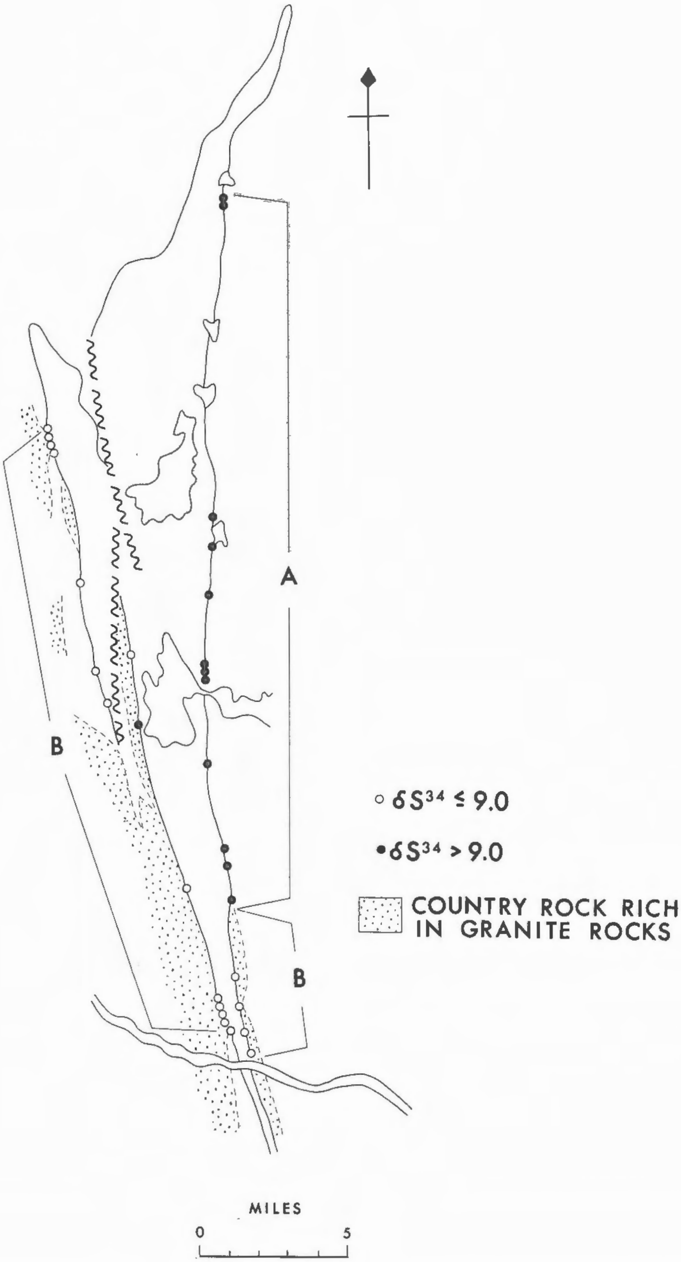


Figure 9. Regularity in the distribution of sulphur isotope data in sulphides occurring near the basal margin of the Muskox intrusion, within 200 feet of the country rock contact 'A' and 'B' outline areas shown in Figure 10.

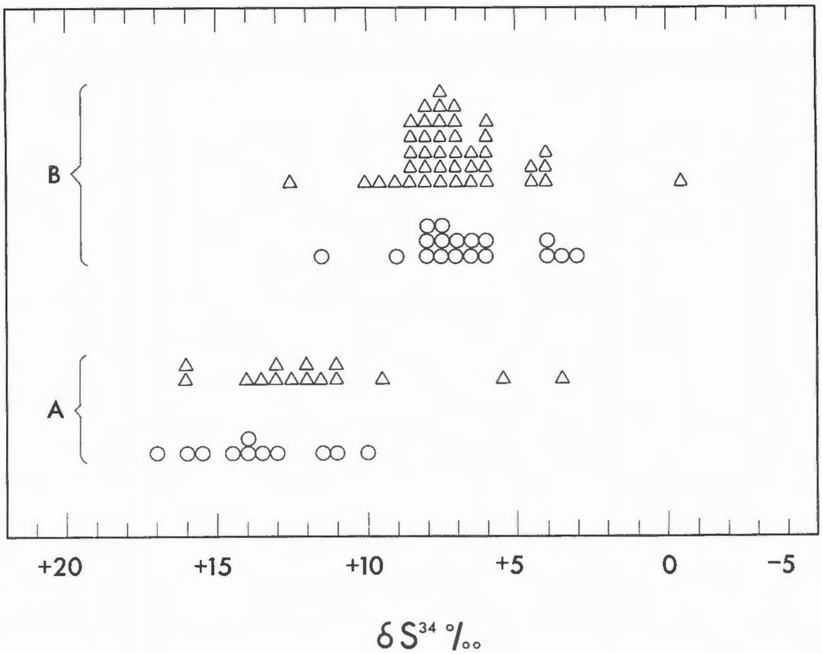


Figure 10. Distribution of sulphur isotope data in sulphides obtained from surface exposures along the basal contact of the Muskox intrusion. A and B correspond to the areas illustrated in Figure 9. Circles represent the specimens from the intrusion body and triangles represent those from the adjacent country rocks.

be examples of such sulphides. These correspond to the lightest two values in group A and the lightest one in group B of Figure 10.

SYNOPSIS

All the analyzed sulphides in the Muskox intrusion contain more S^{34} than meteoritic troilite. Although there still remains a question about the original sulphur isotopic composition in the source magma of this intrusion, the data for the layered series indicate that the magma contained sulphur with an average δS^{34} value of about +5 per mil at the time of emplacement or very shortly afterwards. The isotopic results for the inner parts of the marginal zone, are very similar to those of the layered series and tend to confirm this conclusion. This average value was maintained with little variation throughout the course of crystallization of the main intrusive body but the individual data fluctuate in a range of about 5 per mil above and below this average.

Sulphides along the intrusion wall normally have isotopic values heavier than +5 per mil, and there is a striking correlation between these data and the type of country rock adjacent to the intrusion. As a rule, sulphides with $\delta S^{34} > +9.0$ per mil are restricted to areas where the country rock consists mainly of rather low-grade metasedimentary rocks, whereas sulphides with $\delta S^{34} \leq +9.0$ per mil occur where granitic rocks are the predominant country rock. Apart from the detail of actual process, it cannot be questioned that some interaction between the intrusion and country rock has been responsible for the isotopic composition of these sulphides.

The remarkably heavy average (+10.1 per mil) obtained for the feeder dyke, and the puzzling discrepancy between this value and the average for the layered series, are probably due to the same process that produced the isotopically heavy sulphur ($\delta S^{34} > +9.0$ per mil) along the intrusion wall. The majority of country rocks adjacent to the exposed part of the intrusion feeder are metasedimentary rocks.

Detailed profiles of the isotopic variations across the intrusion contact to be described in the next section will serve as a basis for discussing the possible processes responsible for the heavy isotopic values.

SULPHUR ISOTOPE DISTRIBUTION IN PROFILES ACROSS THE INTRUSION CONTACT

Profile across the basal contact of the intrusion in the South drillhole [1]

A detailed study of the isotopic distribution of sulphur across the basal contact of the Muskox intrusion has been made on samples from the South drillhole which provided a continuous drill-core sample through the marginal zone of the intrusion and into the basement country rock for about 300 feet below the contact (Findlay and Smith, 1964). Results of sulphur isotopic determinations on forty-three sulphide specimens from the contact zone are listed in Table 8 and are plotted in Figures 11 and 12.

Near the contact, sulphides in the intrusion are mainly pyrrhotite, with small amounts of pentlandite, cubanite and chalcopyrite. They occur as fine- to coarse-grained disseminations or massive aggregates such as have been observed in surface samples. δS^{34} values for eleven samples range from +5.3 to +8.9 per mil, averaging +7.7 per mil. In the drill-core section the country rocks are schists and gneisses containing many granitic materials. The relation of the isotopic values in the intrusion ($\delta S^{34} < 9‰$) to the type of country rock is therefore in keeping with the general relationship described above (Fig. 9).

However, in contrast with the rather small fluctuations within the intrusion, the isotopic results show a large variation in the adjacent country rocks, as illustrated in Figures 11 and 12. For purposes of discussion, the area is divided into four zones, I, II, III and IV, increasingly distant from the intrusion contact. Sulphides in each zone show characteristic isotopic compositions and/or mineralogical features.

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[1] Except for a few supplemental observations by the writer, data on sulphide mineralogy presented in this section were supplied by J.A. Chamberlain from his study of the Muskox sulphides (Chamberlain, 1967).

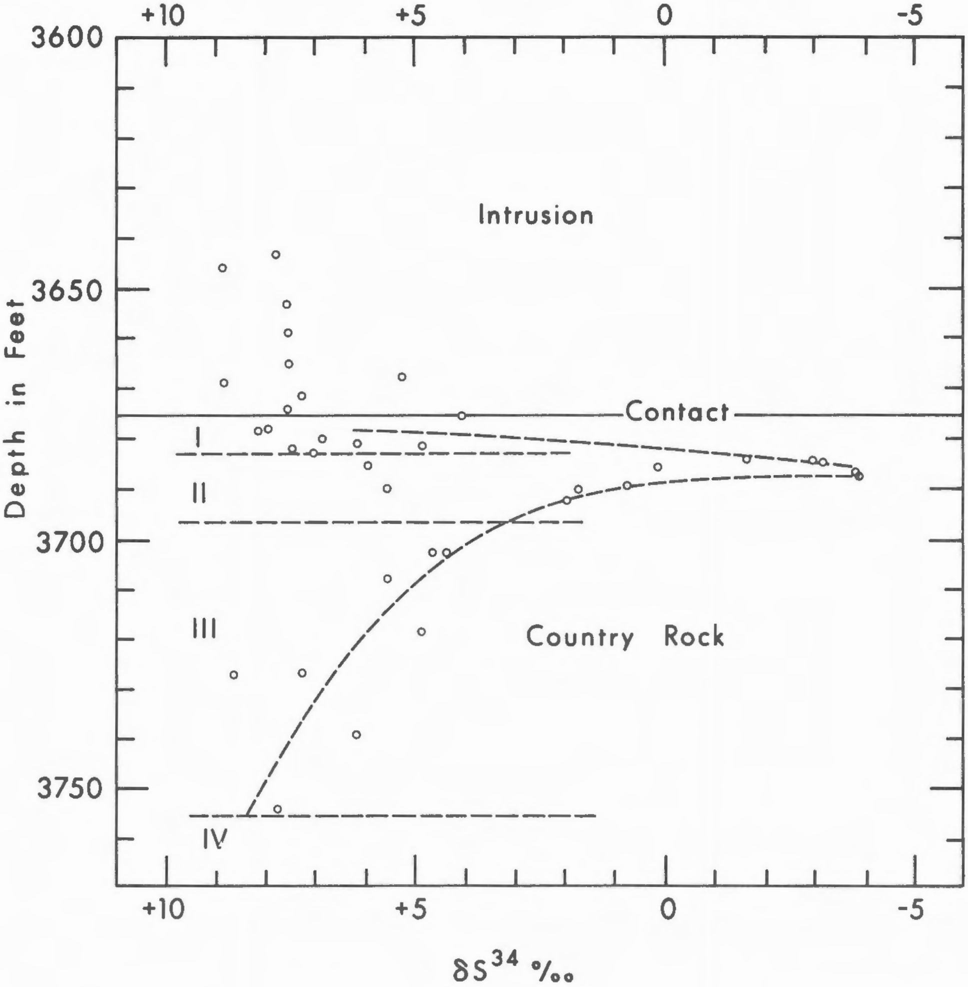

Figure 11. Distribution of sulphur isotope data across the basal contact of the Muskox intrusion in the South drillhole. (Location 63, Fig. 3).

In Zone I, within about 8 feet[1] of the intrusion contact, the country rock sulphides are slightly enriched in S^{32}. δS^{34} for eight samples from this zone ranges from +4.0 to +8.2 per mil (S-3675.5 to S-3683 in Table 8), averaging +6.6 per mil. Mineralogically and also texturally these sulphides appear to be essentially identical with the adjacent sulphides in the intrusion.

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[1] Distances given in this section represent those measured along the axis of drill-core. The inclination of the intrusion base to the core axis is estimated to be 30-35 degrees (Findlay and Smith, 1964).

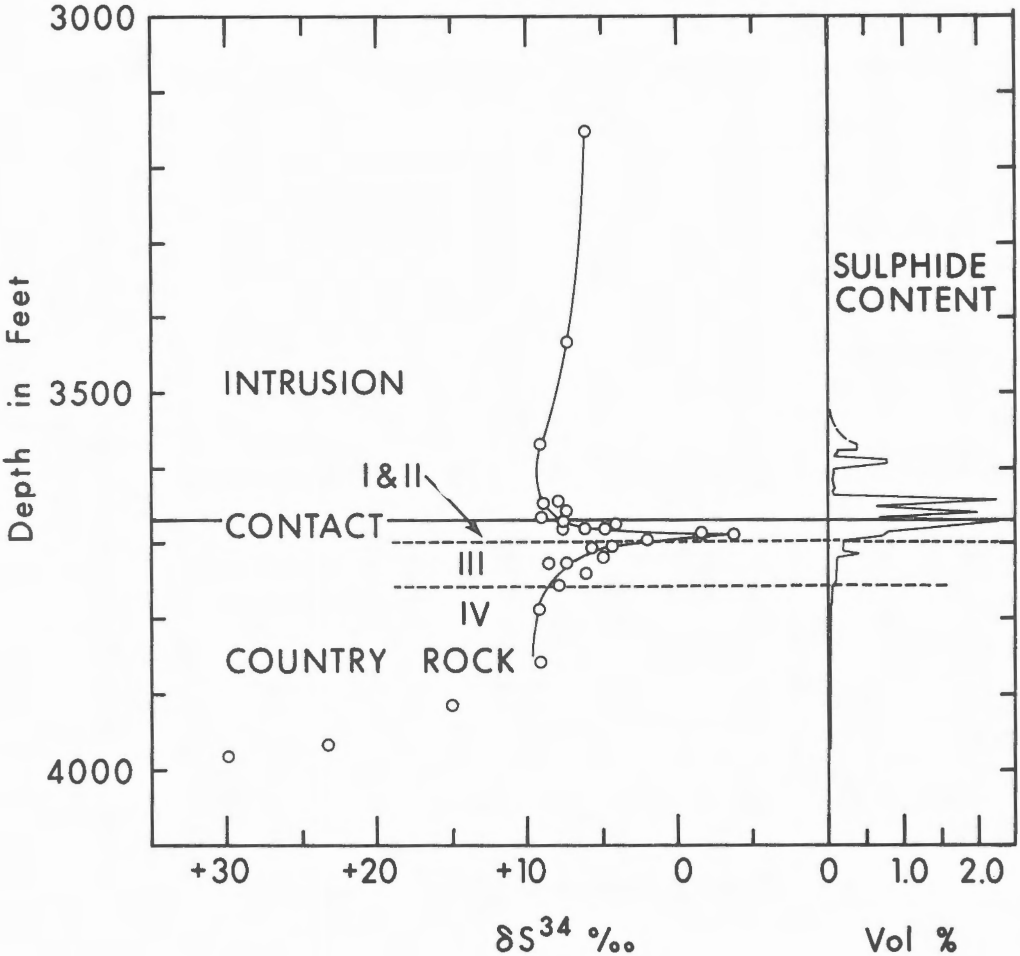

Figure 12. Variation of sulphur isotope data and sulphide content across the intrusive contact in the Muskox South drillhole. Sulphide content data are from J.A. Chamberlain (private communication).

