Strontium and Oxygen Isotopic Data and Age for the Layered Gabbroic Dufek Intrusion, Antarctica

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ABSTRACT

The Dufek intrusion is a mafic, differentiated stratiform igneous complex exposed in the northern Pensacola Mountains. Due to its similar age and geochemistry, it is considered to be part of the Ferrar Dolerites that are the hypabyssal phases of the Jurassic tholeiitic Ferrar group of Antarctica. The intrusion is composed principally of cumulate gabbros with lesser amounts of anorthositic, pyroxenitic, and magnetite cumulates that are capped conformably by a thick unit of granophyre of granodioritic composition. The Dufek intrusion was sampled from its exposed parts in two ranges in the Pensacola Mountains. The stratigraphically lower section is called the Dufek Massif and the upper one is called the Forrestal Range section. This report summarizes Rb and Sr abundances and $^{87}Sr/^{86}Sr$ isotopic values for 89 whole-rock and 52 mineral (plagioclase, pyroxene, apatite) samples, and $\partial^{18}O$ values for 89 whole-rock and 54 mineral (plagioclase, pyroxene, magnetite) samples from the Dufek intrusion.

The calculated initial $^{87}Sr/^{86}Sr$ values for mafic whole-rock specimens generally increase upward within a range between 0.7083 and 0.7121 and indicate the Dufek intrusion crystallized from a mantle derived tholeiitic magma that was variably contaminated with crustal melts. Along with reversals in trends in mineral chemistry, a major reversal in the general upward increase of initial $^{87}Sr/^{86}Sr$ probably reflects an introduction of new magma in the Forrestal Range section about 1000 meters below the top of the intrusion. The initial $^{87}Sr/^{86}Sr$ of the capping granophyre of 0.7128, and values from 0.7154 to 0.7360 for six cross-cutting aplite dikes throughout the intrusion indicate all of these siliceous rocks are crystallized crustal melts. In several specimens initial $^{87}Sr/^{86}Sr$ values of pyroxene, and/or plagioclase and apatite are different and reflect a lack of isotopic equilibrium between cumulate and noncumulus phases in these rocks.

Whole-rock $\partial^{18}O$ values from the Dufek Massif section are within the range (+5.0 to+6.9 per mil) reported for other layered

gabbroic intrusions, whereas $\partial^{18}O$ values for rocks from the lower part of the Forrestal Range section are generally lower (+3.0 to+6.0 per mil) than those of the Dufek Massif. In the rocks from about 1000 meters below, to the top of the intrusion, $\partial^{18}O$ ranges from 0.0 to +5.0 per mil. The low $\partial^{18}O$ values along with elevated initial $^{87}Sr/^{86}Sr$ indicates rocks of the Forrestal Range section were derived from magma variably contaminated with ^{18}O depleted, metamorphosed sedimentary rocks. Reversals of $\Delta^{18}O$ plagioclase-pyroxene in some rocks suggest that some low $\partial^{18}O$ values resulted from subsolidus ^{18}O depletion by interaction with a meteoric water-hydrothermal system.

Regressions of Rb-Sr whole-rock, mineral data for sixteen specimens yield ages that range from 148 Ma to 224 Ma. Many regressions have high MSWD due to the isotopic disequilibrium between cumulate and noncumulate phases in some rocks and ages derived from these regressions indicate only that these rocks are Mesozoic. Regressions with MSWD <1 in other rocks are interpreted to indicate the age of an event. An age of184 ± 4 Ma is calculated from a precise Rb-Sr whole-rock isochron (MSWD=0.27) for six specimens from a 100 meter section of the capping granophyre. This age, along with a similar published U-Pb zircon age for the granophyre and incremental heating $^{40}Ar/^{39}Ar$ isochron ages for two plagioclase separates from gabbros indicate the Dufek intrusion is greater than 180 Ma; older than the main mass of Ferrar dolerites.

INTRODUCTION

The mostly gabbroic Dufek intrusion (82° 30' S 50° W) is more than 50,000 square kilometers in area (Behrendt and others, 1981) and probably 8-9 kilometers thick at its southern end (Ford 1976). The intrusion was mapped and sampled in detail by the U.S. Geological Survey in the austral summer 1965-66 as part of the final phase in completing mapping of the entire Pensacola Mountains (Schmidt and Ford, 1969). The intrusion is exposed in two of the northern ranges of the Pensacola Mountains near the southeastern edge of the Ronne Ice Shelf, Antarctica (fig. 1). The age of the Dufek intrusion is Permian or younger on the basis of field evidence (Ford, 1976). On the basis of radiometric dating, it is assigned to the hypabyssal dolerite phase of the Jurassic Ferrar Group tholeiitic igneous activity that occurred throughout the Transantarctic

Mountains (Ford and Kistler, 1980; Brewer and others, 1996; Fleming and others, 1997).

The layered igneous rocks of the Dufek intrusion formed by the accumulation of crystals by settling. Rocks of this origin are termed "cumulates" and their textures and structures reflect sedimentary processes. The cumulates are composed of cumulus phases that

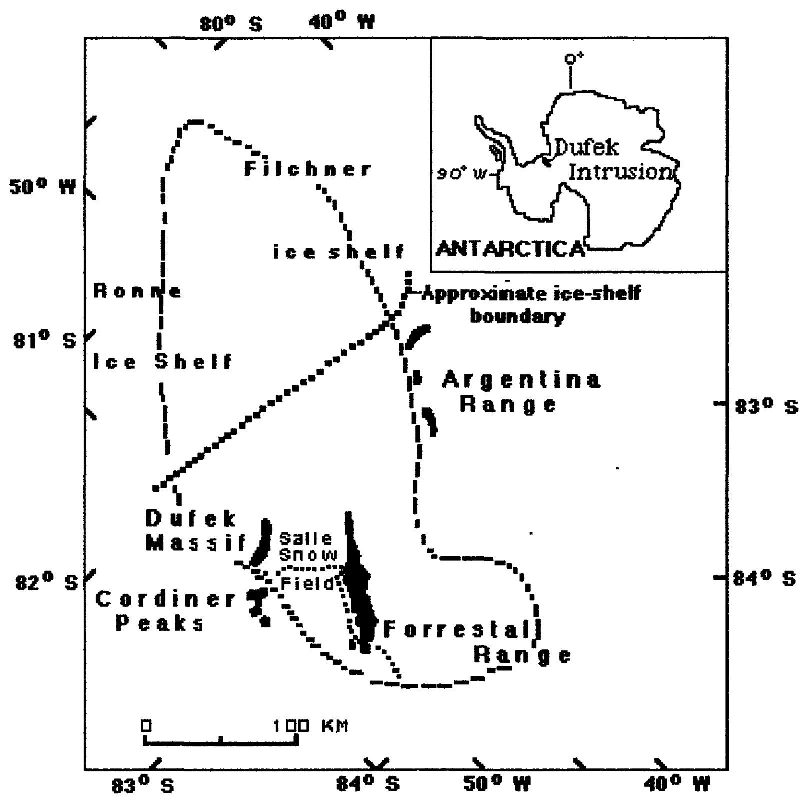

Figure 1. Location of Dufek intrusion in Antarctica and its approximate outline under ice (dashed line) as inferred from geophysical surveys (Behrendt and others, 1981). Major outcrop areas are shown in black.

settled and packed to form the framework of the rock and postcumulus material which formed in the place that it now occupies. Noncumulus rocks are those such as the capping granophyre of the Dufek intrusion. The stratigraphy of the layered Dufek intrusion is described in detail by Ford, (1970, 1976) and by Ford and Nelson (1972). Ten partial stratigraphic sections were measured and sampled in the area of the Dufek Massif and 11 in the Forrestal Range. These sections are intercorrelated within each range by using one or more key marker layers. A composite section was constructed with a 1800 meter thick lower part in the Dufek Massif and a 1700 meter thick upper part in the Forrestal Range (Table 1). A 2-3-km thick section of unexposed rock between the Dufek Massif and the Forrestal Range lies hidden beneath the Sallee Snowfield (fig. 1). A second hidden section 1.8-3.5 km thick, called the "basal section", is inferred to lie beneath the lowest exposed rocks of the Dufek massif on the basis of geophysical surveys (Behrendt and others, 1974). An unknown thickness of the capping granophyre has been eroded away.

