Strontium in plagioclase feldspars from four layered basic masses in Somalia.

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Summary. The petrological and structural characteristics of four layered basic masses in Somalia are described. Sr contents of feldspars from three of the masses are similar for comparable An contents; Sr varies between 1000 and 1850 p.p.m. and tends to increase as An decreases from An_{68} to An_{48}. In feldspars from the other mass Sr also increases with decreasing An content (An_{74} to An_{56}), but is at a much higher general tenure (1650 to 2350 p.p.m.). It is concluded that the four masses were not all part of the same layered intrusion.

THE well-exposed Pre-Cambrian rocks of Somalia include approximately 30 basic masses in the Hargesia and Borama districts. In 1958 Daniels described briefly five such intrusions, namely Dibrawein, Gul Sakar, Rakdasafaka, Hamar, and Dudub, and he considered them to be consanguineous. The masses are emplaced within metamorphosed sediments of various grades and types folded into large anticlinoria and synclinoria, which are affected by subsidiary structures.

In 1959 one of the authors (W. S.) mapped the four layered basic and ultrabasic intrusions of Gul Sakar, Rakdasafaka, Hamar, and Dudub (fig. 1). Detailed laboratory studies on the mineralogy, petrology, and geochemistry of these rocks are now being carried out by the authors. This report includes brief petrological and structural descriptions of the igneous masses, sufficient to provide background for a detailed account of the results of laboratory investigation on the strontium content of the feldspars.

Description of rock masses.

Petrography. The rock types are composed essentially of various combinations of the four minerals olivine, clinopyroxene, amphibole, and basic plagioclase, together with orthopyroxene, magnetite, ilmenite, and spinel as notable accessories. Apatite and biotite are occasionally present. The rocks are usually of medium grain size though coarse patches, layers, and late gabbro pegmatites are also common.