Outside Zone I, the isotopic ratio changes suddenly, and a remarkable concentration of S^{32} is indicated by a value of -1.6 per mil obtained from a sample taken 9 feet from the contact (S-3684). Similar values are found for about another 3 feet with the two lightest values, both -3.8 per mil, occurring 12 and 13 feet from the intrusion (S-3686.5 and S-3688). Beyond this point the isotopic composition becomes heavier, and the sign of δS^{34} goes rapidly from negative to positive. A value of +2.0 per mil is observed at about 18 feet from the contact (S-3692.5). Sulphides in this region (Zone II) show the same four-phase mineral assemblage (po-pn-cb-cp) observed in sulphides of the intrusion and the inner zone country rock (Zone I). However, pentlandite and cubanite are not as abundant as in Zone I; on the average, sulphides in Zone I contain 10 to 20 per cent of pentlandite and about 5 per cent of cubanite, whereas sulphides in Zone II have only 2 to 3 per cent of each.

A characteristic feature can also be seen in the mode of occurrence of these sulphides. In general, they are very fine grained (grain size < 0.1 mm) and are disseminated parallel to the foliation of the host paragneiss, in contrast to the coarser grained and rather randomly disseminated or massive sulphides in Zone I.

A small proportion of the sulphides in Zone II is medium to coarse grained, occurring in sporadically distributed patches similar to those of Zone I. These sulphides also have more pentlandite and cubanite than is found in the majority of sulphides in Zone II. It was found that the isotopic data for these sulphides do not follow the trend observed in Zone II, but have values similar to those in Zone I, with only a slight enrichment in S^{32}. Examples may be seen in S-3685.5(a) and S-3690(a) of Table 8. The two types of sulphide are not always associated, but they are intimately intermixed in S-3685.5 (Fig. 13). It is interesting to note that even in the latter case the isotopic compositions of the two types of sulphide are sharply different. As illustrated in Figure 13, specimen S-3685.5(b) is probably a mixture of both types of sulphide, but with the very fine grained type predominating. This mode of occurrence appears to be responsible for the increase in S^{34} in this specimen with respect to neighbouring samples, S-3685 and S-3686.5. Both of the latter apparently consist of only the very fine grained type of sulphide.

The isotopic variation observed in the major group of sulphides in Zone II seems to continue into Zone III without a major break in trend. At about 28 feet from the intrusion, the isotopic composition is +4.7 and +4.4 per mil (S-3702.5 a and b). An outward increase of δS^{34} continues, but at a decreasing rate. Finally, about 50 feet from the contact, the isotopic data are again comparable to those in the intrusion and Zone I, and similar values exist for more than 20 feet beyond this point. The δS^{34} values in five specimens from this area vary from +6.2 to +8.7 per mil (S-3727 to S-3754). Sulphides in Zone III (S-3702.5 to S-3754) are mainly pyrrhotite accompanied by a little chalcopyrite; they are almost free of pentlandite and cubanite. They occur, in general, as fine- to medium-grained disseminations. With the exception of one sample (S-3719), the sulphide distribution appears independent of the host rock structure. In S-3702.5(a), sulphides occur in a quartz veinlet.

In Zone IV, the abundance of sulphides in the country rock becomes very low. The average sulphide content is not more than 0.01 to 0.05 per cent by volume, compared with 0.1 to 0.3 per cent in Zone III and 1 to 2 per cent in Zones I and II (Fig. 12). Pyrite and chalcopyrite are the predominant species of sulphide in Zone IV. They are usually fine grained, and they commonly occur as a thin, filmy coating or impregnation along minute fracture or schistosity planes. Sulphides in the lowest 200 feet of the South drillhole also show these characteristics. The isotopic values were determined in five specimens from this zone. In the inner half of the area, the data are comparable with those in the preceding zone: a value of +9.1 per mil was obtained for two specimens taken 115 and 184 feet from the intrusion contact (S-3789.5 and S-3859 respectively). In the last 100 feet of the South drillhole, sulphur is relatively heavy: δS^{34} is +15.1 per mil (S-3914) at 239 feet from the contact, +23.3 per mil (S-3970) at 295 feet, and +29.8 per mil (S-3980) at 305 feet. As stated, the presence of pyrite instead of pyrrhotite makes this zone different. Between Zone III and Zone IV there is a transitional zone in which pyrrhotite occurs with some pyrite and chalcopyrite. Microscopic

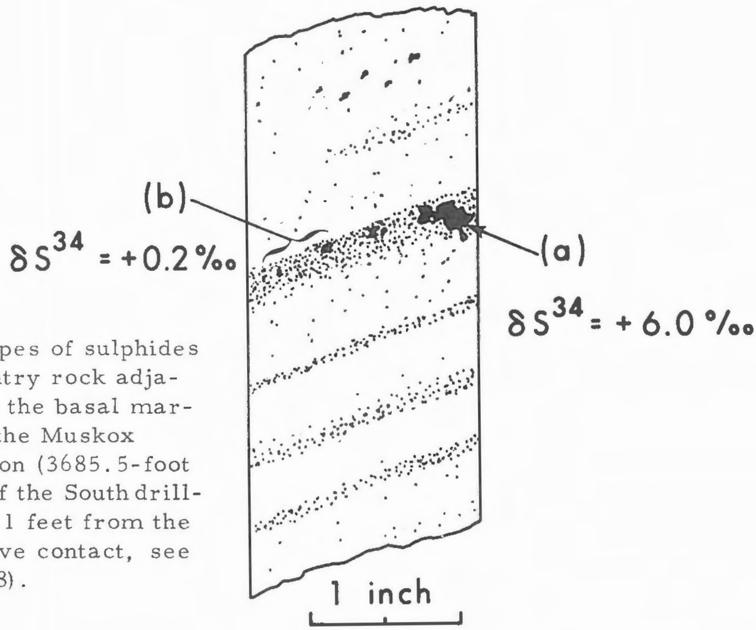

Figure 13. Two types of sulphides in country rock adjacent to the basal margin of the Muskox intrusion (3685.5-foot level of the South drill-hole, 11 feet from the intrusive contact, see Table 8).

observation shows that the range of about 30 feet, between 3760- and 3790-foot level, has this three-phase mineral assemblage. However, all observed grains of pyrrhotite and pyrite are isolated from each other, and there is no positive evidence that the two minerals were in equilibrium when they formed (Chamberlain, 1967, p. 139).

At present, the experimental data are difficult to interpret satisfactorily, both because our knowledge of sulphur isotope geochemistry of this type of intrusion is still limited and because there are many basic facts of geology and mineralogy of this intrusion that remain uncorrelated. However, a discussion will be given, on the basis of several assumptions.

It seems reasonable to assume that sulphur in the majority of sulphides in Zones I, II and III migrated from the intrusion body. (Chamberlain, 1967, pp. 135-146).[1] Sulphides in Zone IV, however, have a different mineral assemblage and also show little positive evidence that their formation was directly related to that of the sulphides in the inner zones. It might be reasonable therefore to consider Zones I to III and Zone IV separately in the present discussion.

If the sulphur in Zones I to III is intrusive in origin its isotopic composition may have changed during the migration. In principle, as the lighter isotope moves faster than the heavier, a simple process-like diffusion may cause an outward decrease in δS^{34} value. However the isotopic profile observed here (Fig. 11) is more complicated, and is difficult to explain by a diffusion mechanism only. Besides, the range of isotopic variation (up to 12 per mil) seems to be too large to have resulted from diffusion isotope effects (cf. Wanless et al., 1960; Field, 1966).

[1] Zones I and II are in Chamberlain's Po-Pn-Cp-Cb Zone. Zone III nearly corresponds to his Po-Cp Zone, and Zone IV to Po-Py-Cp and Py-Cp Zones (Fig. 16 in Chamberlain, 1967).

The isotopic and mineralogical data in Zone II, as illustrated in Figure 13, appear to indicate that two more or less independent sulphide mineralizations are involved in this contact zone. If this is true for the entire part of Zones I to III, the observed isotope profile may be explained by mixing of two kinds of sulphur whose δS^{34} values are significantly different. Apart from the mode of formation of two kinds of sulphur, this process suitably explains highly complicated isotopic patterns, as the variation in relative abundance of the two sulphur species essentially controls δS^{34} value at any given point. An example may be seen in Figure 14. In the diagram, the isotopic compositions of two kinds of sulphur are given by δ_A and δ_B, assuming both are invariable with distance from the intrusion, while the distribution of each sulphur is assumed to vary like the curves X_A and X_B, respectively. Then if the two mineralizations overlap and simple mixing of the two kinds of sulphur takes place, the overall variation of δS^{34} in the region will result in a curve like δ_{A+B}, which is similar to the one observed (Fig. 11). It should be noted, however, that the actual mechanism may have been complicated by other possible variations in δ_A and δ_B and/or incomplete mixing of the two sulphur species as indicated by the example in Figure 13.

Accepting the two sulphide mineralizations in Zones I to III, a question must arise about their genetic relationship. From the mode of occurrence of (b) type sulphides shown in Figure 13, one might suspect that these sulphides formed syngenetically with the country rock and were already there prior to the emplacement of the intrusion. This opinion may be favoured by the fact that while (a) type sulphides are common both in the intrusive margin and the immediately adjacent country rock (b) type sulphides have been recognized so far only in the latter.

If the sulphur in both types of sulphide was derived from a common source, the isotopic composition in this source sulphur may be approximated by the average obtained for the entire contact zone where the two types of sulphide exist. The result determined by weighting the samples according to the variation in sulphide content is given in Table 9, with the basic data used in the calculation. The weighted average for the area, including the intrusion margin and the adjacent country rock (Zones I to III), is +6.2 per mil, nearly identical with the isotopic value observed in the inner part of the marginal zone encountered by the same drillhole (+6.0 per mil in S-3152 in Table 8 and Fig. 12). This is also fairly close to the average isotopic values estimated for the whole layered series or the inner marginal zone of the intrusion (+5 $\pm$ 0.5 per mil) and therefore appears to favour the assumption that the majority of the sulphur in the contact sulphides was derived from the intrusion.

In contrast with Zones I to III, it is difficult to find decisive evidence that the sulphides in Zone IV have also formed from the sulphur migrated from the intrusion. On the basis of the mineral assemblage and very low sulphide content in this zone, Chamberlain (1967, pp. 139 and 146) believes that pyrite and chalcopyrite occurring in this zone represent background sulphides in the country rocks and are not related to the intrusion. However, regardless of the origin of sulphur, it seems highly probable that the intrusion was directly or indirectly involved in formation of the remarkable heavy sulphur in this zone, because, with the exception of several specimens collected from similar spatial environments, no sulphur possessing such a high concentration of S^{34} has been found to date in other regions of the country rock. The mode of occurrence of the sulphides in Zone IV, especially the

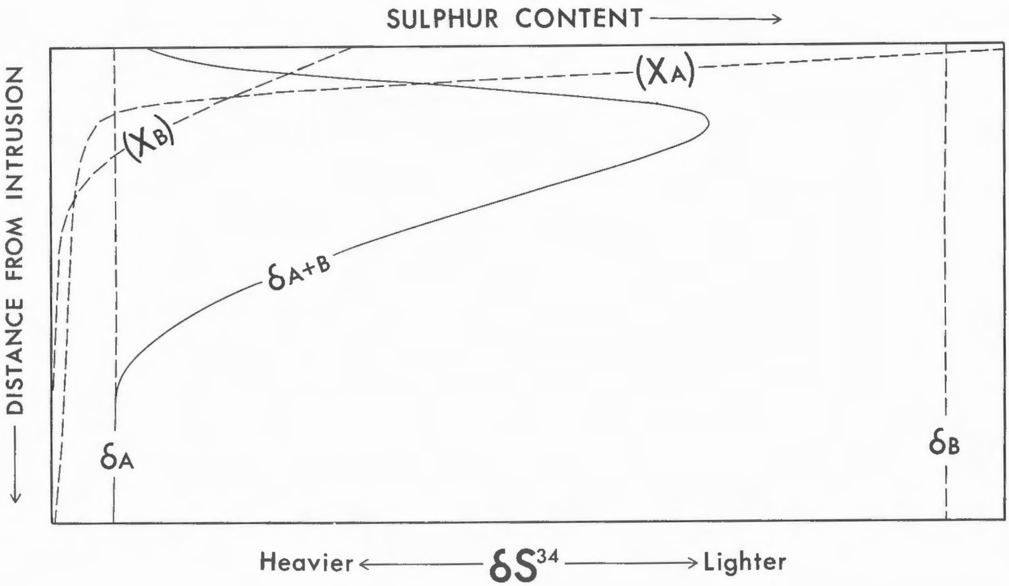

Figure 14. An explanation of sulphur isotopic variation given in Figure 11, by mixing of two kinds of sulphur.

thin filmy coating on minute fractures in host rock and the association with clayey material, are indicative of a fairly low temperature of formation. Therefore, if the sulphides in this zone were also derived from the intrusion, they were probably produced at a much later stage than the sulphides in Zones I to III. A tendancy for more extensive fractionation of sulphur isotopes to occur during low temperature mineralization has been noted by Gavelin et al. (1960); and Ridge (1960) has discussed very high and very low δS^{34} values caused by the replacement of sulphides at low temperatures. Detailed investigations of a single mineral deposit or mineralized area have occasionally revealed the presence of exceptionally heavy or light isotopic compositions in later stage sulphides (e.g. Buschendorf et al., 1963; Friedrich et al., 1964). Thus it seems reasonable to assume that the high δS^{34} values observed in Zone IV resulted from some later stage or low temperature process, although the actual mechanism of fractionation remains unknown. It should be noted that the sulphur involved on this low temperature mineralization need not have come directly from the intrusion. Under suitable conditions brought about by the emplacement of the intrusion, pre-existing sulphide might have been remobilized and redeposited within the localized spatial environment. These pre-existing sulphides might be either syngenetic sulphides in the country rock or early formed sulphides from Zones I to III. In any case, since the abundance of sulphide in this zone is very low, the weighted average of isotopic data in the profile across the intrusion contact is not greatly affected when these sulphides are included in the calculation (Table 9).

Data from other drillholes and surface samples in the basal contact area

It is important to determine if the results obtained in the South drillhole represent the general trend of the sulphur isotope distribution in the profile across the basal contact of the intrusion. Cores from two holes drilled by the International Nickel Company of Canada in 1958 (DDH-58-15804 and DDH-58-15808) were studied for the purpose. However, in neither case was it possible to get enough data to reveal as detailed a pattern as that obtained from the Muskox South drillhole as core samples were available only at intervals of 10 to 15 feet and the sulphide-rich zones from the contact were absent. The results are given in Tables 10 and 11 and plotted in Figures 15 and 16.