Petrologic, mineralogic, and geochronologic studies of the Dufek intrusion by members of the U.S. Geological Survey are reported in Himmelberg and Ford, 1975, 1976, 1983; Drinkwater and others, 1985, 1986; Kistler and Ford, 1979; Ford and Kistler, 1980; Ford and others, 1983, 1986; Ford and Himmelberg, 1991. This report presents Rb and Sr concentration and Sr and oxygen isotopic data for whole-rocks and minerals of the Dufek intrusion. Preliminary results of this isotopic study were summarized in Ford and others (1986).

ANALYTICAL METHODS

The rubidium and strontium concentrations and Sr isotopic data reported in Table 3 were gathered by members of the Intrusive Geochronology Project in the Geologic Division, Sr isotope laboratory at the USGS in Menlo Park, California. Results are presented for whole-rock powders milled to less than 200 mesh, pyroxene separates -100+300 mesh, and plagioclase and apatite separates -170 mesh. Minerals were isolated by standard techniques of magnetic separation and by gravity in heavy liquids. Plagioclase separates with a prefix "A" have specific gravity <2.7 gm/cm^3 whereas those with prefix "B" and all other plagioclase separates have specific gravity > 2.7 gm/cm^3 (Table 3). Rubidium and strontium abundances of whole-rocks and plagioclase separates were determined by energy dispersive X-ray fluorescence methods, whereas standard isotope dilution techniques were used to determined these elemental abundances in pyroxene and apatite. Concentrations of Rb and Sr by X-ray fluorescence are ± 3%, whereas they are ± 1% by isotope dilution. Strontium isotope ratios were determined using a MAT 261, 90° sector mass spectrometer, using the double rhenium filament mode of ionization. Strontium isotopic compositions are normalized to $^{86}Sr/^{88}Sr=0.1194$. Measurements of

Table 1. Sample Number, Rock Type and Elevation of Analyzed Specimens from the Exposed Dufek Massif and Forrestal Range Sections of the Dufek intrusion, Antarctica

Dufek Massif Section

Sample Number	Rock Type	Elevation (meters)
Anorthosite Zone		
192Fb	Anorthosite (plag)	21
193Fa	Anorthosite	55
195Fb	Anorthosite	232
Lower Gabbro Zone		
38Fa	leucogabbro	278
39Fa	anorthosite layer	293
Middle Gabbro Zone		
46Fa	mafic gabbro	506
49Fb	mafic gabbro	585
277Fa	mafic gabbro	643
52Fa	mafic gabbro	698
54Fa	mafic gabbro	827
117Fa	mafic gabbro	936
57Fb	felsic dike	986
58Fb	mafic gabbro	1013
Upper Brown Zone		
252Fb	pegmatite	1066
198Fi	mafic gabbro	1067
226Fa	mafic gabbro	1068
111Fe	mafic gabbro	1070
199Fa	mafic gabbro	1097
Upper Layered Zone		
240Fc	mafic gabbro	1173
230Fb	mafic gabbro	1204
231Fd	mafic gabbro	1213
237Fb	mafic gabbro	1219
270Fa	mafic gabbro	1493
266Fa	mafic gabbro	1604
259Fa	mafic gabbro	1809
259Fb	leucogabbro	1809
257Fa	mafic gabbro	1814

Hidden Section, Sallee Snowfield

Forrestal Range Section

Sample Number	Rock type	Elevation (meters)
Lower Layered zone		
79Fa	anorthosite	20
78Fb	gabbro	53
77Fa	pyroxenite	57
76Fa	anorthosite	103
75Fe	leucocumulate	110
74Fa	gabbro	114
99Fb	gabbro	144
99Ff	leucocumulate	145
99Fg	aplite	147
97Fb	gabbro	221
306Fd	leucocumulate	274
306Fh	gabbro	275
94Fe	gabbro	335
94Fi	leucocumulate	340
87Fa	aplite	429
87Fb	Fe-rich gabbro	430
86Fa	gabbro	465
85Fb	gabbro	491
84Fa	gabbro	515
Lower Inclusion Zone		
83Fa	leucoinclusion	524
83Fb	gabbro	525
300Fb	aplite	594
Henderson Bluff		
284Fa	pyroxenite	670
284Fb	gabbro	672
287Fe	leucoinclusion	674
Upper Layered Zone		
311Fa	gabbro	735
310Fb	gabbro	819
310Fa	gabbro	822
184Fa	leucocumulate	926
309Fb	gabbro	933
309Fa	leucocumulate	937
185Fa	gabbro	942
188Fa	leucocumulate	1021
189Fa	leucocumulate	1059
297Fa-1	gabbro	1070
297Fa-2	contact gabbro	1072
101Fa	leucocumulate	1090
191Fb	gabbro	1116
171Fa	gabbro	1169
72Fa	gabbro	1185
169Fb	gabbro	1231
181Fa	leucocumulate	1234
182Fc	leucocumulate	1250
71Fi	inclusion	1253
167Fa	gabbro	1268
Upper Inclusion Zone		
166Fa	gabbro	1310
157Fd	inclusion	1361

Forrestal Range Section (con't)

Sample Number	Rock type	Elevation (meters)
157Fg1	pegmatite	1364
157Fd	inclusion	1361
157Fg1	pegmatite	1364
157Fg2	pegmatite	1365
Upper Gabbro Zone		
158Fa	gabbro	1405
160Fa	gabbro	1436
161Fa	gabbro	1435
162Fe-2	gabbro	1482
Granophyre		
162Fc	granophyre	1493
163Fa	granophyre	1516
164Fa	grqnophyre	1542
165Fa	granophyre	1558
313Fa	granophyre	1575
315Na	granophyre	1600
317Na	granophyre	1631
17Na	gabbro	1620

NBS strontium carbonate standard SRM 987 yield a mean $^{87}Sr/^{86}Sr$ of 0.710239±0.000015 over this period. Analytical uncertainties in $^{87}Sr/^{86}Sr$ values are about ±0.008%. The initial $^{87}Sr/^{86}Sr$ values reported in Table 3 and whole-rock, mineral isochron ages in Table 2 were calculated using the decay constant for rubidium from Steiger and Jager (1977). and the ISOPLOT program of Ludwig (1988), respectively.

Oxygen was extracted from the samples by the BrF_5 method (Clayton and Mayeda ,1963) and converted to CO_2 by reaction with hot carbon. The CO_2 was analyzed on a MAT-250 isotope ratio mass spectrometer. Extraction and analysis of oxygen was by members of the USGS, Water Resources Division, stable isotope laboratory in Menlo Park, California. All of the ∂-values reported in Table 3 are given in per mil relative to the SMOW standard. All samples were analyzed in duplicate with reproducibility of $\partial^{18}O$ of ± 0.15 per mil or better.