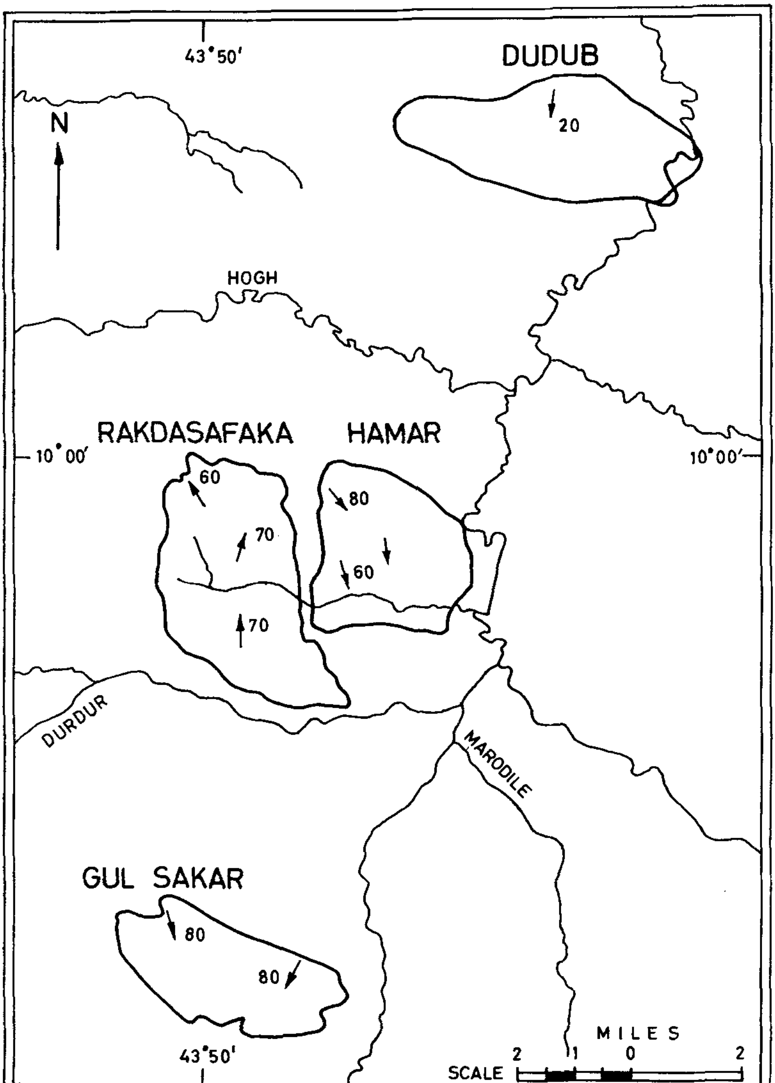

FIG. 1. Location of four basic and ultrabasic masses in the Hargesia district, Somalia. Arrows indicate dip of layering.

The igneous intrusion of Dudub is a mass of ultrabasic and basic rocks, which intrudes mainly amphibolites. In the north-western part of the intrusion the simplified general succession of the main rock types from the exposed base to top is as follows:

Medium grained pyroxenite	Approx. thickness	15 ft
Olivine-melagabbro	,,	20 ft
Olivine-gabbro pegmatite	,,	150 ft
Coarse grained pyroxenite	,,	40 ft
Coarse grained olivine-gabbro	,,	20 ft
Layered olivine-gabbro	,,	500 ft

Interstitial and late cross-cutting gabbro-pegmatites are abundant. The range of An content of feldspars from the exposed base to top is An_{65} to An_{58}.

The ultrabasic rocks in Gul Sakar are represented by dunites and peridotites. They are developed near the base in the eastern part of the intrusive mass where they grade into olivine-gabbros and uralite-gabbros. The western side of the complex is characterized by extensive uralitized varieties of olivine-gabbros. Plagioclase varies from An_{68} to An_{56}.

In marked contrast to Dudub and Gul Sakar, the rocks of Rakdasafaka and Hamar consist of olivine-gabbros, gabbros, amphibole-gabbros, and uralite-gabbros. The ultrabasic rocks are only represented by thin horizons within the layered rocks.

The Rakdasafaka rocks have been divided into three large divisions namely: a layered series, olivine-gabbros, and uralite-gabbros. The layered series can be split into five units, recognition of which is based on the oscillatory variation of the An content of plagioclase feldspars. The units vary in thickness from 500 ft to 4000 ft and consist of a number of strongly-layered olivine-gabbros which grade upwards into troctolites. The feldspars range from An_{75} to An_{56}. Uralite-gabbros are characterized by clear replacement of clinopyroxene and olivine by secondary amphiboles.

The layered rocks of the Hamar intrusion extend along the western and north-western part of the igneous mass. They consist of olivine-gabbros, amphibole-gabbros, dunites, peridotites, and layered olivine-magnetite rock. The layering is only developed in sectors, which grade along the margins into non-layered rocks. A wide belt in the central and eastern part of the intrusion contains uralite-gabbro (apparently not layered) with prehnite and albite veins. The An content of feldspars ranges from An_{61} to An_{35}.

A great variety of textures is displayed by the gabbroic rocks. In general, the textural relations of the mineral components reflect the method of accumulation of early-formed crystals on the floor of the magma chamber and the building up of a solid mass by deposition of layer upon layer.