DDH-58-15804 cuts the intrusion through the eastern marginal zone near the feeder and penetrates the basement complex for about 100 feet. The basement complex in this area consists of gneisses and granite. The geologic environment of this hole is therefore analogous to that of the South drillhole, although they are spatially distant from one another. The isotopic value of the intrusion sulphide is for a single specimen taken from the core about 200 feet above the contact, giving a result of +6.4 per mil (58-15804-480 of Table 10). The decision to let this single result represent the isotopic composition in the intrusion margin is justified, when the data from surface samples near the drillhole (+7.8 per mil in 59-1045B(b) and +7.6 per mil in 59-1087C of Table 6) is considered. It is assumed that the average isotopic composition in this part of the intrusion is about $+7 \pm 1$ per mil, or comparable to the value obtained for the intrusion margin in the South drillhole. The isotope distribution in the adjacent country rock is based on five sulphide samples collected from a zone extending for 75 feet below the intrusion contact. The results show an outward increase of δS^{34}, varying from +2.9 to +7.8 per mil (Fig. 15), and the samples adjacent to the contact are markedly enriched in S^{32} with respect to the value for the intrusion margin. The trend of isotope distribution in this profile is comparable to that in the South drillhole, and with the analysis of closely spaced samples in the zone immediately below the content would be expected to resemble that indicated in Figure 11 for the South drillhole. The two types of sulphides recognized in Zone II of the South drillhole are not clearly distinguished in drillhole 58-15804. However, the sulphides in specimen 58-15804-680 are very fine grained and may be grouped with the (b) type sulphides in Figure 13.

DDH-58-15808 cuts the eastern marginal zone of the intrusion and the underlying country rock. The latter are mainly metasedimentary rocks rather than gneisses and granites as for the South drillhole and DDH-58-15804. Cores were not available for 20 to 30 feet on either side of the intrusion contact, therefore it was not possible to establish a definite isotopic profile (Fig. 16). Three samples of pyrite from the country rock are similar to the sulphides of Zone IV in the South hole, judging from mineral species and mode of occurrence (Table 11). The relatively heavy isotopic values may also support this view.

As mentioned before, a few sulphide samples taken from surface exposures of the country rock adjacent to the basal contact of the intrusion are enriched in S^{32} relative to samples from nearby localities. Typical examples are 60-40A, 62-4027A(c) and 62-4004C in Table 7. It is interesting that these sulphides are rather fine grained and normally occur parallel to the fissility or schistosity plane of host rock. Thus, it might be reasonable

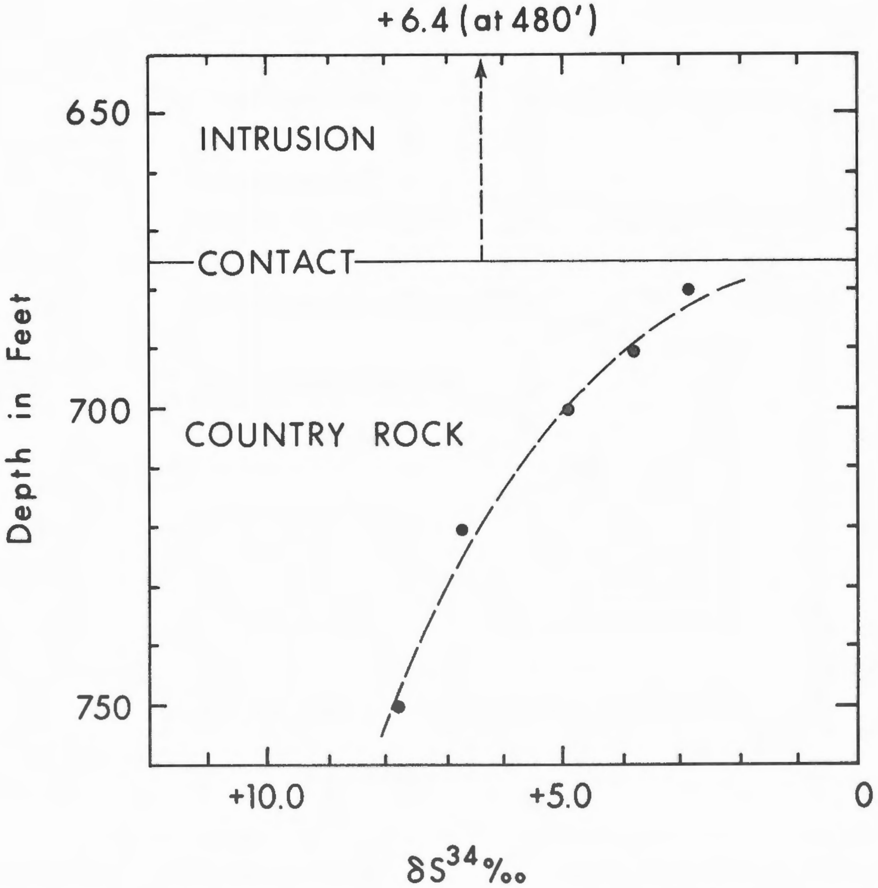

Figure 15. Distribution of sulphur isotope data in the drillhole DDH-58-15804, the Muskox intrusion. (Location 25, Fig. 3).

to think of these sulphides as (b) type or, more probably, intermediate to the (a) and (b) type of sulphide recognized in Zones I to III of the South drillhole. Other examples may also be found in Table 7, for instance, 62-4030A and 62-4003A. Thus, although data are still very limited, the occurrence of these sulphides in the country rock adjacent to the basal contact of the intrusion appears in general to be irrespective of the major differences in the type of country rock along the east and west contacts (Fig. 9). The possibility of overlooking (b) type sulphide during the sampling of the contact-zone sulphides from surface exposures was previously noted (p. 19).

Profiles across the roof contact of the intrusion

The distribution of sulphur isotopes across the roof contact of the intrusion was established for drill-core samples from the top of the North drillhole. This drillhole cuts the sandstone roof-rock for about 200 feet before it enters the intrusion. Sulphides in this profile are pyrite and/or

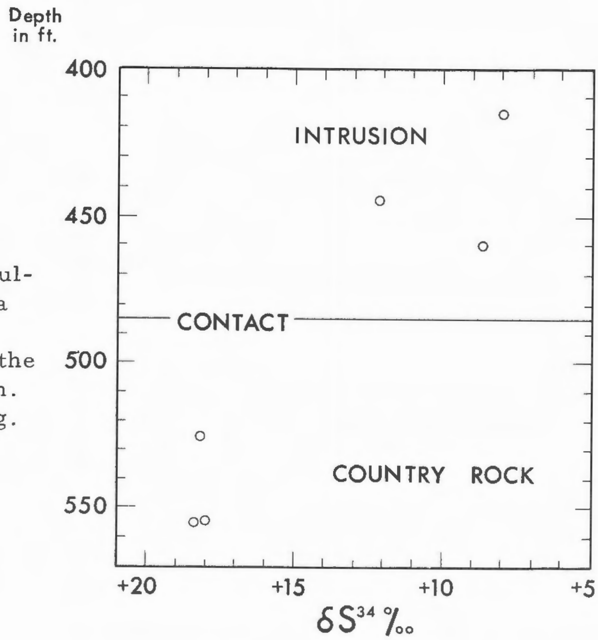

Figure 16. Distribution of sulphur isotope data in the drillhole DDH-58-15808, the Muskox intrusion. (Location 40, Fig. 3).

chalcopyrite as in the upper border zone of the intrusion. No pyrrhotite, cubanite or nickel-bearing sulphide has been observed. Sulphur isotope values were determined for two specimens collected from the intrusive breccia zone and five from the country rocks within about 90 feet of the contact. The results are given in Table 12 and plotted on Figure 17. No isotopic data could be obtained from the upper border zone in this drillhole, but values determined for surface samples from the same zone (59-1766B to 60-609A in Table 3) are plotted in Figure 17 to show the background isotopic composition in this part of the intrusion.

The δS^{34} values of two specimens in the intrusive breccia (+4.0 and +4.2 per mil) are similar to the background data of the upper border zone (+3.3 to +7.1 per mil). In the adjacent country rock, the values obtained are heavier than the values in the intrusive breccia (Fig. 17). However, except for two specimens (N-0018-a and b), they are still close to the values in the upper border zone. The isotopic ratios for sulphides in the country rock were also determined for four samples taken from surface exposures and the East drillhole (Table 12). The results indicate again the isotopic similarity between the upper part of the intrusion and the adjacent country rock. Because the sulphide mineral assemblage also is identical on both sides of the contact, it seems reasonable to assume that the majority of sulphides in the country roof rock simply migrated from the intrusion. Therefore the sulphide mineralization in this part may have been essentially different from that in the basal contact zone where two different types of sulphide appeared to cause a complicated isotopic distribution. The exceptionally heavy values in N-0118(a) and (b) of Table 12 are similar to the data obtained in Zone IV of the South drillhole.

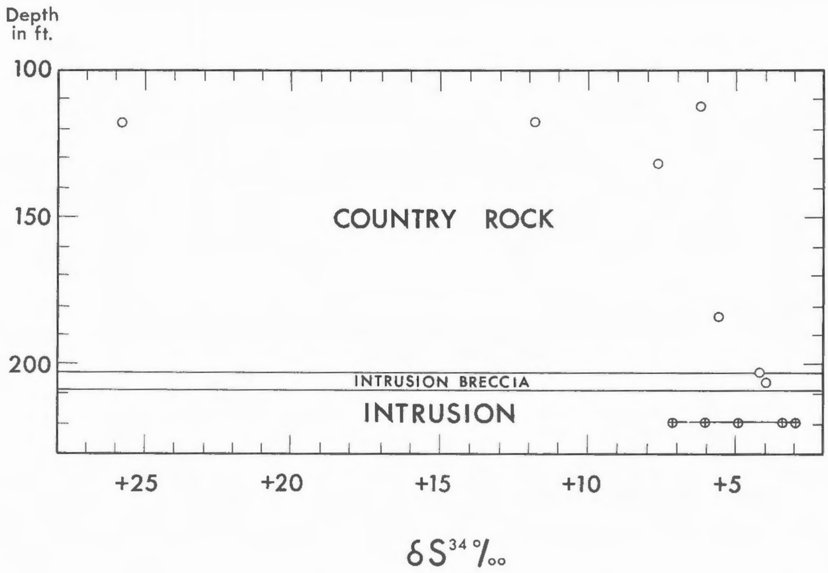

Figure 17. Distribution of sulphur isotope data across the roof contact of intrusion, in the Muskox North drillhole (Location 81, Fig. 3). Data obtained from surface samples in the upper border zone are also given as reference.

Country rock adjacent to the feeder

In view of the mineralogical and isotopic similarity of the feeder and marginal zone sulphides, a profile across the feeder contact would be very valuable. Unfortunately, this could not be obtained because of the discontinuous distribution and low concentration of sulphides in the feeder. The single isotopic result for country rock sulphide has a value of +12.2 per mil for chalcopyrite obtained from granodiorite adjacent to the west contact of the feeder (Table 13). This is comparable to the data observed in this part of the feeder dyke (62-4019A-a, +11.1; 62-4019B-b, +10.0; and 62-4018, +12.2 in Table 2).

Synopsis

The investigation has revealed an extensive sulphur isotope abundance range in sulphides taken across the basal contact of the intrusion in the South drillhole. Results from other drillholes and surface samples indicate the probable existence of similar trends in other parts of the basal contact zone. Two types of sulphide are recognized in the country rock immediately adjacent to the intrusion. The one (a type) is, both mineralogically and isotopically similar to sulphides in the intrusion margin, whereas the other (b type) is isotopically much lighter and may also be distinguishable mineralogically and/or texturally. Isotopic patterns observed across the basal contact are attributed to the mixing of these two types of sulphide.

The result from the South drillhole also indicates that while the average isotopic composition for the intrusion margin is fairly heavy (+8 per mil), the value calculated for the entire sulphide-bearing zone across the intrusion contact is relatively light (+6 per mil), being fairly close to the averages obtained for the layered series and the inner part of the marginal zone ($+5 \pm 0.5$ per mil). This is in accord with the assumption that the two types of sulphide in the country rock, as well as the sulphide in the intrusion margin, are the products of a single source of sulphur, the same sulphur that formed sulphides in the layered series and the inner marginal zone. Thus, the higher concentration of S^{34} in sulphides of the basal margin relative to the inner parts of the intrusion may be explained by preferential migration of the lighter sulphur outside the intrusion contact, where (b) type sulphide predominates. However, the questions of how the two types of sulphur (or sulphide) have differentiated from a single source remain unsolved.

As stated, the isotopic data in the intrusion margin show a strong correlation with the type of adjacent country rock, and may be divided into two groups: (1) $\delta S^{34} \leq +9.0$ per mil in the area adjacent to granitic country rocks and (2) $\delta S^{34} > +9.0$ per mil in the area adjacent to metasedimentary rocks. Such a correlation seems to attest the presence of certain interactions between the intrusive magma and its country rock. From the data, one might consider that the intrusion margin was contaminated by country rock sulphur and that the average sulphur of the metasedimentary rocks was heavier than that of the granitic ones. Although this is a tempting interpretation, our knowledge of the country rock sulphur (see the next section) is still too limited to further evaluate the hypothesis. Rather, the isotopic evidence for the South drillhole favours the assumption that the majority of sulphur in the basal contact zone has been derived from the intrusive body. If this is a general rule in the entire basal contact of this intrusion, then the regular relation observed between sulphur isotopic values in the intrusive margin and type of country rock should not be entirely attributed to the contamination by country rock sulphur. This means that certain other differences in chemical and/or physical properties between the granitic and metasedimentary rocks must have been responsible for this effect. However, further discussion is again difficult because of the limited data. The South drillhole data merely provide us with an example of the isotopic variations across the basal contact in the area of granitic country rocks, and we therefore require at least one similarly detailed profile in the area of metasedimentary rocks. Unfortunately, suitable samples were not available for such a study.

The isotopic distribution of sulphur across the roof contact of the intrusion is different from that determined for the basal contact zone. There are no marked differences such as were observed between the edge of the intrusion and the inner portion of the upper border zone. The majority of sulphides in the roof-rocks appear to be the same as those in the intrusion, both mineralogically and isotopically, and there is no indication of two types of sulphide as along the basal contact zone.

The lack of suitable specimens made it impossible to obtain an isotopic profile across the feeder contact. However, the mineralogical and isotopic similarity of the feeder sulphides to the sulphides in the basal margin of the intrusion suggest that this profile would be analogous to those obtained for the basal contact zone. If so, then the heavy sulphur detected in the now exposed feeder might be explained in a similar way.

According to the composite data discussed above, it seems reasonable to assume that the sulphur that formed the sulphides in the basal margin of the main intrusion body and the feeder dyke originally possessed an isotopic composition identical to the average value obtained for the layered series and the inner part of the marginal zone – that is, about +5 per mil.