STRONTIUM and OXYGEN ISOTOPES

Whole-rock initial $^{87}Sr/^{86}Sr$ at 174 m.y., hereafter called Sri, versus elevation for a composite Dufek Masif-Forrestal Range section is shown figure 2. The variation with stratigraphic height is one of a general increase in Sri from 0.7083 to 0.713. Superimposed on this trend are (1) a reversal of Sri between the lower gabbro zone and the upper gabbro zone in the Dufek Massif section (2) a reversal of Sri at the upper brown zone to a 1 km thick section called the upper layered zone of the Dufek Massif that shows little variation about a value of 0.709 and (3) a marked reversal in Sri from 0.711 to 0.709 about 200 meters above the lower inclusion zone in the Forrestal Range section and about 1000 meters below the top of the body. Reversals in an overall trend of iron enrichment, (Fe/(Fe+Mg) ratio, in cumulus pyroxenes occur near the same intervals in the Dufek intrusion (Himmelberg and Ford, 1976). The smaller variations from the general trend are associated with cyclic units in the intrusion and explained by convective overturn of the magma (Himmelberg and Ford, 1976). The strongest reversal in pyroxenes compositional trends associated with reversal in Al_2O_3 and V_2O_3 contents of ilmeno-magnetite occurs at the level of the lower

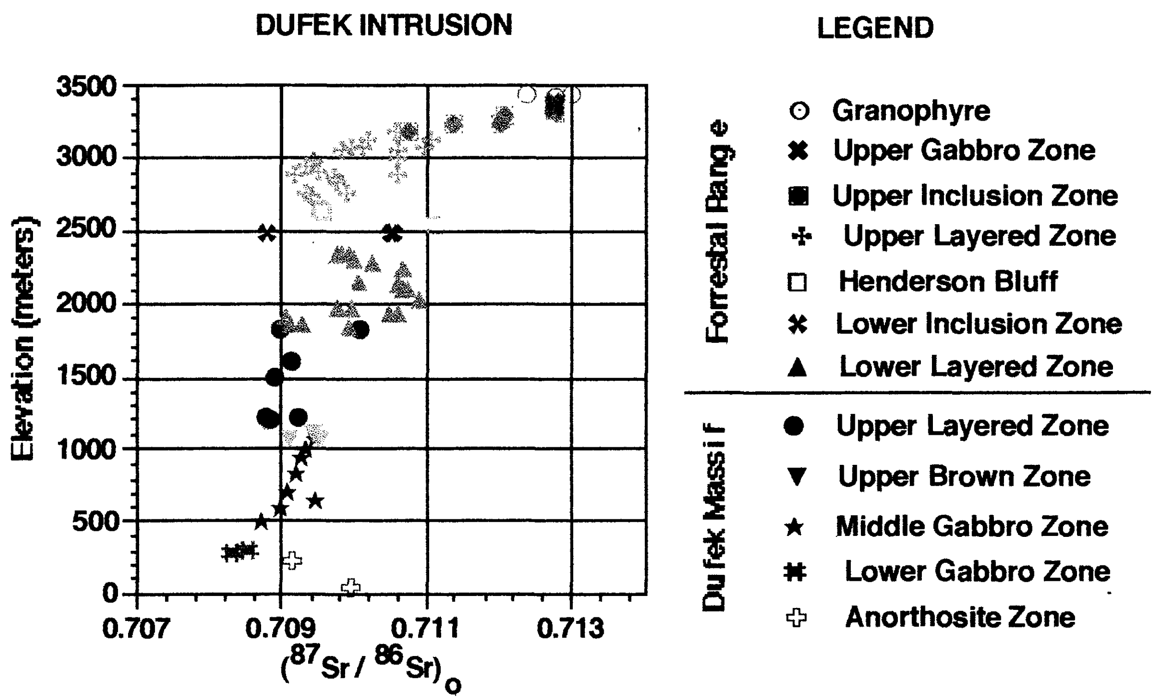

Figure 2. Plot of initial $^{87}Sr/^{86}Sr$ versus elevation in meters for a composite of the Dufek Massif and Forrestal Range sections. The 2000 meter missing section beneath the Sallee snowfield is not accounted for on the diagram

inclusion zone of the Forrestal section (Himmelberg and Ford, 1977, fig. 2). A reversal of compositional trend of plagioclase occurs about 200 meters higher (Ford and Himmelberg, 1986). The reversal in trends of all cumulus minerals and the magnitude of the pyroxene reversal strongly indicate an addition of new magma at this late stage of crystallization of the intrusion (Ford and Himmelberg, 1986). The strongest reversal of Sri in the Forrestal Range section begins just above the lower inclusion zone (fig. 2) and also is due to addition of new magma at this level of the intrusion.

Figures 3 and 4 show variations between Sri of minerals and whole-rocks at different elevations in the Dufek Massif and Forrestal Range sections, respectively. Sri of the pyroxenes from rocks in the Dufek Massif section and the lower layered zone in the Forrestal Range section are much less radiogenic than their whole-rock hosts and coexisting plagioclase and apatite separates. These pyroxenes had to have crystallized in a magma with Sri at least as low as 0.7076 and then settled into their present locations in the intrusion. Smaller differences in Sri between minerals and host rocks persist above the lower layered zone in the Forrestal Range

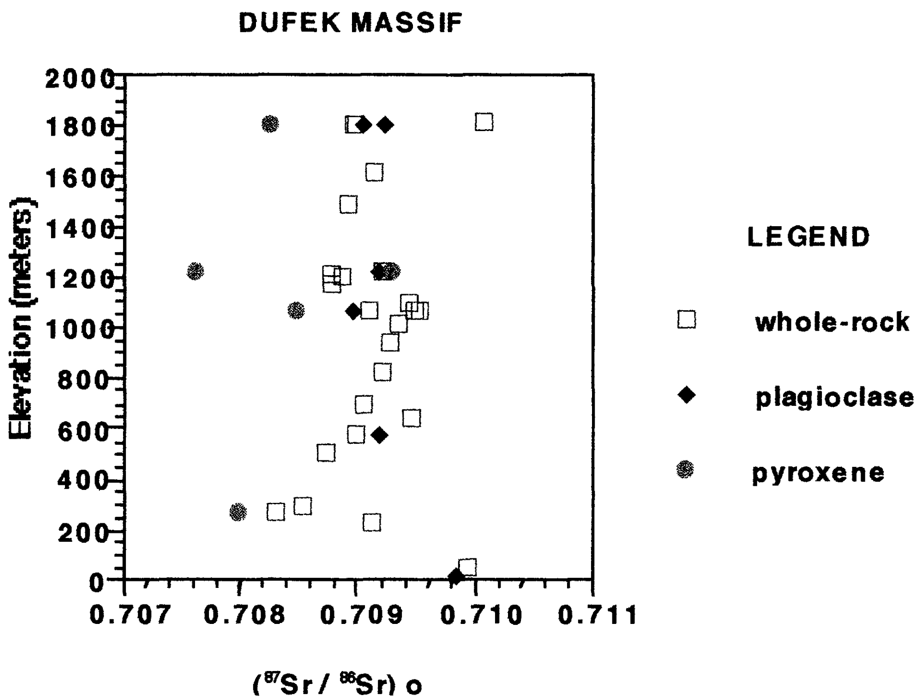

Figure 3. Variations of initial $^{87}Sr/^{86}Sr$ of plagioclase, pyroxene, and their host rocks at different elevations in the Dufek Massif section

section and in some cases pyroxene is the most radiogenic material in a rock (Figure 4). In spite of accumulating at magmatic temperatures, some minerals have not equilibrated isotopically during cooling.

Variation of $\partial^{18}O$ with elevation is shown in figure 5 for whole-rocks in the Dufek intrusion. For the Dufek Massif section all mafic rocks have $\partial^{18}O$ values between +5 and +7 per mil except for one sample with $\partial^{18}O$ of +3.8 per mil. Two aplites that intrude the Dufek Massif have $\partial^{18}O$ of +3.6 and +1.1 per mil. The trend of isotopic variation in $\partial^{18}O$ in rocks of the Dufek Massif is remarkably similar to the strontium isotopic trend discussed above. Values of $\partial^{18}O$ change from decreasing to increasing between the lower and middle gabbro zones, then abruptly decrease again to a constant value near +6 per mil in the 1 km thick upper layered zone. The values of $\partial^{18}O$ for the rock specimens from the Forrestal Range section are much more variable and generally lower (0 to +6.0 per mil) than those from the Dufek Massif. In the Forrestal Range, rocks from the lower layered zone and the lower inclusion zone, excluding two aplites, have $\partial^{18}O$ values that range from +3 to +6 per mil without any trend, and rocks from the upper layered, upper inclusion and upper gabbro