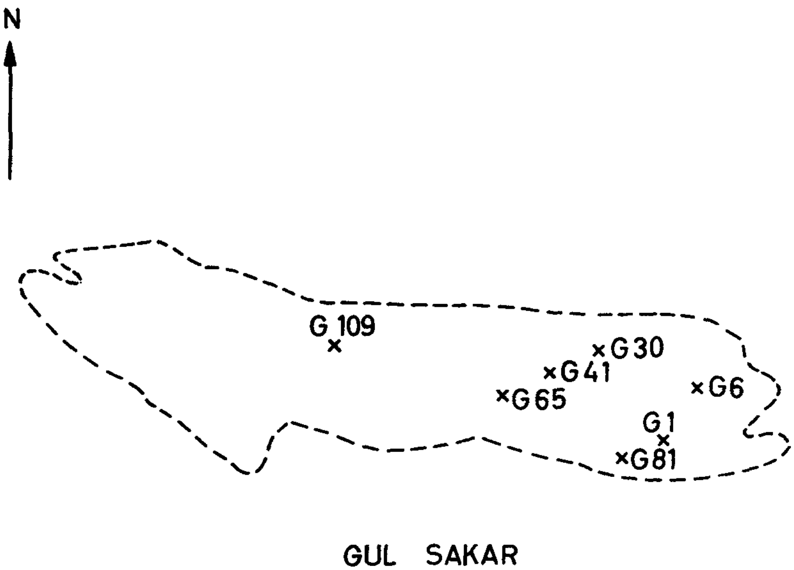

FIG. 2. Location of samples from Gul Sakar.

Rhythmic layering. Rhythmic layering is intermittently developed in all the intrusions mapped. Field and laboratory work clearly indicates that rhythmic layering has been developed by different rates of crystal settling, which was largely controlled by crystal size and shape as well as by variable velocity of the magma current.

Layering is conspicuously developed in the Rakdasafaka intrusion. In the field this layering simulates the rhythmic stratification of a sedimentary succession and in two-dimensional outcrops it produces a striking effect of banding. In general, the layering is caused by an alternation of troctolitic layers with layers rich in clinopyroxene with plagioclase. The well-developed layered sequences are often separated by uniform non-layered olivine-gabbros.

The layering in Dudub is quite different from the regular type of layering exposed in Rakdasafaka. It is characterised by undulating junctions and rapid gradations from very coarse to very fine facies, and many layered sections display the characteristic features of disturbed banding. Such structures as 'slumping', small troughs, undulations, and 'local unconformities' are particularly well developed.

The rhythmic layering in Hamar and Gul Sakar igneous masses is

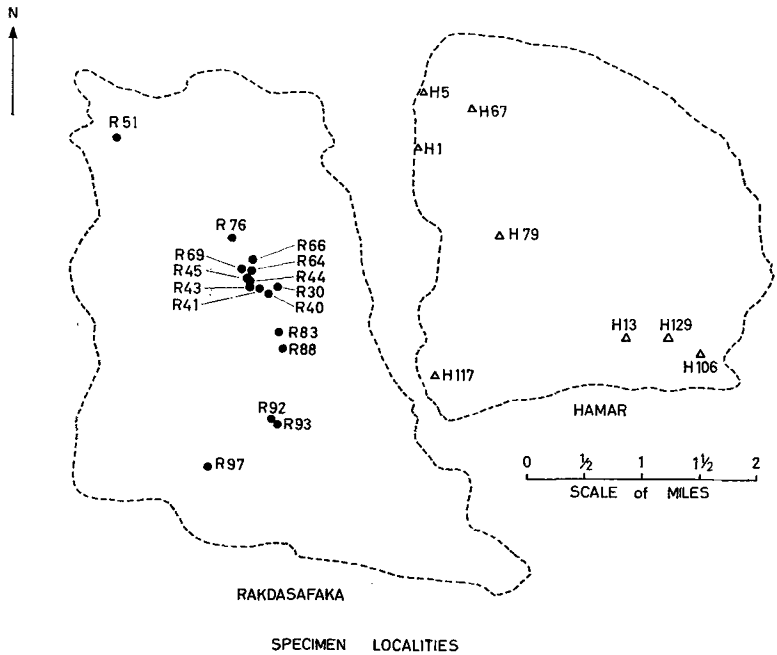

FIG. 3. Location of samples from Hamar and Rakdasafaka.

only intermittently developed, the layers being straight and regular over short distances.