SULPHUR ISOTOPE DISTRIBUTION IN COUNTRY ROCKS OUTSIDE THE THERMAL METAMORPHIC AUREOLE OF THE INTRUSION

Sulphur isotopic compositions were determined for eleven sulphide samples obtained from country rocks in the area outside the thermal metamorphic aureole of the intrusion. The data are presented in Table 14 Figure 4. Although it is difficult to give proof, these sulphides may be considered to have formed syngenetically with their host rocks. The analyzed materials include four samples of pyrite from basement metasedimentary rocks, three of pyrite and one chalcopyrite from the metavolcanic rocks, two of pyrite from granitic gneisses, and one of pyrite from granodiorite intruded into the basement series. Most of these sulphides contain more S^{34} than is found in meteoritic troilite. Arithmetical averages of δS^{34} in per mil for each group are: metasediments, +5.0; metavolcanics, +2.6; granitic gneisses, +5.0; and granodiorite, +5.6. However it will be appreciated that because the sampling is limited, these averages are not very meaningful statistically.

SULPHUR ISOTOPE DISTRIBUTION IN DIABASE DYKES

Twelve sulphide samples from seven apparently separated diabase dykes within or near the Muskox intrusion body were analyzed. The isotopic ratios obtained are listed in Table 15 and displayed in Figure 4. The sulphides are generally pyrite or chalcopyrite, but two are samples of pyrrhotite from a dyke intersected in the North drillhole (N-2678 and N-2811). Although there seems to be little petrographic difference between the dykes, the sulphur isotopic results appear to fall into two groups. In dykes E, F and G in Table 15, the isotopic values have a fairly narrow range, close to the value of the meteoritic standard, from -0.7 to +1.6 per mil, whereas in the dykes A, B, C and D, the isotopic ratios show no resemblance to the meteoritic value, ranging widely from -4.4 to +11.3 per mil. Smitheringale and Jensen (1963) found that sulphides in the normal diabases of the Triassic Newark Group in eastern United States have sulphur isotopic compositions comparable to meteoritic troilite, whereas the sulphides in late stage facies from the differentiated intrusives are variously enriched in S^{34} with respect to the meteoritic value, with δS^{34} values up to +11 per mil. The data given here for dykes E, F and G may roughly be compared to their results for normal diabases, but the isotopic data for the dykes A, B, C and D, can hardly be attributed to differences in rock type. However, it is interesting to note that the differences in isotopic composition may again be correlated with differences in country rock. Dykes A, B, C and D, occur in the basement complex where it is mainly metasedimentary rocks, whereas E, F and G are in the Muskox intrusion or basement granitic gneiss. Thus it is possible that certain interactions between the diabase and its country rock, particularly metasedimentary rocks, are responsible for the wide range of isotopic values obtained for the dykes, with the original value for diabase sulphur being approximately that of meteoritic sulphur. As there does not seem to be much difference in the ages of the diabase dykes and the Muskox intrusion, the apparent difference in the original isotopic composition between them may warrant further consideration.

SULPHUR ISOTOPE DISTRIBUTION IN, AND ASSOCIATED WITH, A MINOR GABBROIC BODY IN THE ROOF ROCK

Visible amounts of pyrrhotite and pyrite are disseminated in a minor exposure of gabbroic rock cropping out near the northeastern roof contact of the intrusion and in the adjacent country rock. The outcrop is very small, only a few tens of feet across, and no additional exposure has been discovered in this vicinity. It therefore is difficult to know if any genetic relationship exists between this body and the Muskox intrusion. The isotopic values determined for six sulphide samples from the gabbro and the adjacent country rocks are given in Table 16. The values range between -3.6 and +0.4 per mil, which is lighter than the values determined for the majority of sulphides in and associated with the Muskox intrusion.

SULPHUR ISOTOPE FRACTIONATION AMONG COEXISTING SULPHIDE SPECIES

The distribution of sulphur isotopes between coexisting sulphide minerals was examined in the following combinations: pyrrhotite-chalcopyrite, cubanite-chalcopyrite, pyrrhotite-cubanite-chalcopyrite, chalcopyrite-galena, pyrrhotite-seagenite and primary pyrrhotite-secondary pyrite or marcasite. A comparison was also made of the isotopic compositions of two types of pyrrhotite separated on the basis of magnetic properties. The majority of specimens were obtained from the sulphides occurring near the basal margin of the intrusion. A total of fifty-three sulphide mineral pairs extracted from forty-one different specimens were examined, and the results are shown in Tables 17 to 20. The difference in δS^{34} between coexisting sulphide species is generally small. It exceeds 1.0 per mil in only six instances, and the averaged difference for all pairs sampled is 0.6 per mil.

Although it is difficult to be certain, inasmuch as the differences are small and not entirely consistent, there does seem to be a tendency for pyrrhotite to be slightly heavier than associated chalcopyrite, as illustrated in Figure 18. The arithmetical average of $\delta S^{34}{}_{po} - \delta S^{34}{}_{cp}$ for twenty-nine pairs is +0.2 per mil. Paragenetically, these two minerals appear to be closely related, but there is some indication that chalcopyrite started to form slightly later because in many specimens it is concentrated near the margins of the pyrrhotite grains, and in some cases as thin rims around the pyrrhotite grains. In a few specimens, pyrrhotite is clearly veined by chalcopyrite. Sulphur isotope fractionation between coexisting sulphide minerals has been reported by several authors for various mineral pairs in several types of sulphide deposit. It is interesting that, in general, the paragenetically later sulphides are variously depleted in S^{34} with respect to the earlier ones in spite of the geologic and mineralogic diversity of specimens (Ault and Kulp, 1960; Wanless et al., 1960; Freidrich et al., 1964; and Tatsumi, 1965),

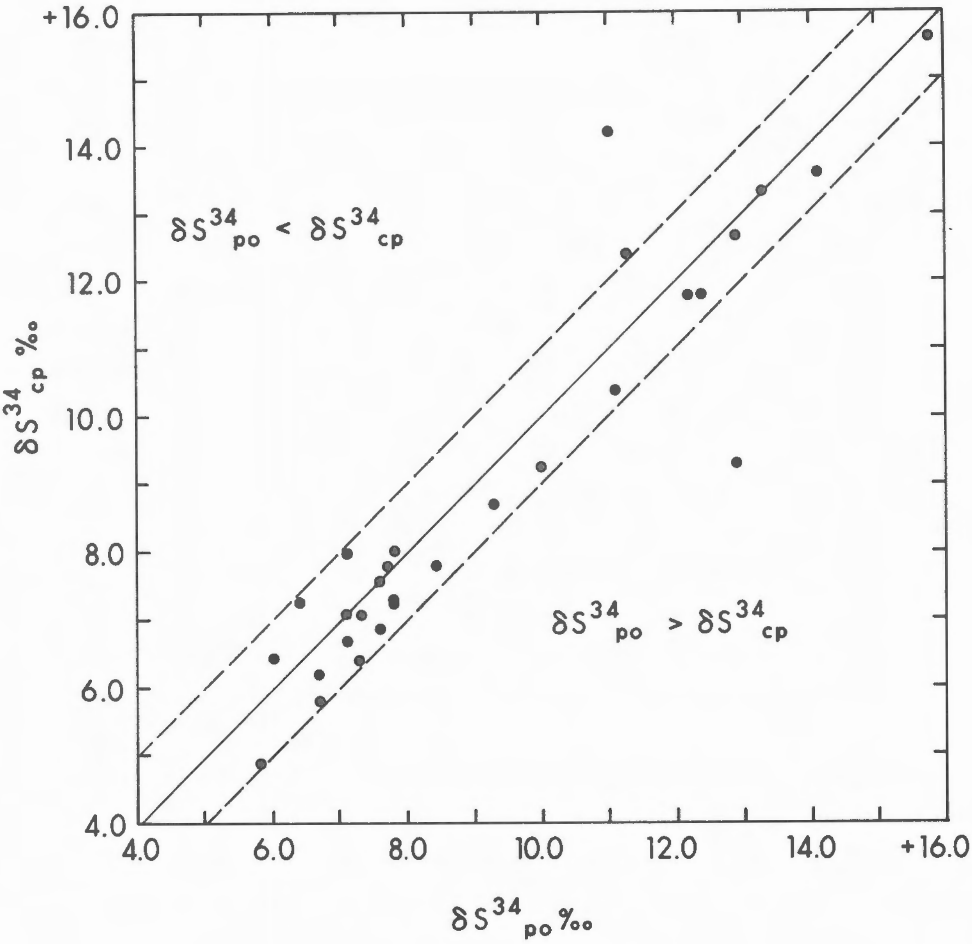

Figure 18. Distribution of sulphur isotopes between coexisting pyrrhotite and chalcopyrite from the Muskox intrusion. Area between two dashed lines corresponds to $|\delta S^{34}_{po} - \delta S^{34}_{cp}| < 1.0$ per mil.

whereas the fractionation factor between the same kinds of minerals is different for different localities. The present data obtained for pyrrhotite-chalcopyrite pairs are consistent with this general tendency. It will be noticed from Table 17 that the isotopic fractionation between the two minerals tends to show abnormal values in specimens in which either they occur as distinctly separate grains or chalcopyrite forms apparently later veins (e.g. 62-4011B, 62-4023, and 62-4054). It seems probable that in these specimens, the two minerals are paragenetically more independent.

The paragenetic relationship of cubanite to pyrrhotite and of pentlandite (now altered to seagenite) to pyrrhotite in the specimens studied may be compared with that of chalcopyrite to pyrrhotite. Chalcopyrite and cubanite generally occur in lamellar intergrowths, clearly as a result of exsolution, whereas in chalcopyrite-galena pairs, galena is the paragenetically later sulphide. Although the data are still too limited to establish any systematic differences (Table 18), a similar tendency to that observed for pyrrhotite and chalcopyrite may be noted in a few instances (e.g. in the chalcopyrite-galena pair).

Comparison of magnetically different pyrrhotites from the same hand specimen was considered necessary because, in the course of separating the sulphide minerals for analyses, many of the pyrrhotite specimens were magnetically concentrated and so might have been isotopically fractionated. Nine specimens were investigated, each of them being roughly divided into two fractions by a hand magnet. The results are given in Table 19. The isotopic difference between the fractions is small, averaging 0.4 per mil and is not systematic with respect to magnetic susceptibility.

Pyrrhotites obtained from surface exposures frequently contain varying amounts of pyrite or marcasite formed by supergene alteration. The isotopic compositions of the primary and secondary sulphides were compared in five specimens as shown in Table 20. There does not seem to have been any significant change of the isotopic composition during the alteration, but there is still room for further investigation.

DISCUSSION OF THE INITIAL SULPHUR ISOTOPIC VALUE IN THE MUSKOX MAGMA

As noted previously, it may be concluded that the average isotopic composition of sulphur in the Muskox intrusion was about +5 per mil when the magma was emplaced at the present site of the intrusion. From present knowledge it seems reasonable to assume that the majority of the magmatic components, including the sulphur, were derived from the upper part of the earth's mantle. Our knowledge of the isotopic composition of sulphur in the mantle is still limited, but several recent investigations of sulphides in other mafic or ultramafic plutons have shown isotopic values similar to the composition of meteoritic sulphur, which may be characteristic of the mantle (Shima et al., 1963; Smitheringale and Jensen, 1963). It is therefore important to consider the meaning of the relatively heavy average isotopic value obtained for the Muskox intrusion.

There are two main possibilities:

(1) The sulphur contained in the Muskox intrusion is isotopically representative of the sulphur in the mantle at the place (and at the time) the Muskox magma was formed. Thus the mantle sulphur would have a δS^{34} value of +5 per mil rather than zero as in meteoritic troilite.

(2) The original isotopic value in the mantle sulphur is not preserved in the Muskox sulphides, in which case we may still assume that mantle sulphur has the meteoritic isotopic ratio. This possibility allows two further alternatives:

(2A) All the sulphur in the intrusion was derived from the mantle, but some process or processes of isotopic fractionation occurred in the ascending magma and caused an enrichment in S^{34}.

(2B) At least a part of sulphur in the intrusion has not come directly from the mantle, but was introduced from country rocks encountered by the ascending magma.

The possibility remains that the sulphur in the earth's mantle has undergone isotopic fractionation during the evolution of the earth, even if originally it had a homogeneous composition similar to meteoritic sulphur. In this regard Shima et al. (1963, p. 2846) made the following comment based on their study of the Palisades, Cobalt, Leitch and Insizwa mafic sills: "Four basic sills, whose intrusion was widely separated in space and time, all have δS^{34} values similar to meteorites; it may be concluded that the mantle has a uniform ratio of S^{32}/S^{34} which has not changed with time". However, the results of the Muskox intrusion suggest that it is still early to deny the possibility (1) above. Before drawing a final conclusion on this question, we should investigate more mafic and ultramafic intrusives of different ages and from different localities.

If one considers possibility (2A), assuming that the original sulphur in the magma was isotopically identical to meteoritic sulphur, questions to be answered are: How did the isotopic fractionation take place and where should we expect to find the rest of the sulphur necessary to make the average isotopic value be zero per mil? As pointed out before, there is a general tendency for the sulphur in the intrusion walls to be enriched in S^{34} as compared with the average in the intrusion and, although the interpretation is still tentative, the available data indicate that this may be explained by the preferential migration of the lighter sulphur into the country rocks in response to some type of interaction between the magma and the country rock. If this is the case, then it seems possible that a similar process might have taken place in the ascending magma on its way to the present site of the intrusion. This would permit the lighter isotope to move preferentially away from the magma, thereby causing the gradual relative enrichment of the heavier isotope in the residual sulphur, until finally a value of about +5 per mil was reached.

The Coppermine basaltic lava flows, which are up to 11,000 feet thick, cover an extensive area north of the present exposure of the intrusion (Fraser, 1960; Smith, 1962). The chemical similarity of these basalts to the chilled margin of the Muskox intrusion and their close spatial relation suggest that the basalt may be the extrusive equivalent of the Muskox magma. If this is the case, a more reliable average of sulphur isotopic composition in the original Muskox magma might be obtained by taking into account the composition of the sulphur in the flows as well as in emanations expelled during the volcanic activity. Unfortunately, no isotopic data are available for these materials. However, considering the isotopic data on volcanic material by previous workers (e.g. Sakai, 1957; Ault and Kulp, 1959; Smitheringale and Jensen, 1963), it is possible that the sulphur related to the extrusive facies, including emanations, was generally enriched in S^{32} relative to that of the intrusive facies, and so would compensate for the enrichment in S^{34} in the latter.