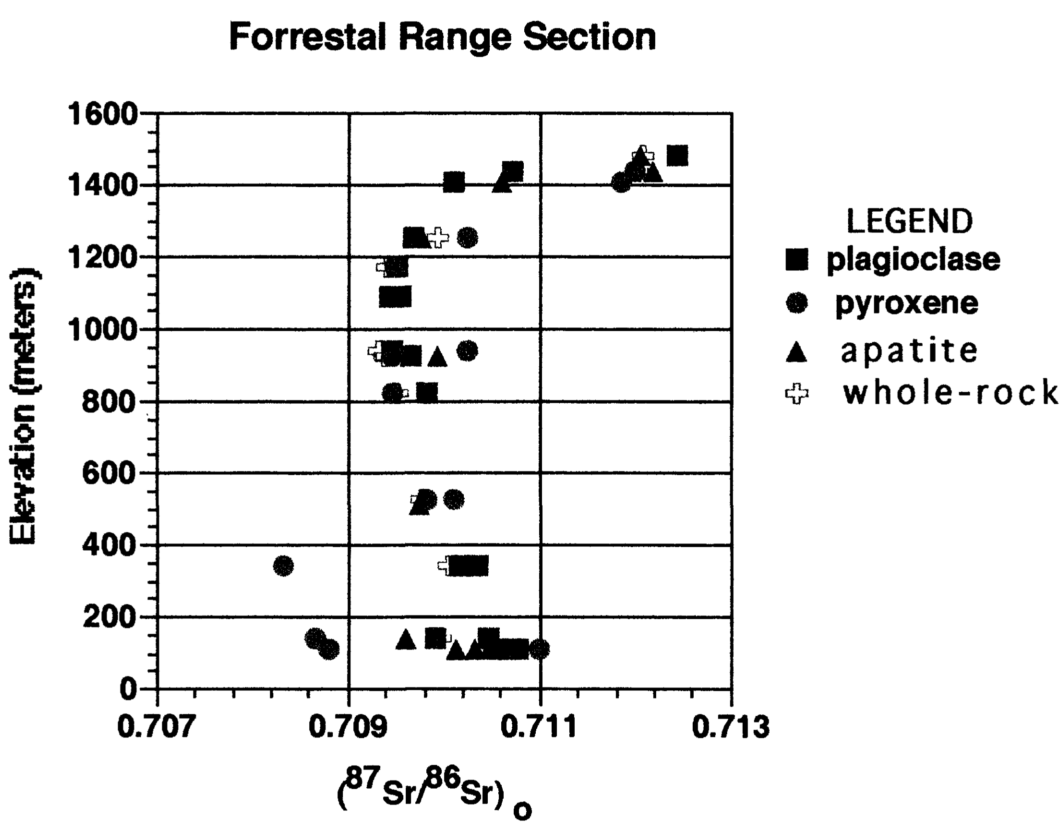

Figure 4. Variations of initial $^{87}Sr/^{86}Sr$ of plagioclase, pyroxene, apatite, and their host rocks at diffferent elevations in the Forrestal Range section.

zones have $\delta^{18}O$ values that range from 0 to +5 per mil also without any trend. However, as seen in the Sr isotope versus elevation trend , a major change occurs at the base of the upper layered zone. The overall oxygen isotope trend, however, is one of a general decrease in $\delta^{18}O$ values. An aplite in the upper inclusion zone has $\delta^{18}O$ of -2.3 per mil. Specimens of the capping granophyre have $\delta^{18}O$ values that range from +4 to +6 per mil except for the specimen from the contact with the upper gabbro zone that has $\delta^{18}O$ of +1 per mil.

Values of $\delta^{18}O$ of plagioclase versus $\delta^{18}O$ values of coexisting pyroxene or magnetite from rocks of the Dufek intrusion are plotted in figure 6 and figure 7, respectively. Lines of equal $\delta^{18}O$ fractionations (Δ) between the minerals are labeled on each figure.

Figure 6 is modified from Schiffries and Rye (1989). At magmatic temperatures, plagioclase and pyroxene in equilibrium

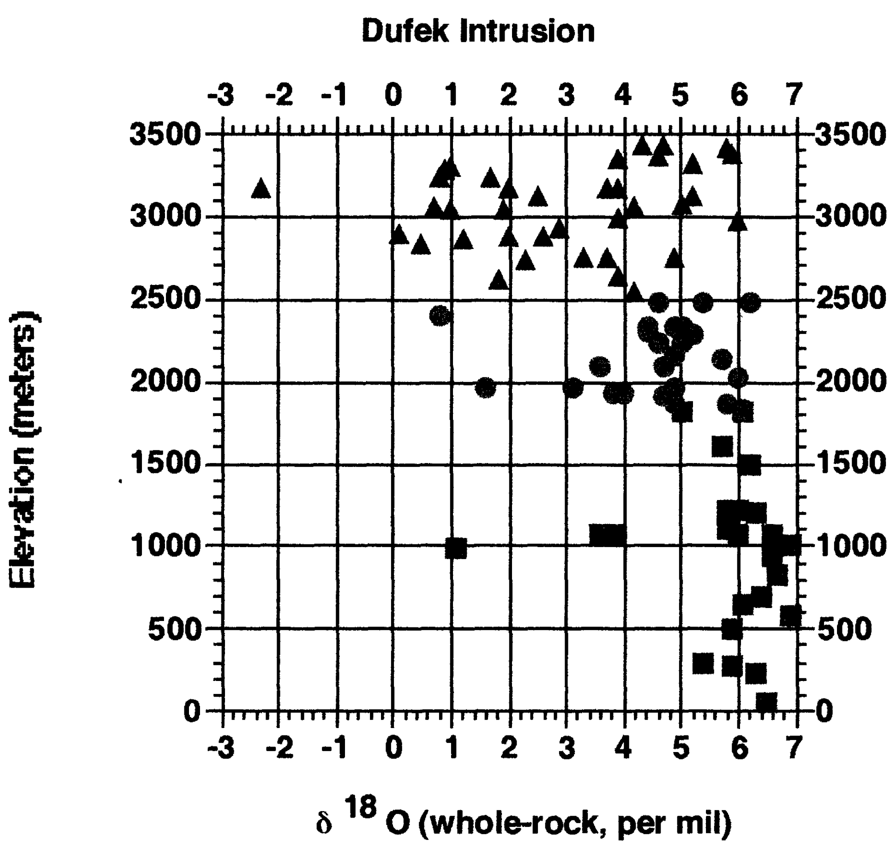

Figure 5. Variation of $\delta^{18}O$ (whole-rock, per mil) for the composite Dufek intrusion. Solid squares are Dufek Massif specimens, solid circles are the lower and solid triangles are the upper Forrestal Range specimens, respectively.

with a "normal" mafic magma have $\partial^{18}O$ values of +6.0 and +5.5 per mil, respectively (point B, figure 6). If pyroxene and plagioclase are the dominant minerals in the rock, closed-system, equilibrium cooling will result in compositions that lie in triangle ABC. Subsolidus exchange between a normal basalt and externally derived aqueous fluids produces a steeply sloping disequiblibrium trend (long arrow) because plagioclase is more susceptible to isotopic exchange than pyroxene. The lines defined by $\Delta^{18}O$=1.5, and $\Delta^{18}O$=0.5, correspond to equilibration temperatures of approximately 550°C, and 1200°C, respectively (Schiffries and Rye, 1989). A regression of available emperical and experimental data of plagioclase-pyroxene $\partial^{18}O$ fractionation factors for magmatic temperatures gives (Dunn, 1986):

$$T(^\circ C)=1320-239\ (\Delta^{18}O\ \text{plag-opx}).$$

Using this equation, the apparent temperatures of equilibration for the minerals with $\Delta^{18}O$ Plag-pyx >= 0.0 in Fig 6 ranges from about 750°C to 1320°C. This equation is not pertinent to those specimens with $\Delta^{18}O$ plag-pyx < 0.0 because reversal of this partitioning resulted from subsolidus exchange with externally derived aqueous fluids. Dufek specimen 259Fa has $\partial^{18}O$ values for plagioclase >2.7 gm/cm^3 and <2.7gm/cm^3 of +6.2 and +7.7 per mil, with $\Delta^{18}O$ plagioclase-pyx values of 0.9 and 2.4, respectively. Using the plagioclase-pyroxene $\partial^{18}O$ partitions above, these Δplag-pyx values convert to temperatures of equilibration of about 1100°C and 750°C for the pyroxene and plagioclase >2.7 and <2.7gm/cm3, respectively. These apparent temperatures may not have much meaning because the Sr isotopic composition of pyroxene (0.70825) is not equilibrated with the two plagioclase species (0.70924 and 0.70926) in this gabbro. By analogy, the oxygen isotopes may not have equilibrated between plagioclase and pyroxene during cooling of this rock. However, in rock from the Dufek intrusion, compositions of coexisting cumulus Ca-rich (augite) and ca-poor pyroxenes projected on the Lindsley (1983) 1-atmosphere geothermometer indicate temperatures of crystallization from 1140°C to 1030°C and pairs of coexisting late-stage pyroxenes by the same geothermometer indicate formation of augite at 770°C and 650°C and of Ca-poor pyroxene at 800°C (Ford and Himmelberg, 1986). In spite of the