Another characteristic feature of most rocks is marked parallel alignment of plagioclase and olivine crystals, which are well oriented with their longer axes parallel to the plane of layering, thereby often imparting to the rock a well-laminated structure. This strong igneous lamination is best developed in the prominently layered sections but is also obvious in most horizons of the non-layered succession.

The layered rocks appear to provide a clear example of gravity settling of crystals from a magma current. Petrofabric analysis (Skiba and Brothers, 1962) shows that during the differentiation and crystallization of the Rakdasafaka intrusion there was a significant circulation of magma by flow. The petrofabric diagrams show conclusively that the feldspars and olivines lie with their flat faces parallel to the surface of cumulation and their orientation is also parallel to the direction of flow.

Structure. The basic and ultrabasic masses form steeply dipping lenticular sheets intruded into Pre-Cambrian schists, gneisses, and amphibolites. Their contacts are approximately vertical and concordant with the strike of the country rocks. Gabbros pass gradationally into the prevalent amphibolites, whereas their contact with schists and gneisses is characterized by sharp junctions. In many places, particularly in the Hamar intrusion, gneisses and amphibolites have been incorporated as large and small inclusions within the igneous mass.

The strike and dip of layering varies considerably (fig. 1). In general low dips ranging from 0° to 30° characterise the Dudub gabbros, while high dips of 60° to 80° are prevalent within the Hamar, Rakdasafaka, and Gul Sakar intrusions. At Dudub the layers display wavy structures with a general dip ranging from S. 60° E. at 20° to S. 20° W. at 30°. At Hamar discontinuous banded sections dip SE. to S. 20° W. at 60° to 80°. In the centre of the Rakdasafaka mass the strongly layered gabbros dip N. to N. 10° E. at 70°, changing south-westwards to N. 70° W. at 30° and into a steep southerly dip near the western margin. At Gul Sakar the layering generally dips S. 20° W. at 80° in the central sector and S. 30° E. at 80° in the western. The steep dips of the gravity-layered sheets in which the constituent minerals and rhythmic layering were originally horizontal must have been caused by folding or tilting of the basic masses after consolidation of the gabbro magma. Unequivocal corroboration of post-consolidation tilting or folding of the basic masses must await further structural studies of the country rocks.

In several places the rocks are sheared, with the shear-planes ranging in dip from horizontal to vertical. The sheared rocks reveal evidence of dynamic metamorphism, cataclastic textures, pronounced mylonitic banding, and schistosity. Chloritization, sericitization, and amphibolitization are associated with the shearing and some of the schistose rocks bear a very close resemblance to amphibolites.

Strontium in plagioclase.

Previous work on the relationship between Sr and An content in plagioclase (above An_{15}) is not extensive but it is clear that Sr trends can vary in feldspars from different areas. Nockolds and Mitchell (1948) analysed nine plagioclase feldspars from Scottish Caledonian igneous rocks, including tonalite, granodiorite, and adamellite; they found little difference in