Although there is no positive evidence that the intrusive magma was subjected to large scale contamination by the crustal material, it seems rather improbable that the sulphur in the intrusion is completely free from such contamination. Examples of magmatic assimilation of country rock sulphur have been discussed in the studies of the copper-nickel sulphide deposits associated with mafic to ultramafic intrusive bodies in Noril'sk area, northern Siberia, by Goldevskii and Grinenko (1963) and Vinogradov and Grinenko (1964). These authors concluded that fairly heavy isotopic values (+8 to +9 per mil on the average) measured in sulphides from the deposits are due to the contamination of magmatic sulphur by heavy sulphur that was originally contained as sulphates in the underlying sedimentary rocks penetrated by the magma. If homogeneous mixing of the original and introduced sulphur was accomplished, the isotopic composition of such a mixture would simply be a function of the amounts and the isotopic composition of the two kinds of sulphur. Assuming that the sulphur in the Muskox intrusion has been changed in isotopic composition from 0 to +5 per mil by such contamination, the required amounts of foreign sulphur would vary according to its isotopic value as follows: 50, 34, 25 and 21 per cent of the total sulphur, when the isotopic values are +10, +15, +20 and +25 per mil, respectively. Although it is impossible to know the distribution of sulphur isotopes in the country rocks penetrated by the magma, the data obtained for sulphides in the enclosing rocks at the present erosion surface are generally heavier than the meteoritic standard, showing a measured maximum of +13 per mil in a pelitic schist (Table 14). However, in order to go into further discussion of such a possibility, we require more data on the isotopic composition and abundance of the sulphur in the country rocks. At present, the situation does not look as favourable as in the Noril'sk area.

As discussed above, our knowledge is still too limited to draw any conclusion of the meaning of the relatively heavy isotopic composition of the sulphur of the Muskox intrusion. So far none of the possibilities given above appears to have enough evidence to exclude the others. However, if we must choose, the most acceptable interpretation at the moment seems to be the one described in (2A) with probable participation of that in (2B).

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APPENDIX

Table 1. Reproducibility of sulphur isotope analyses in five separately prepared samples of Cañon Diablo troilite.

A. STD-1112 (Date prepared: 1-2-1963)

δS^{34} ‰	Date Analyzed	δS^{34} ‰	Date Analyzed
0.0	16-10-63	0.0	16-12-63
-0.2	24-10-63	-0.4	17-12-63
-0.2	28-10-63	-0.2	17-12-63
-0.2	4-11-63	-0.2	31-12-63
-0.2	15-11-63	-0.4	13- 1-64
-0.6	28-11-63	-0.2	5- 5-64
-0.2	11-12-63	+0.2	23-11-64
	Average	$-0.2\pm0.1_9$*	

B. STD-1113 (Date prepared: 1-2-1963)

δS^{34} ‰	Date Analyzed	δS^{34} ‰	Date Analyzed
-0.2	21-10-63	0.0	13-12-63
0.0	25-10-63	0.0	21-12-63
0.0	30-10-63	+0.4	31-12-63
-0.2	8-11-63	+0.2	3- 1-64
0.0	22-11-63	+0.2	9- 1-64
0.0	29-11-63	+0.2	20- 1-64
0.0	2-12-63	0.0	12- 5-64
0.0	6-12-63	+0.2	30-11-64
+0.2	10-12-63		
	Average	$+0.1\pm0.1_6$*	

C. STD-1348 (Date prepared: 13-3-1964)

δS^{34} ‰	Date Analyzed	δS^{34} ‰	Date Analyzed
+0.2	27- 4-64	+0.2	8- 5-64
+0.2	30- 4-64	+0.2	26- 5-64
+0.2	4- 5-64	+0.4	10- 8-64
0.0	6- 5-64		
	Average	$+0.2\pm0.1_1$*	

D. STD-1357 (Date prepared: 14-3-1964)

δS^{34} ‰	Date Analyzed	δS^{34} ‰	Date Analyzed
0.0	24- 4-64	+0.2	7- 5-64
+0.6	27- 4-64	0.0	22- 5-64
+0.2	28- 4-64	+0.2	11- 8-64
+0.2	1- 5-64	+0.4	20-11-64
+0.2	5- 5-64		
	Average	$+0.2\pm0.1_8$*	

E. STD-1536 (Date prepared: 11-6-1964)

δS^{34} ‰	Date Analyzed	δS^{34} ‰	Date Analyzed
0.0	19- 6-64	0.0	2- 7-64
0.0	26- 6-64	0.0	3- 7-64
0.0	29- 6-64	0.0	13-10-64
	Average	0.0 ± 0.0*	

| | Grand Average | $0.0\pm0.2_2$* | |

* Standard deviation.

Table 2. Sulphur isotope data from the feeder dyke of the Muskox intrusion

Specimen No.	Location No. in Fig. 3	Mineral[1]	δS^{34} ‰	Description
SDC-60-442F	1	cp	+ 6.4	Fine- to medium-grained (< 1-2 mm) disseminations in bronzite gabbro, near centre of dyke (ca. 200 feet from both walls). cp-cb[2].
62-4000	3	po	+10.4	Massive aggregates in chilled bronzite gabbro. po-cp-sg.
60-1367	4	cp	+10.9	Fine- to medium-grained (< 1-2 mm) disseminations in chilled bronzite gabbro, within 50 feet from east contact. cp-cb.
60-1365A	5	po-cp	+14.4	Fine- to medium-grained (mostly < 1 mm) disseminations in chilled bronzite gabbro. 4 feet east of west contact. Sample was collected from a single grain (4 mm across) by hand picking. po-cp.
59-806	8	cp-po	+ 8.9	Fine- to medium-grained (< 3 mm) disseminations in chilled bronzite gabbro at western edge. cp-po-cb.
59-123	9	cp-po	+ 9.8	Fine-grained (< 0.5 mm) disseminations in picrite, near centre of dyke (ca. 300 feet from both walls). cp-po.
62-4019A(a)	10	po	+11.1	Fine- to medium-grained (< 1-3 mm) disseminations in bronzite gabbro. po-cp-sg.
62-4019B(b)	10	po	+10.0	Fine- to medium-grained (< 1-3 mm) disseminations in bronzite gabbro. po-sg-cp.
62-4018	12	po	+12.2	Medium- to coarse-grained (2-5 mm) disseminations in bronzite gabbro. po-cb-sg-cp.
59-933	13	cb	+ 9.6	Fine- to medium-grained (< 2 mm) disseminations in bronzite gabbro.
59-231V2	16	cb-cp	+ 9.6	Single grain (5 mm across) in bronzite gabbro. cb-cp-sg-po.
59-217C	17	cp-po	+ 8.0	Fine-grained (< 1 mm) disseminations in picrite. ca. 200 feet from west contact. cp-po.
59-984A	19	cp-po	+10.7	Fine-grained (< 1 mm) disseminations in bronzite gabbro. po-cp.
59-952) 59-955) 59-959) 59-963) 59-964) 59-966) 59-967) 59-969)	15	po-cb-cp	+ 9.6	Very fine-grained (< 0.3 mm, mostly 0.005-0.1 mm) disseminations in bronzite gabbro and picrite. 59-952, 59-955 and 59-963 are bronzite gabbro, while the remainder are picrite. Sulphides were extracted from a 10-pound composite rock sample, using a flotation cell and gravimetric techniques.
	Average		+10.1	

[1] Main sulphides in analyzed specimen. Minerals cited form more than 80 per cent of total sulphides in each specimen. Symbols in all tables: po, pyrrhotite; cp, chalcopyrite; cb, cubanite; sg, siegenite; pn, pentlandite; py, pyrite; mc, marcasite; sl, sphalerite; gn, galena; vl, valleriite.

[2] Minerals identified in a polished section made from a chip of the same hand specimen are given in order of predominance (J.A. Chamberlain, private communication).

Table 3. Sulphur isotope data from the layered series of the Muskox intrusion

Specimen No.[1]	Location No. in Fig. 3	Mineral	δS^{34}‰	Description[2]
SDC-N-0203	81	py	+ 4.2	Quartz-rich matrix in roof contact breccia zone. Veinlet (2-3 mm thick) along minute fracture. py-cp.
N-0206	81	cp	+ 4.0	Quartz-rich matrix in roof contact breccia zone. Irregular-shaped dissemination (3-5 mm across) or minute vein. cp-py.
59-1766B	93	py	+ 6.0	Granophyre of Upper Border Zone.
59-1752B	91	py	+ 7.1	Same as above.
60-553B	99	py	+ 4.9	Same as above, py-cp.
60-155A	101	py	+ 2.9	Same as above.
60-609A	83	py	+ 3.3	Granophyric gabbro of Upper Border Zone, cp-py.
59-1826	90	py	+ 7.8	Granophyre-bearing gabbro (layer No. 35[3]), py-cp.
60-225C	80	po	+10.2	Picritic websterite (layer No. 34), po-cp.
59-1814D	92	po	+ 6.0	Gabbro (layer No. 33).
N-0671	81	po	+ 3.8	Gabbro (layer No. 33), po-cp.
N-0752	81	po	+ 2.9	Picritic websterite (layer No. 32), po-cp.
60-1108A	65	py	+ 5.8	Picritic websterite (layer No. 32), py.
60-602B	79	po	+ 8.7	Picritic websterite (layer No. 32).
60-1223) 60-1224) 60-1225) 60-1236) 60-1237) 60-1245) 60-1247)	66	po	+ 4.7	Feldspathic websterite (layer No. 31) and gabbro (layer No. 30). Sulphides were extracted from composite a total of 15-pound rock sample, using a flotation cell and as gravimetric and magnetic techniques.
N-1064	81	po	+ 4.2	Gabbro (layer No. 30), po-cb.
60-1220	72	po	+10.4	Gabbro (layer No. 30).
60-756	106	po-cp	+ 4.2	Gabbro (layer No. 30), po-cb-cp-sg.
60-361	112	cp	+ 3.6	Orthopyroxenite (layer No. 29), cp-po.
60-48	111	po	+ 5.3	Orthopyroxenite (layer No. 29), cp-cb-sg.
60-255A	64	po	+ 1.8	Feldspathic peridotite (layer No. 28).
60-1138	68	cp	+ 6.0	Feldspathic peridotite and chromitite (layer No. 28). Fine- to medium-grained (< 4 mm) disseminations, cp.
60-252B	69	cp-cb	+ 5.8	Feldspathic peridotite and chromitite (layer No. 28). Fine-grained (< 1 mm) disseminations and sporadically distributing specks (5-10 mm), cp-cb-po.
DDH-18618-363.5	71	po	+ 5.1	Feldspathic peridotite and chromitite (layer No. 28). Medium-grained (2-4 mm) dissemination.
60-251B	73	cb	+ 6.0	Feldspathic peridotite and chromitite (layer No. 28). Fine- to medium-grained (< 3 mm) disseminations, cp-cb.
60-250B(b)	74	cb	+ 6.4	Feldspathic peridotite and chromitite (layer No. 28). Fine- to coarse-grained (< 7 mm) disseminations, cp-cb.

Table 3. (cont'd.)

Specimen No.[1]	Location No. in Fig. 3	Mineral	δS^{34}‰	Description[2]
60-249A	75	po	+ 6.7	Feldspathic peridotite and chromitite (layer No. 28). Sporadically distributed specks (2-5 mm).
60-248D	76	po-cb	+ 6.9	Feldspathic peridotite and chromitite (layer No. 28). Sporadically distributed specks (up to 10 mm), po-cb-cp-sg.
62-4051	78	cb-po	+ 7.3	Feldspathic peridotite and chromitite (layer No. 28). Medium-grained (2-5 mm) disseminations, cb-po-cp-sg.
N-1222	81	po	+ 4.9	Feldspathic peridotite and chromitite (layer No. 28). Medium-grained (2-4 mm) dissemination, po-cb-pn.
E-1288	85	po	+ 6.0	Feldspathic peridotite and chromitite (layer No. 28). Fine- to medium-grained (< 5 mm) dissemination, po-cb-pn.
E-1423	85	cp-po	+ 5.3	Websterite (layer No. 23), cb-pn.
60-239	67	po	+ 1.1	Feldspathic peridotite (layer No. 22), po-cp-pn-sg.
N-1562	81	po	+ 3.1	Peridotite (layer No. 22), po-pn-cb.
N-1655	81	po	+ 4.2	Serpentinized dunite (layer No. 21).
N-1779	81	pn	+ 4.0	Serpentinized dunite (layer No. 21), pn.
E-1871	85	po	+ 5.3	Peridotite (layer No. 18), po-pn.
N-2325	81	po	+ 3.3	Serpentinized dunite (layer No. 14), po-cp-pn.
E-2181	85	po	+ 6.0	Dunite (layer No. 12), po-pn-cb-vl.
E-2441	85	po	+ 5.6	Dunite (layer No. 12), po-pn-vl.
N-3116	81	po-pn	+ 4.2	Serpentinized dunite (layer No. 12), pn-po-vl.
N-3366	81	po-pn	+ 4.0	Feldspathic peridotite (layer No. 10), pn-po-cp-vl.
60-68	126	po	+ 4.2	Feldspathic peridotite (layer No. 10), po-cb-sg.
60-62	127	po	+ 4.2	Feldspathic peridotite (layer No. 10), po-cp-cb.
60-108B	62	po	+ 4.2	Feldspathic peridotite (layer No. 10), po-cp-cb-pn-sg.
60-737	52	po	+ 8.2	Serpentinized dunite (layer No. 7), po-cb-pn-sg.
S-2259	63	po	+ 6.4	Olivine clinopyroxenite (layer No. 4).
59-1242	132	po-pn	+ 6.0	Olivine clinopyroxenite (layer No. 2).
59-1072) 59-1075) 59-1076)	26	po-pn	+ 4.4	Weakly serpentinized dunite (layer No. 1). Sulphides were extracted from a composite of 6-pound rock sample, using a flotation cell and gravimetric and magnetic techniques.

[1] Samples of N- E- and S-series are from the North, East and South drillholes, respectively. Accompanied figures represent footage of specimen in each hole (Findlay and Smith, 1964).

[2] Sulphides occur as fine-grained (< 1 mm) and sparsely disseminated grains, unless otherwise indicated.

[3] The layers in the intrusion are numbered for reference purpose from the base to the top of the layered series (1-35). The sequence and petrographic character of layers are given by Findlay and Smith (1964).

Table 4. Distribution of sulphur isotope data in various sulphide zones of the layered series of the Muskox intrusion.

Zone defined by sulphide mineral assemblage[1]	Approximate stratigraphic horizon	δS^{34}‰[2]	Sulphur content expressed as relative %[3]
Fe	Upper Border Zone	+4.6	81.7
Cu-Fe	Layers 31-35, including lower portion of Upper Border Zone	+6.2	9.4
Ni-Fe-Cu	Layers 8-30	+5.0	8.5
Ni-Fe	Layers 1-7	+6.3	0.4
Weighted average of δS^{34} in the whole layered series: +4.8‰			

[1] Corresponds to metal-sulphide facies in Table I by Chamberlain (1967).

[2] Means of the data observed in the corresponding stratigraphic horizons.

[3] Calculated from the data given in Tables I and II by Chamberlain (1967).

Table 5. Sulphur isotope data from the inner part of the marginal zone of the Muskox intrusion[1].