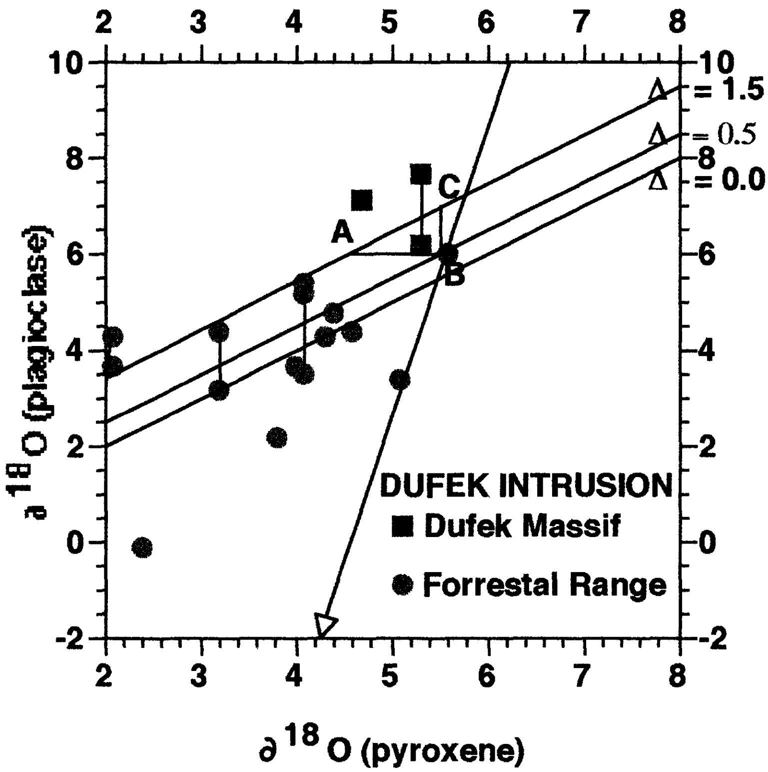

Figure 6. Plot modified from Schiffries and Rye (1989), of $\partial^{18}O$ plagioclase versus $\partial^{18}O$ pyroxene for coexisting pairs in the Dufek intrusion. Vertical lines connect points for plagioclase "A" and "B" in three Forrestal Range rocks and one Dufek Massif rock.

possible lack of oxygen isotopic equilibration between some minerals, apparent crystallization temperatures derived from either oxygen isotope or pyroxene geothermoeters are similar in these rocks.

Figure 7 is a plot of $\partial^{18}O$ of plagioclase versus $\partial^{18}O$ of magnetite separates from Dufek intrusion rocks. Lines of equal fractionation factors, $\Delta^{18}O$ plagioclase-magnetite, 1.5, 2, and 3 are shown. Temperatures of plagioclase-magnetite equilibration for most specimens on this plot range from about 800°C to 1320°C (Anderson and others, 1971). However, like pyroxene and plagioclase, magnetite is a cumulate mineral in many of the rocks investigated, and the partitioning of $\partial^{18}O$ plagiolase-magnetite may not represent equilibrium attained between these minerals during closed system cooling.

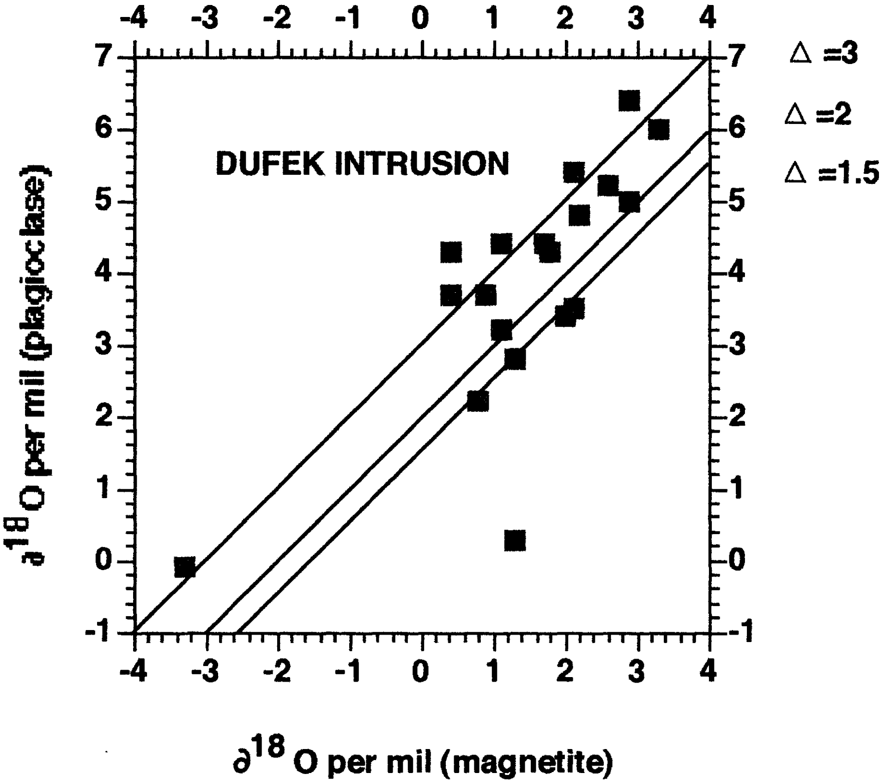

Figure 7. Plot of $\partial^{18}O$ plagioclase versus $\partial^{18}O$ magnetite for Dufek intrusion rocks Lines of equal $\Delta^{18}O$ plagioclase-magnetite are shown.

AGE of the DUFEK INTRUSION

Samples from the Dufek intrusion dated by the US Geological Survey (Table 2) include conventional K-Ar ages of three plagioclase separates from cumulate anorthosites, a pyroxene separate from gabbro, and a whole rock fine-grained gabbro from widely spaced stratigraphic intervals in the Dufek Massif and Forrestal Range (Kistler and Ford, 1979). Total gas $^{40}Ar/^{39}Ar$ ages for two pyroxenes from the Dufek Massif and Forrestal Range were reported by Ford and Kistler (1980). The conventional K-Ar determinations showed considerable age discordancy between plagioclase, pyroxene, and whole-rock samples from different parts of the body, but showed concordancy between 3 plagioclase samples that average 171.6±4.3 Ma. The pyroxene K-Ar and $^{40}Ar/^{39}Ar$ ages ranged from 189 to 98 Ma. The difficulty of interpreting pyroxene ages due to the possibility of excess argon or to argon loss because of exsolution lamellae (Kistler and Dodge, 1966) gave little weight to these data and the plagioclase average (171.6±4.3 Ma) was accepted as the best age for the intrusion (Ford and Kistler, 1980).

Brewer and others (1996) reported incremental heating $^{40}Ar/^{39}Ar$ isochron ages of 182.1±2.4 Ma and 182.9±2.5 Ma for plagioclase separates from the Dufek intrusion. Zircons from the intrusion yield U-Pb dates of 183.9±0.3 Ma for the capping granophyre and 182.7±0.4 Ma for a late cross-cutting dike (Minor and Mukasa, 1995).