Sr (3000 p.p.m.) in feldspars of composition An_{63}, An_{59}, An_{45}, An_{38}, and An_{25} (twice); two more acid feldspars, An_{22} and An_{20}, gave lower Sr contents at 2000 and 15000 p.p.m. Wager and Mitchell (1951) analysed five feldspars from the Skaergaard Layered Complex, Greenland, and concluded that Sr increased from about 1000 p.p.m. in the more basic plagioclase (An_{65}) to about 5000 p.p.m. in more acid varieties (An_{38}); in the most acid sample, however, Sr was down to 2000 p.p.m. (An_{30}). Although they pointed out that their optical spectrographic errors might have been rather considerable in absolute amount (but that the trend was correct), concentrations of between 2000 and 3000 p.p.m. Sr were obtained for three of the five feldspars by wet chemical methods. Emmons (1952) recorded Sr values between 500 and 1900 p.p.m. for 25 feldspars from widely scattered localities with compositions ranging between An_{82} and An_{16}. Plagioclase from troctolite, Merrill, Wisconsin, U.S.A., had An_{82} and 1200 p.p.m. Sr, whereas that from a gabbro at the same locality had An_{60} and Sr 1900 p.p.m.; a slight increase in Sr with decreasing An content was noted for two plagioclase samples (An_{71}, 900 p.p.m. Sr and An_{65}, 1000 p.p.m. Sr) from anorthosites in Grand Marais, Minnesota, U.S.A. Wilkinson (1959) examined ten plagioclase feldspars from a differentiated teschenite sill in New South Wales, Australia; a clear Sr–An relationship was not apparent. Plagioclases with composition An_{68}, An_{62}, An_{60} (twice), An_{59}, An_{56}, and An_{55} all contained 3000 p.p.m. Sr, but those with An_{48}, An_{30}, and An_{65} had, respectively, 2300, 2000, and 1000 p.p.m. Sr. Turekian and Kulp (1956) noted a regular increase in Sr with decreasing An content for feldspars from the Stillwater Layered Complex, Montana, U.S.A. Their highest Sr value was only 270 p.p.m. (in An_{62}) but it represented a twofold increase on the values for the most basic varieties (An_{86}). A quite different relationship between Sr and An content exists in plagioclases from norites, gabbros, tonalites, granodiorites, etc., of the Southern Californian Batholith, U.S.A. (Sen *et al.*, 1959). Sr *decreases* fairly steadily as An decreases: it is in the range 1300–1000 p.p.m. for feldspars An_{93} to An_{59}; in the range 900–600 p.p.m. for feldspars An_{64}–An_{38}; and in the range 430–140 p.p.m. for feldspars An_{33}–An_{21}.

Strontium in plagioclase from Somalia.

Preliminary work showed that the basic and ultrabasic rocks from the different layered intrusions had Sr contents rather above values generally expected for such rock types (Turekian and Kulp, 1956). It was established that plagioclase held the vast bulk of the Sr and that associated pyroxene and hornblende contained less than 75 p.p.m. Sr; olivine, ilmenite, and magnetite contained negligible amounts of Sr; sphene is absent in thin section and apatite is uncommon.

Several plagioclase feldspars from Gul Sakar (An_{68}–An_{56}), Dudub (An_{65}–An_{58}), and Hamar (An_{61}–An_{48}) were analysed for Sr, and localities are shown in figs. 2 and 3; samples from Dudub were collected along a N.–S. traverse from the central margin of the mass. There is a clear

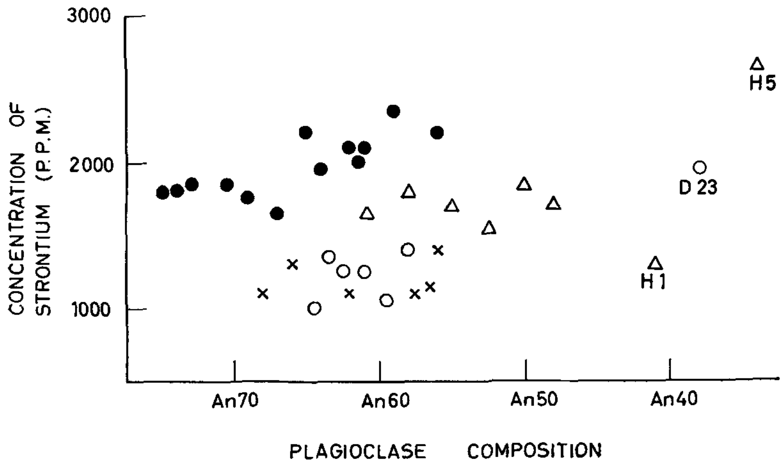

FIG. 4. Relation between plagioclase composition and strontium content. Solid circles for feldspars from Rakdasafaka, open circles for feldspars from Dudub, crosses for feldspars from Gul Sakar, and triangles for feldspars from Hamar.