Specimen No.	Location No. in Fig. 3	Mineral	δS^{34}‰	Description[2]
			Eastern margin	
SDC-				
59-1091	28	po	+5.3	Peridotite, po-cp-sg.
60-1083C	70	po-cp	+3.3	Feldspathic peridotite, po-cp-cb.
60-692	89	po	+7.1	Feldspathic peridotite. Some grains of sulphides exceed 2 mm across, po-cp-sg.
62-3086A	94	po-cp	+3.3	Picrite, cp-po.
			Western margin	
59-1038H	153	cp	+3.1	Olivine bronzite gabbro, cp-po.
62-4032	152	po-cb	+6.7	Olivine bronzite gabbro, po-cb-cp-sg.
59-1452	135	po	+6.4	Bronzite gabbro, po-cb-sg.
59-1500	130	po	+6.4	Picrite. Sulphides occur as intergranular minute stringers (width < 0.5 mm, length < 2-3 mm) among silicate grains, po-cp-cb-sg.
60-41	128	po	+7.1	Feldspathic peridotite. Sulphides occur as intergranular minute stringers (width < 0.5 mm, length < 1 mm) among silicate grains.
59-1514	121	cp-pn	+3.6	Feldspathic peridotite, cp-pn-po.
60-720	119	po	+5.1	Feldspathic peridotite, po-pn-cp-sg.
62-4007D	120	po-py	+5.8	Feldspathic peridotite, po-cb-cp and secondary py and mc after po.
59-1859	113	po	+3.6	Feldspathic peridotite, po-pn.
60-748	110	po	+3.3	Picrite, po-cp.
60-751	109	po	+6.0	Feldspathic peridotite. Some grains of sulphides exceed 1-2 mm across, po-sg-pn.
60-755	107	po	+3.6	Feldspathic peridotite, po-sg-cb.
S-3152	63	po	+6.0	Peridotite, po-pn.
		Average	+5.0	

[1] The inner part of the marginal zone is arbitrarily defined as the portion over 200 feet from the country rock contact for sulphides obtained less than 200 feet from the country rock contact, see Table 6.

[2] Sulphides occur as fine-grained (< 0.5-1 mm) disseminations, unless otherwise indicated.

Table 6. Sulphur data from the outer part of the marginal zone of the Muskox intrusion[1].

Specimen No.	Location No. in Fig. 3	Mineral	δS^{34}‰	Description
			Eastern margin	
SDC-59-1045B(b)	23	cp	+ 7.8	Fine- to medium-grained (< 5 mm) disseminations and massive aggregates in picrite, near feeder dyke, po-cb-cp-gn.
58-15804A	25	cp	+ 6.4	See 58-15804-480 of Table 10.
59-1087C	27	cb-po	+ 7.6	Fine- to medium-grained (< 5 mm) disseminations in bronzite gabbro, 10 feet from contact.
59-1146B	29	po-cb	+ 8.2	Massive aggregates in bronzite gabbro. Pyrrhotite crystals have edges exceeding 2 cm. po-cb-sg and secondary mc after po.
59-1288A	37	po	+10.0	Coarse-grained (5-10 mm) disseminations in picrite.
58-15808A	40	po(cp)	+ 9.6	Average of three values from 58-15808-415 to 58-15808-460 in Table 11.
62-4054(a)	41	po	+11.3	Massive aggregates along basal contact of intrusion. Big pyrrhotite crystals (up to 7 cm along edge) are veined by chalcopyrite, po-cp-sg-cb.
62-4055	45	po	+14.2	Massive aggregates and irregular veins in bronzite gabbro. Pyrrhotite crystals have edges up to 3 cm, po-cb-sg-cp.
62-4011A(b)	47	po	+13.3	Medium- to coarse-grained (2-10 mm) disseminations to massive aggregates in bronzite gabbro, po-cp.
62-4011B(a)	47	po	+12.9	Fine- to coarse-grained (< 1-7 mm) disseminations in bronzite gabbro, cp-po.
62-4012(b)	48	po	+15.8	Medium- to coarse-grained (2-10 mm) disseminations to irregular veinlike masses in bronzite gabbro, po-sg-cp.
60-1006	50	po	+14.7	Medium- to coarse-grained (< 10 mm) disseminations in bronzite gabbro, po-cp-cb-sg.
62-4025	53	po	+15.6[2]	Fine- to medium-grained (< 5 mm) disseminations in bronzite gabbro, ca. 20 feet from contact, po-cb-cp.
62-4014	60	po	+16.9[2]	Fine- to medium-grained (< 5 mm) disseminations in bronzite gabbro, po-cp-sg.
62-4050	87	po	+14.1[2]	Massive aggregates along basal contact of intrusion, po-cp-sg.
62-4050A	87	po	+10.9	Fine- to medium-grained (< 1-2 mm) disseminations in picrite, po-sg-cb-cp.
			Western margin	
59-1068A	154	po	+ 6.4	Fine- to medium-grained (< 5 mm) disseminations in bronzite gabbro, po-cb-pn.
62-4031(a)	151	po	+ 5.8	Fine- to medium-grained (< 3 mm) disseminations in bronzite gabbro, po-cb-cp and secondary mc after po.
62-4033(a)	150	po	+ 6.7	Massive aggregates along basal contact of intrusion. Pyrrhotite crystals have edges up to 8 cm, po-cp-sl-gn and secondary py and mc after po.

Table 6. (cont'd.)

Specimen No.	Location No. in Fig. 3	Mineral	δS^{34} ‰	Description
SDC- 62-4037A	148	po	+ 7.7[2]	Massive aggregates along basal contact of intrusion, po-cp-cb-sg.
62-4037B(b)	148	po	+ 7.3	Fine- to coarse-grained (<10 mm) disseminations in bronzite gabbro, po-cp.
62-4047(a)	141	po	+ 7.1	Massive aggregates along basal contact of intrusion. Pyrrhotite crystals have edges exceeding 2 cm, po-cp and secondary py after po.
59-1522	131	po	+11.3	Fine- to medium-grained (< 3 mm) disseminations in bronzite gabbro, po-cb-cp.
60-5	129	po	+ 8.9	Fine- to medium-grained (< 3 mm) disseminations in picrite, po-cp.
62-4007B	120	po-cb	+ 3.3	Fine-grained (< 1 mm) disseminations in bronzite gabbro, po-cb-sg-pn-cp.
62-4006B	117	cb-po	+ 6.9	Fine- to medium-grained (< 5 mm) disseminations in picrite, ca. 30 feet from contact, cb-po-cp.
60-753	108	po	+ 4.0	Fine- to medium-grained (< 2 mm) disseminations in olivine bronzite gabbro, po-cb-cp.
62-3089A	105	po-cp	+ 3.1	Fine- to medium-grained (< 5 mm) disseminations in picrite. Within 2 feet from contact, po-cp-pn-sg.
62-4020	104	po	+ 3.8	Fine- to medium-grained (< 3 mm) disseminations in bronzite gabbro, po-cp.
60-712	103	po	+ 8.2	Fine- to medium-grained (< 2 mm) disseminations in feldspathic peridotite, ca. 2 feet from contact.
60-165	102	po	+ 6.0	Fine- to medium-grained (< 2 mm) disseminations in bronzite gabbro, po-cp and secondary mc after po.
63-SH-A	63	po(cp)	+ 7.7	Average of eleven values from S-3433 to S-3674 in Table 8.

[1] The outer part of the marginal zone is arbitrarily defined as the portion less than 200 feet from country rock contact. For sulphides from the inner part of marginal zone, see Table 5.

[2] Mean of two measurements for magnetically different pyrrhotites. See Table 19.

Table 7. Sulphur isotope data from sulphides in country rocks adjacent to the basal margin of the Muskox intrusion[1].

Specimen No.	Location No. in Fig. 3	Mineral	δS^{34}‰	Description
			Eastern contact	
SDC-62-4030A	24	po	+ 4.7	Fine- to medium-grained (< 3 mm) disseminations or thin layers (1-2 mm thick) in quartz-biotite-plagioclase gneiss. ca. 15 feet from intrusion contact, po-cp.
62-4030B	24	po	+ 7.1	Medium- to coarse-grained (3-10 mm) disseminations to massive aggregates in quartz-biotite-plagioclase gneiss, po-cp-sg.
58-15804B	25	po	+ 5.2	Average of five values from 58-15804-680 to 58-15804-750 in Table 10.
62-4042	30	po	+ 8.7	Medium- to coarse-grained (2-7 mm) disseminations in quartz-biotite-plagioclase gneiss, po-cp-sg.
62-4043(a)	31	po	+ 7.1	Fine- to medium-grained (< 1-5 mm) disseminations to massive aggregates in quartz-biotite-plagioclase gneiss, po-cp-cb.
62-4045	32	po	+ 8.9	Massive aggregates in quartz-biotite-plagioclase gneiss, po-cb-sg-cp.
62-4046	36	po	+ 9.6	Massive aggregates in quartz-biotite-plagioclase gneiss, po-cb-sg-cp and secondary mc after po.
59-1283	39	sl	+11.1	Sphalerite-calcite veins (up to 3 cm in width) in paragneiss, sl-mc.
58-15808B	40	py	+18.2	Average of three values from 58-15808-525 to 58-15808-555(b) in Table 11.
62-4049	42	po	+16.2	Fine- to coarse-grained (< 10 mm) disseminations in paragneiss, po-cb-sg and secondary mc after po.
62-4052(a)	43	po	+12.2	Medium- to coarse-grained (< 3-15 mm) disseminations to massive aggregates in paragneiss, cb-po-cp-sg.
62-4053	44	po	+12.7	Fine- to medium-grained (< 1-4 mm) disseminations in paragneiss, po-cp-sg-cb.
60-40A	49	cp	+ 3.6	Fine-grained (< 1 mm) disseminations in paragneiss. Distribution is parallel to schistosity plane of host rock.
62-4026(a)	54	po	+12.9	Massive aggregates in biotite quartzite. Pyrrhotite crystals have edges up to 5 cm, po-cp-cb-sg and secondary mc after po.
62-4027A(c)	55	cp	+ 5.6	Fine- to medium-grained (< 3 mm) disseminations or thin layers (1-2 mm thick) along fissility plane of biotite quartzite, 10-20 feet from intrusion contact, cp-cb.
62-4027B	55	po	+13.6	Coarse-grained (up to 15 mm) disseminations to massive aggregates in quartzite, po-cb-cp.
62-4024	56	po	+11.6	Irregular veinlike masses (up to 1 cm in width) in biotite quartzite, po-cp-sg.
62-4023	57	po	+11.0[2]	Medium- to coarse-grained (3-10 mm) disseminations to massive aggregates in biotite quartzite, po-cb-cp-sg and secondary mc after po.
62-4028(b)	58	po	+12.9	Massive aggregates in biotite quartzite, po-sg-cb-cp.

Table 7. (cont'd.)

Specimen No.	Location No. in Fig. 3	Mineral	δS^{34}‰	Description
SDC-62-4029A(a)	59	po	+12.0	Massive aggregates in biotite quartzite, po-cp-cb-sg.
62-4029B(c)	59	cb	+13.8	Irregular veins (up to 1 cm in width) in biotite quartzite, cp-cb-po.
62-4013	61	po	+16.0	Medium- to coarse-grained (2-10 mm) disseminations in biotite quartzite, po-sg-cp.
			Western contact	
62-4034(a)	150	po	+ 7.1	Massive aggregates in paragneiss, po-cp-sg.
62-4035	149	po	+ 7.1	Fine- to medium-grained (< 5 mm) disseminations in granitic gneiss, ca. 20 feet from intrusion contact, po-cp-sg.
62-4036A(a)	149	po	+ 9.3	Fine- to medium-grained (< 4 mm) disseminations in quartz-biotite-plagioclase gneiss, po-cp-sg.
62-4036B	149	po	+ 8.4[2]	Coarse-grained (up to 15 mm) disseminations in granitic gneiss, po-cp-sg.
62-4038A	147	po	+ 7.6	Coarse-grained (up to 10 mm) disseminations in granitic gneiss, po-cp-sg.
62-4038B(a)	147	po	+ 7.3	Medium- to coarse-grained (3-15 mm) disseminations in granitic gneiss, 5-10 feet from intrusion contact, po-cp-sg.
62-4039	146	po	+ 7.6	Fine- to medium-grained (< 5 mm) disseminations in quartz-biotite-plagioclase gneiss, po-cb-sg.
62-4040	145	po	+10.2	Medium-grained (2-3 mm) disseminations in quartz-biotite-plagioclase gneiss, po-cp.
62-4041	144	po	+ 7.8[2]	Medium- to coarse-grained (5-15 mm) disseminations to massive aggregates in quartz-biotite-plagioclase gneiss. Within 10 feet from intrusion contact, po-cb-cp-sg.
62-4044(a)	143	po	+ 7.8	Massive aggregates in granitic gneiss, po-cb-cp-sg and secondary mc after po.
62-4048(a)	140	po	+ 6.0	Fine- to coarse-grained (< 1-15 mm) disseminations in granitic gneiss, po-cp-sg and secondary mc after po.
59-1332B	139	po	+ 7.6	Massive aggregates in granitic gneiss, po-cp-sg and secondary mc after po.
59-1433B(a)	138	cp	+ 5.8	Fine- to medium-grained (< 1-5 mm) disseminations to massive aggregates in paragneiss, sl-gn-cp.
62-4056	137	po	+ 6.3[2]	Massive aggregates in paragneiss, po-cb-sg-cp and secondary mc after po.
62-4057(a)	136	po	+ 6.7	Coarse-grained (up to 15 mm) disseminations in granitic gneiss, po-cp and secondary mc after po.
62-4058	134	po	+ 6.9	Medium- to coarse-grained (2-7 mm) disseminations in paragneiss, po-cp and secondary mc after po.
62-4059(a)	133	po	+12.4	Massive aggregates in granitic gneiss, po-sl-cp and secondary mc after po.

Table 7. (cont'd.)

Specimen No.	Location No. in Fig. 3	Mineral	δS^{34} ‰	Description
SDC-59-1479	125	po-cb	+ 7.8	Fine-grained (< 1 mm) disseminations in quartz-biotite-plagioclase gneiss, po-cb-cp-sg.
59-1543	124	gn	+ 4.0	Massive aggregates in quartz-biotite-plagioclase gneiss, gn.
62-4009	123	po	+ 6.2	Fine- to medium-grained (< 3 mm) disseminations in paragneiss, po-cp-cb-sg.
62-4008A(a)	122	po	+ 5.8	Coarse-grained (up to 15 mm) disseminations in paragneiss, po-cp-sg and secondary mc after po.
62-4008B	122	po	+ 4.0	Coarse-grained (up to 10 mm) disseminations in paragneiss, po-cp.
62-4007A	120	po	+ 4.4	Massive aggregates in paragneiss, po-sg-cb-cp.
62-4007C	120	po	+ 5.8	Coarse-grained (5-10 mm) disseminations in paragneiss, po-cb-cp-sg.
62-4010	118	po	+ 8.7	Medium- to coarse-grained (3-10 mm) disseminations in paragneiss.
62-4006A(a)	117	po	+ 7.8	Massive aggregates in paragneiss, po-sg-cp.
62-4005	116	po	+ 7.3	Fine- to medium-grained (< 3 mm) disseminations in paragneiss, po-cp and secondary mc after po.
62-4004A	116	po	+ 8.4	Massive aggregates in paragneiss, po-cp-sg and secondary py and mc after po.
62-4004B(a)	116	po	+ 7.6	Fine- to medium-grained (< 3 mm) disseminations to massive aggregates in paragneiss, po-sg-cp.
62-4004C	116	po	- 0.4	Fine-grained (< 1 mm) disseminations in paragneiss. Distribution is parallel to schistosity plane of host rock, po-cp-sg.
62-4004D	116	po	+ 7.3	Massive aggregates in paragneiss. Pyrrhotite crystals have edges exceeding 2 cm, po-cp-sg.
62-4003A	116	po	+ 4.0	Fine- to medium-grained (< 5 mm) disseminations in paragneiss. Distribution is roughly parallel to schistosity plane of host rock, po-cp and secondary mc after po.
62-4003B	116	cp	+ 8.7	Medium-grained (3-5 mm) disseminations in granitic gneiss, cp-po.
62-4002A	115	po-mc	+ 8.0	Fine- to medium-grained (< 2 mm) disseminations in granitic gneiss, po-cp and secondary mc after po.
62-4002B	115	po	+ 7.8	Fine- to medium-grained (< 2 mm) disseminations in granitic gneiss, po-cp.
62-4002C	115	po	+ 7.1	Fine- to medium-grained (< 2 mm) disseminations in granitic gneiss, po-cp-cb-sg.
62-4002D(a)	115	po	+ 6.4	Medium-grained (2-4 mm) disseminations and massive aggregates in quartzite, po-cp-sg-cb.
63-SH-B	63	po(cp, py)	+ 5.4	Average of thirty one values, ranging from -3.8 to +29.8‰, taken from S-3675.5 to S-3980 in Table 8. Calculation was weighted according to sulphide content in rock specimens See Table 9.