Rb-Sr whole-rock, mineral ages calculated from regressions of data for two specimens from the Dufek Massif section and 14 specimens from the Forrestal Range section range between 224 and 147 Ma (Table 2). Values of MSWD greater than 1 for many of these regressions indicates scatter of data about the lines is due to factors other than analytical errors. The factor in these cases is most likely the Sri differences between cumulus and intercumulus minerals shown for some rocks in Figures 3 and 4. Due to this, the ages derived from regressions with MSWD greater than 1, even though they are all Mesozoic, do not represent crystalization ages of the Dufek intrusion. The two Dufek Massif, three of the Forrestal Range section, and the capping granophyre regressions all have MSWD less than 1. The error for these regressions is due only to analytical error, and the ages calculated for these specimens could represent crystallization ages.

The precise isochron for the capping granophyre (Table 2) yields an age of 183.9±7.1 Ma, the same as the zircon U-Pb age of 183.9±0.3 Ma (Minor and Musaka, 1995) for this unit of the Dufek intrusion. The age for this unit along with the two Dufek Massif gabbro Rb-Sr isochrons at 178.4±8.9 Ma and 182.0±17 Ma (Table 2) and the $^{40}Ar/^{39}Ar$ isochron ages of 182.1±2.4 Ma and 182.9±2.5 for two plagioclase separates (Brewer and others, 1996) from the Dufek intrusion strongly suggest the intrusion is greater than 180 Ma and most likely 184 Ma.

The three remaining precise whole-rock mineral isochrons are for two gabbros and a leucocumulate from the Forrestal Range section and yield ages that range from 176.1±5.6 Ma to 169.3±7.3Ma. These ages are the same within experimental error and their average age of 173±5 Ma overlaps with the average 171.6±4.3 Ma of the conventional K-Ar ages for three plagioclase separates (Kistler and Ford, 1979) from the intrusion. It is not likely it took 8 to 10 m.y. to cool after emplacement of the Dufek intrusion. These dates probably reflect eqilibration of isotope systems in Dufek intrusion rocks during heating at the culminating 176.6±1.8 Ma time of emplacement of the Ferrar tholeiitic rocks elsewhere in Antarctica (Fleming and others,1997).

SUMMARY

The extreme variation of strontium and oxygen isotope compositions of rocks from the Dufek layered mafic intrusion shows that it was formed from magma of tholeiitic composition, probably derived from the mantle, that was variably contaminated with siliceous melts derived from crustal rocks. The strontium isotopic composition of a cumulate pyroxene from the Dufek Massif indicates the primary tholeiitic magma had Sri at least as primitive as 0.7076. Compositional variation in the magmas was reinforced by fractional crystallization. In spite of accumulating at magmatic temperatures, not all minerals isotopically equilibrated as the intrusion cooled and crystallized. Oxygen isotope fractionation between plagioclase and pyroxene and magnetite generally indicate equilibration from about 1300°C to about 800°C. Some mafic rocks from the Forrestal Range with Sri values as radiogenic as 0.712 have values of $\partial^{18}O$ as low as +1 per mil. These same rocks have magmatic oxygen isotope temperatures of partition between plagioclase and pyroxene and require that the contaminating crustal melts were derived from rocks with ^{18}O depleted by interaction with meteoritic hydrothermal systems prior to melting. The capping granophyre is derived from a crustal melt, and is not derived from the mafic Dufek magma by fractional crystallization. Rb-Sr whole-rock mineral ages from the Dufek Massif, a Rb-Sr whole-rock isochron for the capping granophyre, two $^{40}Ar/^{39}Ar$ plagioclase ages from the Dufek intrusion, and an U-Pb zircon age for the capping granophyre indicate the intrusion is at least 180 Ma and is probabably 184 Ma.

Table 2. Sample number, elevation, rock type, material dated and apparent Rb-Sr, K-Ar, or $^{40}Ar/^{39}Ar$ ages for samples of the Dufek Massif and Forrestal Range sections of the Dufek intrusion

Sample, Elevation meters, (reference)	Rock type	Material dated	Apparent Age, MSWD, $(^{87}Sr/^{86}Sr)_o$
DUFEK MASSIF			
192Fb, 21 (1)	anorthosite	plag., K-Ar	171.2±4.3 Ma
38Fa, 278 (1)	leucogabbro	pyx, $^{40}Ar/^{39}Ar$	189.5±31.7 Ma
198Fa,1067 (1)	mafic gabbro	pyx, K-Ar	97.5±2.4 Ma
237Fb, 1219	mafic gabbro	wr, pyx, plag	178.4±8.9 Ma, 0.28, 0.70919
259Fa, 1809	mafic gabbro	wr, plag, plag	182.0±17 Ma, 0.46, 0.70901
FORRESTAL RANGE			
75Fe, 110 (1)	leucocumulate	plag., K-Ar	169.5±4.2 Ma
75Fe, 110	leucocumulate	wr, plag, plag, apatite, pyx	189.1±30 Ma, 43.1 0.71055
74Fa, 114	gabbro	wr, plag, apatite, pyx	146.7±17.7 Ma, 11.5, 0.71057
99Ff, 145	leucocumulate	wr, plag, plag, apatite	224.2±52 Ma, 5.62, 0.70967
94Fi,340 (1)	leucocumulate	pyx, $^{40}Ar/^{39}Ar$	148.4±7.3 Ma
94Fi, 340	leucocumulate	wr, plag, plag	201.1±50 Ma, 7.3, 0.71005
84Fa, 83Fb, 515,525	gabbro, gabbro	wr, apatite, wr, pyx, plag	176.1±5.6 Ma, 0.42, 0.70978
310Fa, 310Fb, 822, 819	gabbro gabbro	wr, wr, plag, pyx	194.6±38 Ma, 4.3, 0.70957
184Fa, 926	leucocumulate	wr,plag, plag, apatite, pyx	165.5±31 Ma 18.2, 0.70966
185Fa, 942	gabbro	wr, plag, pyrx	174.0±6.6 Ma, 1.9, 0.70939
297Fa, 1070 (1)	gabbro	wr, K-Ar	111.9±2.8 Ma, 106.3±4.2 Ma
101Fa, 1090 (1)	leucocumulate	plag, K-Ar	174.1±4.4 Ma
101Fa, 1090	leucocumulate	wr, plag, plag	173.7±22 Ma, 0.24, 0.70949

Table 2. (con't) Sample number, elevation, rock type, material dated and apparent Rb-Sr, K-Ar, or $^{40}Ar/^{39}Ar$ ages for samples of the Dufek Massif and Forrestal Range sections of the Dufek intrusion

Sample, Elevation meters, (reference)	Rock type	Material dated	Apparent Age, MSWD, $(^{87}Sr/^{86}Sr)_o$
171Fa, 1169	gabbro	wr, pyx, plag	190.2±50 Ma, 19, 0.70951
182Fc, 1250	leucocumulate	wr, plag, pyx, apatite	161.5±24 Ma, 11.2, 0.70996
158Fa, 1405	gabbro	plag, pyx, apatite	156.8±5.3, 1.55, 0.71068
160Fa, 1436	gabbro	wr, plag, pyx, apatite	162.5±23 Ma, 10.7, 0.71226
162Fe-2, 1482	gabbro	wr, plag, pyx, apatite	169.3±7.3 Ma, 0.34, 0.71208
162Fc-315Na, 1493-1600, n=6	granophyre	6 wr	183.9±7.1 Ma, 0.32, 0.71276

Reference
(1) Ford and Kistler (1980), all others, this report

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Table 3. Rubidium, strontium abundance and isotopic data, $\partial^{18}O$ values, and elevations for rocks and minerals in the Dufek Layered Intrusion Antarctica.

Sample Number material analyzed	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ measured	$(^{87}Sr/^{86}Sr)_o$	$\partial^{18}O$ per mil	elev. meters
Dufek Massif minerals								
192Fb plagioclase	5.30	216	0.025	0.071	0.71002	0.70985	6.9	21
38Fa pyroxene	0.54	9	0.06	0.174	0.70841	0.70799		278
49Fb plagioclase	1.1	262	0.004	0.012	0.70921	0.70918	6.2	585
111Fa plagioclase	1	283	0.035	0.01	0.70899	0.70897	7.1	1070
111Fa pyroxene	0.64	13.8	0.046	0.1341	0.70882	0.70849	4.7	1070
237Fb pyroxene	2.94	6.5	0.452	1.31	0.71083	0.70763	4.6	1219
237Fb pyroxene2	5.41	13.54	0.399	1.154	0.71212	0.7093		1219
237Fb plagioclase	5.42	296	0.018	0.053	0.70931	0.70918		1219
237Fb magnetite	na	na					3.8	1219
A259Fa plagioclase	97.1	189	0.514	1.487	0.71287	0.70924	7.7	1809
B259Fa plagioclase	1.1	309	0.004	0.01	0.70908	0.70906	6.2	1809
259Fa pyroxene	5.29	9.2	0.575	1.666	0.71232	0.70825	5.3	1809
Forrestal Range minerals								
A75Fe plagioclase	83.8	237	0.353	1.023	0.71327	0.71077	4.4	110
B75Fe plagioclase	8.8	316	0.028	0.081	0.71073	0.71053	3.2	110
75Fe pyroxene	1.69	30.2	0.056	0.162	0.7114	0.711	3.2	110
75Fe apatite	6.67	176.6	0.038	0.109	0.71041	0.71014		110
75Fe magnetite	na	na					1.1	110
74Fa plagioclase	6	315	0.019	0.055	0.71079	0.71066	3.7	114
74Fa pyroxene	14.22	9.36	1.52	4.401	0.71975	0.70881	4.0	114
74Fa apatite	6.14	181.2	0.034	0.098	0.71057	0.71033		114
74Fa magnetite	na	na					0.9	
A99Ff plagioclase	57	154	0.37	1.071	0.71307	0.71046	5.4	145
B99Ff plagioclase	17.9	334	0.054	0.155	0.71028	0.7099	3.5	145
99Ff pyroxene	16.09	18.88	0.693	2.007	0.71366	0.70867	4.1	145
99Ff apatite	6.38	182.02	0.035	0.101	0.70986	0.70961		145
99Ff magnetite	na	na					2.1	145

Table 3. (cont.) Rubidium, strontium abundance and isotopic data, $\partial^{18}O$ values, and elevations for rocks and minerals in the Dufek Layered Intrusion Antarctica.

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94Fi pyroxene	4.8	11.5	0.417	1.208	0.7113	0.70834		340
A94Fi plagioclase	40.4	187	0.216	0.625	0.71189	0.71037	6.4	340
B94Fi plagioclase	5.5	313	0.018	0.051	0.71027	0.71015	5.0	340
94Fi magnetite	na	na					2.9	340
84Fa apatite	6.21	238.9	0.026	0.075	0.70994	0.70975		515
83Fb plagioclase	12.2	307	0.04	0.115	0.71011	0.70983	5.2	525
83Fb pyroxene	9.78	14.77	0.662	1.907	0.71458	0.70982	4.1	525
83Fb magnetite	na	na					2.6	525
310Fa pyroxene	8.23	15.1	0.545	1.578	0.71397	0.71012	5.1	822
310Fa plagioclase	1.00	307	0.003	0.009	0.70968	0.70966	3.4	822
310Fa magnetite	na	na					2.0	822
A184Fa plagioclase	74.6	215	0.347	1.004	0.71211	0.70966	4.3	926
B184Fa plagioclase	17.2	299	0.058	0.166	0.70989	0.70948	3.7	926
184Fa pyroxene	15.57	20.42	0.762	2.207	0.71486	0.70947	2.1	926
184Fa apatite	6.61	176.3	0.037	0.108	0.7102	0.70993		926
184Fa magnetite	na	na					0.4	926
185Fa pyroxene	12.64	15.24	0.829	2.402	0.71535	0.70948	4.6	942
185Fa plagioclase	0	287	0	0	0.70944	0.70944	4.4	942
185Fa magnetite	na	na					1.7	942
A101Fa plagioclase	105	222	0.473	1.369	0.71288	0.70954	2.8	1090
B101Fa plagioclase	87	316	0.275	0.797	0.71148	0.70953	0.3	1090
101Fa magnetite	na	na					1.3	1090
171Fa plagioclase	9.3	283	0.033	0.095	0.70991	0.70968	6	1169
171Fa pyroxene	11.66	12.11	0.963	2.79	0.71707	0.71026	5.6	1169
171Fa magnetite	na	na					3.3	1169
182Fc plagioclase	3.5	336	0.01	0.03	0.71019	0.71012	4.8	1250
182Fc pyroxene	16.04	15.2	1.055	3.058	0.71698	0.70951	4.4	1250
182Fc apatite	2.12	203.4	0.01	0.03	0.70984	0.70977		1250
182Fc magnetite	na	na					2.2	1250

Table 3. (cont.) Rubidium, strontium abundance and isotopic data, $\partial^{18}O$ values, and elevations for rocks and minerals in the Dufek Layered Intrusion Antarctica.

Sample Number material analyzed	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ measured	$(^{87}Sr/^{86}Sr)_o$	$\partial^{18}O$ per mil	elev. meters	elev. meters
158Fa plagioclase	0.2	373	0.0005	0.0016	0.71073	0.71073	4.3	1405	
158Fa pyroxene	11.6	19.34	0.6	1.736	0.71455	0.71024	4.3	1405	
158Fa apatite	5.17	240.7	0.021	0.062	0.71077	0.71062		1405	
158Fa magnetite	na	na					1.8	1405	
160 Fa plagioclase	5.8	491	0.012	0.034	0.71253	0.71245	2.2	1436	
160Fa pyroxene	26.36	23.21	1.136	3.29	0.71989	0.71185	3.8	1436	
160Fa apatite	5.44	312.7	0.017	0.05	0.7123	0.71218		1436	
160Fa magnetite	na	na					0.8	1436	
162Fe plagioclase	7.8	436	0.018	0.052	0.71221	0.71209	-0.1	1482	
162Fe pyroxene	13.83	22.55	0.613	1.776	0.71633	0.71199	2.4	1482	
162Fe apatite	7.79	265	0.029	0.085	0.71225	0.71204		1482	
162Fe magnetite	na	na					-3.3	1482	
Dufek Massif whole-rocks									
193Fa wr	3.3	176	0.019	0.054	0.71007	0.70994	6.5	55	55
195Fb wr	0.9	237	0.004	0.011	0.70916	0.70913	6.3	232	232
38Fa wr	5.1	230	0.022	0.064	0.70845	0.7083	5.9	278	232
39Fa wr	6.2	229	0.027	0.078	0.7087	0.70852	5.4	293	293
46Fa wr	4	163	0.025	0.071	0.7089	0.70873	5.9	506	506
49Fb wr	4.5	190	0.024	0.069	0.70916	0.70899	6.9	585	585
277Fa wr	0.3	199	0.002	0.004	0.70948	0.70947	6.1	643	643
52Fa wr	6.8	169	0.04	0.116	0.70935	0.70907	6.4	698	698
54Fa wr	3.6	160	0.023	0.065	0.70936	0.7092	6.7	827	827
117Fa wr	2.3	185	0.012	0.036	0.70937	0.70928	6.6	936	936
57Fb wr	225	186	1.21	3.506	0.72397	0.71541	1.1	986	986
58Fb wr	1.6	137	0.012	0.034	0.70942	0.70934	6.9	1013	1013
252Fb wr	99.3	128	0.776	2.246	0.71496	0.70948	3.6	1066	1066
198Fi wr	2.6	196	0.013	0.038	0.70963	0.70954	3.8	1067	1067
226Fa wr	1.8	178	0.01	0.029	0.70956	0.70949	6.6	1068	1068
111Fe wr	1.3	153	0.008	0.025	0.70917	0.70911	6	1070	1070

Table 3. (cont.) Rubidium-Strontium abundance and isotopic data, $\partial^{18}O$ values, and elevations for rocks and minerals in the Dufek Layered Intrusion Antarctica.