[1] Except for drill-cores (58-15804B and 63-SH-B), samples were obtained within less than 50 feet, normally 10-20 feet, from the intrusion contact.

[2] Mean of two measurements for magnetically different pyrrhotites. See Table 19.

Table 8. Sulphur isotope data across the basal contact of the Muskox intrusion in the South drillhole.[1]

Specimen No.[2]	Mineral	δS^{34} ‰	Description
SDC-			
S-3152	po	+ 6.0	See Table 5.
S-3433	po	+ 7.3	Fine- to medium-grained (< 3 mm) disseminations in olivine bronzite gabbro, po-cp-cb.
S-3571	po	+ 8.9	Fine- to coarse-grained (< 6 mm) disseminations in picrite, po-pn.
S-3643	po-cp	+ 7.8	Fine- to medium-grained (< 2 mm) disseminations in picrite.
S-3646	po	+ 8.9	Massive band (2.5 cm wide) in picrite, po-pn-cp.
S-3653	po	+ 7.6	Fine-grained (< 1 mm) disseminations in picrite, po-pn-cb-cp.
S-3659	po	+ 7.6	Medium- to coarse-grained (< 1.5 cm) disseminations in bronzite gabbro, po-pn-cb-cp. Sample was taken from a single grain (1-1.5 cm across).
S-3665	po	+ 7.6	Fine-grained (< 1 mm) disseminations in bronzite gabbro.
S-3668	po	+ 5.3	Fine-grained (< 1 mm) disseminations in bronzite gabbro, po-pn-vl.
S-3669	po-cp	+ 8.9	Fine- to coarse-grained (< 1.5 cm) disseminations in bronzite gabbro. Sample was taken from a single grain (1.5 cm across).
S-3671.5	cp-po	+ 7.3	Fine- to medium-grained (< 3 mm) disseminations in bronzite gabbro, po-cp-pn.
S-3674	po	+ 7.6	Fine- to coarse-grained (< 1 cm) disseminations in bronzite gabbro.
---------- Intrusion contact, 3674.8 feet ----------			
			Zone I
S-3675.5	po	+ 4.0	Fine-grained (< 1 mm) disseminations in paragneiss in contact breccia zone. Maucherite-po.
S-3678	po	+ 8.0	Coarse-grained (< 2.5 cm) disseminations to massive aggregates in paragneiss, po-pn-cb-cp.
S-3678.5	po	+ 8.2	Fine- to medium-grained (< 4 mm) disseminations in paragneiss. Fine-grained parts (<1 mm) were collected and analyzed.
S-3680	po	+ 6.9	Fine- to medium-grained (< 3 mm) disseminations in paragneiss.
S-3681	po	+ 6.2	Fine- to medium-grained (< 4 mm) disseminations in paragneiss.
S-3681.5	po	+ 4.9	Fine- to medium-grained (< 3 mm) disseminations in paragneiss. Distribution is roughly parallel to schistosity plane of host rock.
S-3682	po	+ 7.6	Fine- to medium-grained (< 3 mm) disseminations in paragneiss. Distribution is roughly parallel to schistosity plane of host rock.
S-3683	po	+ 7.1	Fine- to medium-grained (< 2 mm) disseminations in paragneiss. Distribution is roughly parallel to schistosity plane of host rock.
			Zone II
S-3684	po	- 1.6	Very fine grained (mostly < 0.03 mm) disseminations in paragneiss. Distribution is parallel to schistosity plane of host rock.
S-3684.5	po	- 2.9	Very fine grained (mostly < 0.05 mm) disseminations in paragneiss. Distribution is parallel to schistosity plane of host rock.
S-3685	po	- 3.1	Same as above.

Table 8. (cont'd.)

Specimen No.[2]	Mineral	δS^{34}‰	Description
SDC-			
S-3685.5(a)	po	+ 6.0	Medium- to coarse-grained (< 6 mm) disseminations embedded in very fine-grained (< 0.1 mm) dense disseminations in paragneiss. Fine grained ones are distributed parallel to schistosity plane of host rock. Sample was taken from a single grain (4-6 mm across). See Figure 13.
S-3685.5(b)	po	+ 0.2	Same as above. Sample was collected from fine-grained part including a few of medium-grained disseminations. See Figure 13.
S-3686.5	po	- 3.8	Very fine grained (< 0.1 mm) disseminations in paragneiss. Distribution is parallel to schistosity plane of host rock.
S-3688	po	- 3.8	Same as above.
S-3689.5	po	+ 0.8	Fine-grained (< 1.5 mm) disseminations in paragneiss. Distribution is roughly parallel to schistosity plane of host rock.
S-3690(a)	po-pn	+ 5.6	Medium-grained (< 5 mm) disseminations in paragneiss, po-pn-cb-cp.
S-3690(b)	po	+ 1.8	Fine-grained (< 0.5 mm) disseminations in paragneiss. Distribution is parallel to schistosity plane of host rock.
S-3692.5	po	+ 2.0	Very fine grained (mostly < 0.3 mm) disseminations in paragneiss. Distribution is parallel to schistosity plane of host rock, po-cb-pn-cp.
			Zone III
S-3702.5(a)	po	+ 4.7	Pyrrhotite-bearing quartz veinlet (2 mm wide) in paragneiss.
S-3702.5(b)	po	+ 4.4	Fine-grained (< 1 mm) disseminations in paragneiss.
S-3708	po	+ 5.6	Fine-grained (< 1.5 mm) disseminations in paragneiss with quartz-biotite-plagioclase gneiss bands, po-cp.
S-3719	po	+ 4.9	Fine-grained (< 0.5 mm) dense disseminations in paragneiss with quartz-biotite-plagioclase gneiss bands. Distribution is parallel to schistosity plane of host rock, po-cp.
S-3727(a)	po	+ 8.7	Small (< 0.5 mm) euhedral crystals in minute druselike cavity in quartz-biotite-plagioclase gneiss with paragneiss bands. Associated with quartz.
S-3727(b)	po	+ 7.3	Fine-grained (< 0.5 mm) disseminations in host rock.
S-3739.5	po	+ 6.2	Fine- to medium-grained (< 3 mm, mostly < 1 mm) disseminations in quartz-biotite-plagioclase gneiss with paragneiss bands, po-cp.
S-3754	po	+ 7.8	Fine- to medium-grained (< 2 mm) disseminations in quartz-biotite-plagioclase gneiss with granitic bands, po-cp.
			Zone IV
S-3789.5	cp	+ 9.1	Fine- to medium-grained (< 2 mm) disseminations in quartz-biotite-plagioclase gneiss.
S-3859	py-cp	+ 9.1	Fine-grained (< 0.5 mm) disseminations and thin filmy concentration along schistosity plane of paragneiss.
S-3914	cp	+15.1	Fine-grained (< 1 mm) dissemination in quartz rich part of paragneiss.
S-3970	py	+23.3	Fine- to medium-grained (< 3 mm) dissemination along minute fracture in quartz-biotite-plagioclase gneiss.
S-3980	py	+29.8	Thin filmy coating on minute fracture in quartz-biotite-plagioclase gneiss with granitic bands, py-cp.

[1] Geographic location of hole is represented by No. 63 in Figure 3.

[2] Figures represent footage of specimen in drill-cores.

Table 9. Summary of sulphur isotopic composition and sulphide content in profile across the basal contact of intrusion in the Muskox South drillhole.

	Width, in feet	Sulphide content, vol. %[1].	δS^{34}‰[2] Average
Intrusion margin (3570'-3675')	105	0.5	+ 7.7
Country rock			
Zone I (3675'-3683')	8	2.0	+ 6.6
Zone II (3683'-3698')	15	1.0	+ 0.1
Zone III (3698'-3754')	56	0.2	+ 6.2
Zone IV (3754'-3980')	226	0.02	+17(?)

Weighted average of sulphur isotopic data[3] for:

Intrusion margin – Zone I – Zone II – Zone III: δS^{34} = +6.2‰,

Intrusion margin – Zone I – Zone II – Zone III – Zone IV: δS^{34} = +6.6‰,

Zone I – Zone II – Zone III: δS^{34} = +4.2‰,

Zone I – Zone II – Zone III – Zone IV: δS^{34} = +5.4‰,

[1] Determined from the microscopic modal analysis data by J.A. Chamberlain.

[2] Arithmetical average of the data obtained in each zone (Table 8).

[3] In calculation, sulphur content in each zone is approximated by sulphide content by volume.

Table 10. Sulphur isotope data across the basal contact of the Muskox intrusion in drillhole, DDH-58-15804[1].

Specimen No.	Mineral	$\delta S^{34}‰$	Description
SDC-58-15804-480[2]	cp	+ 6.4	Fine-grained (< 0.5 mm) disseminations in bronzite gabbro.
----------	----------	Intrusion contact (675 feet)	----------
680	po	+ 2.9	Fine-grained (<0.5 mm) disseminations in quartz-biotite-plagioclase gneiss.
690	po	+ 3.8	Medium-grained (< 5 mm) disseminations in quartz-biotite-plagioclase gneiss with granitic band.
700	po	+ 4.9	Fine- to coarse-grained (< 2 cm) disseminations in quartz-biotite-plagioclase gneiss.
720	po	+ 6.7	Fine- to medium-grained (< 2 mm) disseminations in quartz-biotite-plagioclase gneiss.
750	po	+ 7.8	Fine- to medium-grained (< 3 mm) disseminations in para-gneiss with granitic bands.

[1] Geographic location of hole is represented by No. 25 in Figure 3.

[2] Figures represent footage of drill-cores.

Table 11. Sulphur isotope data across the basal contact of the Muskox intrusion in the drillhole, DDH-58-15808[1].

Specimen No.	Mineral	$\delta S^{34}‰$	Description
SDC-58-15808-415[2]	po-cp	+ 8.0	Fine-grained (< 0.5 mm) disseminations in olivine bronzite gabbro.
445	po	+12.2	Medium-grained (2-5 mm) disseminations in olivien bronzite gabbro.
460	po	+ 8.7	Fine- to medium-grained (< 2 mm) disseminations in olivine bronzite gabbro.
----------	----------	Intrusion contact (485 feet)	----------
525	py	+18.2	Very thin (< 0.2 mm) filmy concentration along schistosity plane of paragneiss.
555(a)	py	+18.0	Same as above.
555(b)	py	+18.4	Fine-grained (< 1 mm) disseminations in paragneiss.

[1] Geographic location of hole is represented by No. 40 in Figure 3.

[2] Figures represent footage of drill-cores.

Table 12. Sulphur isotope data from the roof contact zone of the Muskox intrusion.

Specimen No	Location No. in Fig. 3	Mineral	δS^{34}‰	Description
			North drillhole	
SDC-N-0112[1]	81	py	+ 6.2	Fine-grained (< 0.5 mm) cubes in minute cavities in sandstone.
N-0118(a)	81	py	+25.8	Thin filmy coating along minute fracture in slate.
N-0118(b)	81	py	+11.8	Fine-grained (< 0.5 mm) euhedral crystals along boundary between sandstone and slate.
N-0132	81	py	+ 7.6	Fine-grained (< 0.5 mm) euhedral crystals in minute cavities in sandstone.
N-0184	81	py	+ 5.6	Same as above.
			Intrusion contact (202.8 feet)	
N-0203	81	py	+ 4.2	See Table 3.
N-0206	81	cp	+ 4.0	See Table 3.
			Miscellaneous locations	
60-559	100	py	+ 4.7	Fine-grained (< 1 mm) disseminations in sandstone, py-cp.
62-4001	82	py	+ 6.9	Fine- to medium-grained (< 1-3 mm) disseminations in sandstone, py.
E-0037	85	py	+ 6.2	Fine-grained (< 0.5 mm) disseminations in quartzite, py-cp.
62-4022	86	py	+ 6.4	Fine- to medium-grained (< 3 mm) disseminations in slate, or euhedral crystals in small cavities, py.

[1] Figures represent footage of drill-cores.

Table 13. Sulphur isotope data from country rock adjacent to the feeder dyke of the Muskox intrusion.

Specimen No.	Location No. in Fig. 3	Mineral	δS^{34}‰	Description
SDC-59-837A	11	cp	+12.2	Fine- to medium-grained (< 4 mm) disseminations in granodiorite at west contact of feeder.

Table 14. Sulphur isotope data from country rocks, outside the thermal metamorphic aureole of the Muskox intrusion.

Specimen No.	Location No. in Fig. 3	Mineral	δS^{34}‰	Description
		Metasedimentary rocks		
SDC-62-3005	33	py	- 5.8	Medium-grained (2-3 mm) specks in dolomitic sandstone.
62-4070	35	py	+13.1	Minute blebs or stringers (< 0.5x2 mm) along schistosity plane of pelitic schist.
60-1011	51	py	+ 4.7	Fine-grained (< 0.5 mm) disseminations in pelitic schist.
60-1152	77	py	+ 8.0	Minute elongated concretions (< 1-2 mm) along cleavage plane of black slate.
		Average	+ 5.0	
		Metavolcanic rocks		
59-713	20	cp	+ 2.2	Filmy concentration (< 1 mm thick) along schistosity plane of mafic gneiss.
62-3023	34	py	+ 0.7	Cube crystals (up to 1.5 mm along edge) in chlorite schist.
FD-256-59	88	py	+ 7.8	Fine-grained (< 0.5 mm) disseminations in meta-andesite.
60-591	98	py	- 0.4	Fine-grained (< 0.3 mm) disseminations in metabasalt.
		Average	+ 2.6	
		Granitic gneisses		
DA-133-59	18	py	+ 7.1	Fine-grained (< 1 mm) disseminations in granitic gneiss with paragneiss bands.
59-1852	114	py	+ 2.9	Fine-grained (< 1 mm) disseminations in quartz-biotite-plagioclase gneiss.
		Average	+ 5.0	
		Granodiorite intruded into basement series		
59-652	7	py	+ 5.6	Fine-grained (< 0.5 mm) disseminations.