Sample Number material analyzed	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ measured	$(^{87}Sr/^{86}Sr)_o$	$\partial^{18}O$ per mil	elev. meters	elev. meters
199Fa wr	0	163	0	0	0.70944	0.70944	5.8	1097	1097
240Fc wr	2.6	152	0.017	0.05	0.70891	0.70879	5.8	1173	1173
230Fb wr	4.9	145	0.034	0.098	0.7091	0.70886	6.3	1204	1204
231Fd wr	3.6	158	0.023	0.066	0.70894	0.70878	6	1213	1213
237Fb wr	5.3	124	0.043	0.124	0.70953	0.70923	5.8	1219	1219
270Fa wr	6.3	183	0.034	0.1	0.70916	0.70892	6.2	1493	1493
266Fa wr	2.8	140	0.02	0.058	0.70929	0.70915	5.7	1609	1609
259Fa wr	12.5	181	0.069	0.2	0.70947	0.70898	6.1	1809	1809
259Fb wr	15.1	246	0.061	0.178	0.7094	0.70897	6.1	1810	1810
257Fa wr	10.2	177	0.058	0.167	0.71047	0.71007	5	1814	1814
Forrestal Range whole-rocks								Forrestal	+Dufek
79Fa wr	25.3	151	0.168	0.485	0.71109	0.70991	6.1	20	1834
78Fb wr	24.8	183	0.136	0.392	0.71022	0.70926	5.8	53	1867
77Fa wr	21.9	152	0.144	0.417	0.71013	0.70912	4.9	57.2	1871
76Fa wr	13	176	0.074	0.214	0.70958	0.70906	4.7	103	1917
75Fe wr	24.8	253	0.098	0.184	0.71115	0.71046	3.8	110	1924
74Fa wr	15.7	207	0.076	0.219	0.71114	0.71061	4	114	1928
99Fb wr	30.8	183	0.168	0.487	0.71096	0.70977	4.9	144	1958
99Ff wr	30.4	257	0.118	0.342	0.7108	0.70996	3.1	145	1959
99Fg wr, aplite	241	50.5	4.772	13.88	0.76282	0.72891	1.6	147	1961
97Fb wr	18.9	219	0.086	0.25	0.71151	0.7109	6	221	2035
306Fd wr	19.6	255	0.077	0.223	0.71121	0.71067	3.6	274	2088
306Fh wr	17.2	173	0.099	0.288	0.71144	0.71074	4.7	275	2089
94Fe wr	28.6	164	0.174	0.505	0.71184	0.71061	5.7	335	2149
94Fi wr	21.9	225	0.097	0.282	0.71074	0.71005	4.9	340	2154
87Fa wr, aplite	318	53.3	5.966	17.37	0.76802	0.7256	5	429	2243
87Fb wr	26.8	178	0.151	0.436	0.71173	0.71067	4.6	430	2244
86Fa wr	29.5	186	0.159	0.459	0.71137	0.71025	5.2	465	2279
85Fb wr	9.2	143	0.064	0.186	0.71045	0.71	4.4	491	2305

Table 3. (cont.) Rubidium-Strontium abundance and isotopic data, $\partial^{18}O$ values, and elevations for rocks and minerals in the Dufek Layered Intrusion Antarctica.

Sample Number material analyzed	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ measured	$(^{87}Sr/^{86}Sr)_o$	$\partial^{18}O$ per mil	elev. meters	elev. meters
84Fa wr	18.4	163	0.113	0.327	0.71061	0.70981	5	515	2329
83Fa wr	26.7	242	0.11	0.319	0.71071	0.70993	4.4	524	2338
83Fb wr	21.1	184	0.115	0.332	0.71058	0.70977	4.9	525	2339
300Fb wr, aplite	213	57.6	3.7	10.74	0.74819	0.72195	0.8	594	2408
284Fa wr	23.8	167	0.143	0.412	0.70981	0.7088	4.6	670	2484
284Fb wr	17.2	219	0.079	0.227	0.7111	0.71054	5.4	672	2486
287Fe wr	88.4	268	0.33	0.955	0.71283	0.7105	6.2	674	2488
311Fa wr	16.2	206	0.064	0.186	0.71158	0.71113	4.2	735	2549
310Fb wr	15.9	206	0.077	0.223	0.71021	0.70955	1.8	819	2633
310Fa wr	12.7	159	0.08	0.231	0.71008	0.70952	3.9	822	2636
184Fa wr	35.9	217	0.165	0.479	0.71057	0.7094	2.3	926	2740
309Fb wr	19.1	132	0.145	0.419	0.71037	0.70935	3.7	937	2751
309Fa wr	15.1	220	0.069	0.199	0.71037	0.70988	3.3	937	2751
185Fa wr	11.2	137	0.0872	0.237	0.70992	0.70934	4.9	942	2756
188Fa wr	20.4	217	0.094	0.272	0.71043	0.70977	1.5	1021	2835
189Fa wr	26.2	211	0.124	0.359	0.71059	0.70971	1.2	1059	2873
297Fa1 wr	13.7	164	0.084	0.242	0.70977	0.70918	2.6	1070	2884
297Fa2 wr	15.2	168	0.09	0.262	0.71105	0.71061	2.0	1072	2886
101Fa wr	71.1	229	0.31	0.899	0.71169	0.70949	0.1	1090	2904
191Fb wr	18.9	133	0.142	0.411	0.71035	0.70935	2.9	1116	2930
171Fa wr	23.4	144	0.162	0.47	0.71058	0.70943	6.0	1169	2983
72Fa wr	26.7	188	0.142	0.411	0.7116	0.7106	3.9	1185	2999
169Fb wr	32.2	273	0.118	0.341	0.71143	0.7106	1.0	1231	3045
181Fa wr	32.7	221	0.148	0.428	0.71087	0.70982	1.9	1234	3048
182Fc wr	33	226	0.146	0.423	0.71098	0.70995	4.2	1250	3064
71Fl wr	26.9	255	0.105	0.305	0.7117	0.71095	0.7	1253	3067
167Fa wr	25.3	166	0.152	0.441	0.71118	0.7101	5.0	1268	3082
166Fa wr	17.9	153	0.117	0.339	0.71102	0.71019	5.2	1310	3124
173Fc wr	47.7	271	0.176	0.51	0.71228	0.71104	2.5	1322	3136

Table 3. (cont.) Rubidium-Strontium abundance and isotopic data, $\partial^{18}O$ values, and elevations for rocks and minerals in the Dufek Layered Intrusion Antarctica.

Sample Number material analyzed	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ measured	$(^{87}Sr/^{86}Sr)_o$	$\partial^{18}O$ per mil	elev. meters	elev. meters
157Fb wr, aplite	515	77.1	6.68	19.47	0.78359	0.73603	-2.3	1360	3174
157Fd wr	56.6	176	0.322	0.932	0.72583	0.72355	2.0	1362	3176
157Fg1 wr, gabbro pegmatite	26.4	144	0.183	0.531	0.71187	0.71057	3.7	1364	3178
157Fg2 wr	31.9	132	0.242	0.7	0.71246	0.71075	3.9	1365	3179
160Fa wr	37.2	199	0.187	0.541	0.71336	0.71204	1.7	1436	3250
161Fa wr	47.9	188	0.255	0.738	0.71317	0.71137	0.8	1435	3249
162Fe2 wr	49.3	248	0.199	0.575	0.71349	0.71209	0.9	1482	3296
162Fc wr, granodiorite	98.6	197	0.501	1.449	0.71656	0.71276	1	1493	3307
163Fa wr, granodiorite	139	152	0.914	2.649	0.71963	0.71276	5.2	1516	3330
164Fa wr, granodiorite	144	137	1.051	3.045	0.72083	0.71276	3.9	1542	3356
165Fa wr, granodiorite	151	142	1.063	3.081	0.72076	0.71276	4.6	1558	3372
313Fa wr, granodiorite	100	175	0.571	1.655	0.71709	0.71276	5.9	1575	3389
315Na wr, granodiorite	149	131	1.137	3.295	0.72139	0.71276	5.8	1600	3414
17Na wr, gabbro	40.2	260	0.155	0.448	0.71347	0.71238	4.7	1620	3434
317Fa wr, granodiorite	147	141	1.043	3.02	0.72139	0.71301	4.3	1631	3445

Notes

wr= whole-rock

na= not analyzed

Plagioclase separates with prefix "A" have specific gravity <2.7 gm/cm^3, specimens with prefix "B" and all other specimens have specific gravity >2.7 gm/cm^3.