Table 15. Sulphur isotope data from diabase dykes in the Muskox area.

Specimen No.	Location No. in Fig. 3	Mineral	δS^{34} ‰	Description[1]
		A. Dyke in southeastern country rock.		
SDC-62-3018A	2	py	+ 2.4	Fine-grained, chilled, normal diabase.
		B. Dyke along west contact of intrusion feeder.		
60-1278	6	py-cp	+11.3	Fine-grained, chilled, granophyre-bearing diabase, py-cp.
		C. Dyke adjacent to intrusion feeder.		
59-935B	14	cp	+ 8.0	Medium-grained normal diabase, cp-py. Sulphides are generally fine grained (< 1 mm), but some grains are up to 2-3 mm across. At about 0.5 mile north of this location, the same dyke is traversed by the intrusion feeder.
		D. Dyke in eastern country rock, parallel to general strike of intrusion.		
59-728B	21	py	+ 6.4	Medium-grained normal diabase, partly granophyric, py-cp.
59-743	22	cp	+ 3.8	Medium-grained normal diabase, partly granophyric, cp-po.
59-2266	38	py	- 4.4	Medium-grained normal diabase, py-cp.
59-798C	46	py	+ 7.3	Medium-grained normal diabase, py-cp.
		E. Dyke in intrusion body, 2640- to 2830-foot level in North drillhole.		
N-2678[2]	81	po	+ 1.6	Medium-grained normal diabase, po-cp.
N-2679[2]	81	cp	+ 1.1	Medium-grained normal diabase, cp-po.
N-2811[2]	81	po	- 0.7	Medium-grained normal diabase, po-cp.
		F. Dyke in intrusion roof.		
60-610	84	py	+ 0.7	Medium-grained, granophyre-bearing diabase, cp-py.
		G. Dyke in western country rock, north of Coppermine River.		
59-2173A	142	cp	+ 0.2	Medium-grained normal diabase. Sulphides are generally fine grained (< 0.5 mm), but a few grains are up to 2 mm across.

[1] Sulphides occur as sparsely disseminated grains, less than 1 mm in diameter, unless otherwise indicated.

[2] Figure represents footage of drill-core.

Table 16. Sulphur isotope data from minor gabbroic body in the roof rock of the Muskox intrusion.

Specimen No.	Location No. in Fig. 3	Mineral	δS^{34}‰	Description
SDC-				
62-4015A	96	py	- 3.6	Fine- to medium-grained (< 3 mm) disseminations in gabbro.
62-4015B	96	po	- 1.6	Fine-grained (< 1 mm) disseminations and irregular massive aggregates in slate.
62-4016(a)	97	po	- 0.4	Fine- to medium-grained (< 4 mm) disseminations in altered gabbro.
62-4016(c)	97	py	0.0	Same as above.
62-4017(b)	95	po	+ 0.4	Irregular veinlike masses (up to 5 mm wide) in mafic gneiss.
62-4017(e)	95	py	- 0.2	Same as above.

Table 17. Sulphur isotope data in coexisting sulphides (pyrrhotite-chalcopyrite).

Specimen No.	Location No. in Fig.	Mineral	δS^{34}‰	Description	$\delta S^{34}_{po} - \delta S^{34}_{cp}$ ‰
SDC-62-4002D(a)	115	po	+ 6.4	See Table 7.	+0.9
(c)		cp	+ 7.3	Discontinuous rims (< 0.2 mm thick) or irregular areas (< 0.5 mm) about po, and isolated grains (< 1 mm) outside po.	
62-4004B(a)	116	po	+ 7.6	See Table 7.	0.0
(c)		cp	+ 7.6	Discontinuous rims (0.1-0.5 mm thick) about po.	
62-4006A(a)	117	po	+ 7.8	See Table 7.	+0.5
(c)		cp	+ 7.3	Irregular areas (0.2-2 mm) near margin of po.	
62-4008A(a)	122	po	+ 5.8	See Table 7.	+0.9
(c)		cp	+ 4.9	Rims (< 0.3 mm thick) and irregular areas (< 0.5 mm) about po, and isolated grains (< 1 mm) outside po.	
62-4011A(b)	47	po	+13.3	See Table 6.	0.0
(c)		cp	+13.3	Rims (< 0.2 mm thick) round po, and isolated grains (< 0.05 mm) outside po.	
62-4011B(a)	47	po	+12.9	See Table 6.	+3.6
(b)		cp	+ 9.3	In general po and cp occur as separated grains, cp also occurs as irregular veinlets (< 3 mm wide).	
62-4012 (b)	48	po	+15.8	See Table 6.	+0.2
(c)		cp	+15.6	Irregular areas (< 0.3 mm) near margin of po, sometimes forming rims (< 0.1-0.2 mm thick).	
62-4019A(a)	10	po	+11.1	See Table 2.	+0.7
(d)		cp	+10.4	Irregular areas (< 0.3 mm) near margin of po, and isolated grains (< 1 mm) outside po.	
62-4019B(b)	10	po	+10.0	See Table 2.	+0.7
(a)		cp	+ 9.3	Similar to 62-4019A(d).	
62-4023(a, c)	57	po	+11.0[1]	See Table 7.	-3.2
(d)		cp	+14.2	po and cp tend to occur as separated grains. po grains generally contain some cb but little cp.	
62-4026 (a)	54	po	+12.9	See Table 7.	+0.2
(c)		cp	+12.7	Discontinuous rims (< 1 mm thick) about po, and isolated grains (< 1-2 mm) outside po.	
62-4033 (a)	150	po	+ 6.7	See Table 6.	+0.5
(c)		cp	+ 6.2	Lenses or blebs (< 1x3 mm) paralleling basal partings of po crystals, and veinlets (1 mm wide).	

Table 17. (cont'd.)

Specimen No.	Location No. in Fig.	Mineral	δS^{34}‰	Description	$\delta S^{34}_{po} - \delta S^{34}_{cp}$ ‰
SDC- 62-4034 (a)	150	po	+ 7.1	See Table 7.	-0.9
(b)		cp	+ 8.0	Irregular areas (< 1 mm) near margin of po, and veinlets (< 0.5 mm wide) in massive po.	
62-4036A(a)	149	po	+ 9.3	See Table 7.	+0.6
(c)		cp	+ 8.7	Irregular areas (< 0.2 mm) near margin of po.	
62-4036B(a, b)	149	po	+ 8.4[1]	See Table 7.	+0.6
(d)		cp	+ 7.8	Similar to 62-4036A(c).	
62-4037A(a, b)	148	po	+ 7.7[1]	See Table 6.	-0.1
(d)		cp	+ 7.8	Irregular areas (< 0.5 mm) or discontinuous rims about po, and isolated grains (< 0.05 mm) outside po.	
62-4037B(b)	148	po	+ 7.3	See Table 6.	+0.9
(c)		cp	+ 6.4	po and cp generally occur as separated grains (< 0.1 mm). Some grains (0.5-2 mm) show equigranular association of both minerals.	
62-4038B(a)	147	po	+ 7.3	See Table 7.	+0.2
(b)		cp	+ 7.1	Irregular areas (< 0.5-1 mm) near margin of po, sometimes forming rims (< 0.1 mm thick).	
62-4041(a, b)	144	po	+ 7.8[1]	See Table 7.	-0.2
(c)		cp	+ 8.0	Discontinuous rims (0.1 mm thick) about po, and isolated grains (< 0.2 mm) outside po.	
62-4043 (a)	31	po	+ 7.1	See Table 7.	0.0
(d)		cp	+ 7.1	Irregular areas (< 0.3 mm) near margin of po, and isolated grains (< 0.1 mm) outside po.	
62-4044 (a)	143	po	+ 7.8	See Table 7.	+0.5
(d)		cp	+ 7.3	Irregular areas (< 0.3 mm) near margin of po. A few veinlets (< 0.3 mm wide) in massive po.	
62-4047 (a)	141	po	+ 7.1	See Table 6.	+0.4
(c)		cp	+ 6.7	Discontinuous rims (< 0.5 mm thick) and irregular areas (< 0.3 mm) about po, and isolated grains (< 0.4 mm) outside po.	
62-4048 (a)	140	po	+ 6.0	See Table 7.	-0.4
(c)		cp	+ 6.4	Irregular areas (< 1 mm) near margin of po, partly showing veinlike penetration into po.	
62-4050(a, b)	87	po	+14.1	See Table 6.	+0.5
(c)		cp	+13.6	Discontinuous rims (< 0.2 mm thick) about po, and isolated grains (< 0.2 mm) outside po. A few irregular veinlets (< 0.1 mm wide) in massive po.	

Table 17. (cont'd.)

Specimen No.		Location No. in Fig.	Mineral	δS^{34}‰	Description	$\delta S^{34}_{po} - \delta S^{34}_{cp}$ ‰
SDC-62-4052	(a)	43	po	+12.2	See Table 7.	+0.4
	(d)		cp	+11.8	Exsolution lamellae in cb-rich irregular areas (< 1 mm) near margin of po and in cb-cp isolated grains (< 2-10 mm).	
62-4054	(a)	41	po	+11.3	See Table 6.	-1.1
	(b)		cp	+12.4	Veinlets (< 0.1-5 mm wide) in massive po.	
62-4057	(a)	136	po	+ 6.7	See Table 7.	+0.9
	(c)		cp	+ 5.8	Rims (< 0.3 mm thick) and irregular areas (<0.3 mm) about po, and isolated grains (<0.2 mm) outside po.	
62-4059	(a)	133	po	+12.4	See Table 7.	+0.6
	(c)		cp	+11.8	Irregular areas (< 0.3 mm) near margin of po, and isolated grains (< 0.3 mm) outside po.	
S-3665	(a)	63	po	+ 7.6	See Table 8.	+0.7
	(b)		cp	+ 6.9	Fine-grained (< 1 mm) disseminations. po and cp generally occur as separated grains.	
					Average of $\delta S^{34}_{po} - \delta S^{34}_{cp}$	+0.2
					Average of $\delta S^{34}_{po} - \delta S^{34}_{cp}$	0.7

[1] Mean of two measurements for magnetically different pyrrhotites. See Table 19.

Table 18. Sulphur isotope data in coexisting sulphides (cubanite-chalcopyrite, pyrrhotite-cubanite-chalcopyrite, chalcopyrite-galena and pyrrhotite-seagenite).

Specimen No.	Location No. in Fig. 3	Mineral	δS^{34}‰	Description	$\delta S^{34}_{cp} - \delta S^{34}_{cb}$ ‰	$\delta S^{34}_{po} - \delta S^{34}_{cb}$ ‰
SDC-62-250B (a)	74	cp	+ 6.7	Exsolution lamellae intergrown with cb.	+0.3	
(b)		cb	+ 6.4	See Table 3.		
62-4027A(c)	55	cp	+ 5.6	See Table 7.	+0.5	
(b)		cb	+ 5.1	Exsolution lamellae intergrown with cp.		
62-4029B(a)	59	po	+14.2	Irregular areas embayed by cb and cp.		+0.4
(c)		cb	+13.8	See Table 7.		
62-4043 (a)	31	po	+ 7.1	See Table 7.		+0.4
(c)		cb	+ 6.7	Irregular areas (< 0.2 mm) near margin of po, associating with cp.	+0.4	
(d)		cp	+ 7.1	See Table 15.		
62-4052 (a)	43	po	+12.2	See Table 7.		-0.7
(b)		cb	+12.9	See Table 17.	-1.1	
(d)		cp	+11.8	See Table 17.		
				Average of $\delta S^{34}_{cp} - \delta S^{34}_{cb}$	0.5	
				Average of $\delta S^{34}_{po} - \delta S^{34}_{cb}$		0.5
					$\delta S^{34}_{cp} - \delta S^{34}_{gn}$ ‰	
59-1045B(b)	23	cp	+ 7.8	See Table 6.		
(a)		gn	+ 6.4	Intergranular nets around cp.	+1.4	
59-1433B(a)	138	cp	+ 5.8	See Table 7.		
(b)		gn	+ 5.3	Rims (< 0.5 mm thick) round cp, and monomineralic veinlets (< 1 mm wide).	+0.5	
				Average of $\delta S^{34}_{cp} - \delta S^{34}_{gn}$	1.0	
					$\delta S^{34}_{po} - \delta S^{34}_{sg}$ ‰	
62-4028 (b)	58	po	+12.9	See Table 7.		
(a)		sg	+13.1	Irregular areas near margin of po.	-0.2	

Table 19. Sulphur isotope data on two fractions of pyrrhotite separated magnetically from the same specimen.

Specimen No.	Location No. in Fig. 3	Mineral[1]	δS^{34} ‰	Description	$\delta S^{34}_{po-s} - \delta S^{34}_{po-w}$ ‰
SDC-					
62-4014 (a)	60	po-s	+17.1	See Table 6.	+0.4
(b)		po-w	+16.7		
62-4018 (a)	12	po-s	+12.0	See Table 2.	0.0
(b)		po-w	+12.0		
62-4023 (a)	57	po-s	+10.9	See Table 7.	-0.2
(c)		po-w	+11.1		
62-4025 (a)	53	po-s	+15.6	See Table 6.	0.0
(b)		po-w	+15.6		
62-4036B (a)	149	po-s	+ 8.7	See Table 7.	+0.7
(b)		po-w	+ 8.0		
62-4037A (a)	148	po-s	+ 7.3	See Table 6.	-0.7
(b)		po-w	+ 8.0		
62-4041 (a)	144	po-s	+ 8.0	See Table 7.	+0.4
(b)		po-w	+ 7.6		
62-4050 (a)	87	po-s	+14.4	See Table 6.	+0.6
(b)		po-w	+13.8		
62-4056 (a)	137	po-s	+ 6.2	See Table 7.	-0.2
(b)		po-w	+ 6.4		
				Average of $\delta S^{34}_{po-s} - \delta S^{34}_{po-w}$	0.4

[1] po-s represents magnetically stronger fraction compared with po-w. Laboratory hand magnet for mineral separation (Sepor No. 903 "Automagnet" --- Sepor Laboratory Supply, Chicago, Illinois) was used as rough divisional standard.

Table 20. Sulphur isotope data in secondary pyrite or marcasite after pyrrhotite.

Specimen No.	Location No. in Fig. 3	Mineral	δS^{34} ‰	Description	$\delta S^{34}_{po} - \delta S^{34}_{py, mc}$ ‰
SDC-					
62-4011B (a)	47	po	+12.9	See Table 6.	0.0
(c)		mc	+12.9		
62-4029A (a)	59	po	+12.0	See Table 7.	-1.1
(b)		py	+13.1		
62-4031 (a)	151	po	+ 5.8	See Table 6.	-0.4
(c)		mc	+ 6.2		
62-4047 (a)	141	po	+ 7.1	See Table 6.	+0.7
(d)		py	+ 6.4		
62-4054 (a)	41	po	+11.3	See Table 6.	-0.3
(c)		py	+11.6		
				Average of $\delta S^{34}_{po} - \delta S^{34}_{py, mc}$	0.5