positive correlation between increasing Sr and decreasing An content (fig. 4) if feldspars from the sheared rock SD23 and the marginal rocks SH1 and SH5 are not considered. This trend is similar to that found (on a small number of samples) by Turekian and Kulp (1956) for feldspars from the Stillwater Complex. The Sr tenors in plagioclases from the two areas differ, however, by a factor of five (for similar An content): 1000 p.p.m. Sr is the lowest concentration of Sr found in plagioclases (An_{64}) from Somalia, and 270 p.p.m. is the maximum found in those (An_{62}) from Stillwater. Referring to fig. 4 it can be seen that points representing analyses for feldspars from Gul Sakar, Dudub, and Hamar occupy a band or belt; variation about a mean straight line is considered to be the result of natural as well as analytical processes. It will be observed that all the feldspars are quite basic (except those from marginal and recrystallised rocks); Wager and Mitchell (1951) noted that Sr tended to fall with decreasing An content only when An was as low as An_{30}—appreciably more acid than any of the Somalian plagioclases (fig. 4). The data for the feldspars from Gul Sakar, Dudub, and Hamar are compatible with the suggestion that the three areas are outcrops of layered rocks that might have originally formed part of one continuous

TABLE I. Anorthite and Sr contents of plagioclases from Gul Sakar (SG), Dudub (SD), and Hamar (SH). The arrangement within each mass is one of increasing An content. See appendix for the quality of the data. Localities shown in figs. 2 and 3.

Code and description of host rock.		Plagioclase composition. An (opt.).	An (chem.).	Sr (p.p.m.).
SH5	Amphibole-gabbro (marginal)	35	34½	2650
SH1	Amphibole-gabbro (marginal)	45	41	1300
SH106	Olivine-gabbro	50	48	1700
SH129	Uralite-gabbro	50	50	1850
SH117	Hypersthene-gabbro	50–52	52½	1550
SH79	Gabbro	55	55	1700
SH67	Olivine-gabbro	58	58	1800
SH13	Coarse olivine-gabbro	60	61	1650
SD23	Sheared gabbro (amphibole and plagioclase)	36	38	1950
SD46	Uralite-gabbro	60	58	1400
SD Peg. II.	Anorthosite from pegmatite pyroxenite	60	59½	1050
SD14	Sheared gabbro (amphibole and plagioclase)	60	61	1250
SD45	Coarse olivine-gabbro	60	61	1250
SD42	Pyroxenite (titanaugite)	62	62½	1250
SD13	Sheared gabbro (amphibole and plagioclase)	66–68	63½	1350
SD78	Gabbro (melanocratic)	65	64½	1000
SG81	Uralite-gabbro	60	56	1400
SG41	Uralite-gabbro	60	56½	1150
SG16	Uralite-gabbro	60	57½	1100
SG1	Olivine-gabbro	65	62	1100
SG109	Uralitized gabbro	65	64	1000
SG30	Anorthosite with titanaugite	70	66	1300
SG65	Olivine-gabbro	70	68	1100

layered intrusion. The size of any original magma chamber giving rise to these rocks is hypothetical. The structural relationship between the three outcrops and the country rocks is not yet elucidated and, therefore, the area of any magma chamber need not have been sufficient to include the outcrops in their present position. However, if the three outcrops represent part of the same layered intrusion an *exact* correlation between Sr and An (to give, graphically, a smooth line with only analytical scatter) is not necessarily to be expected. The layered intrusions at Gul-Sakar, Dudub, and Hamar may, of course, have been part of two or three separate intrusions and then the parent magma and cooling histories might well have been similar in order to produce the An–Sr relationship found.

Fourteen plagioclase feldspars were separated from rocks in the Rakdasafaka area (fig. 3). Their An range was An_{75} to An_{56} compared with An_{68} to An_{48} for the feldspars from the three other areas and it was anticipated that comparable Sr values would result; however, the Sr contents of the plagioclase feldspars from Rakdasafaka are distinctly higher, and none of the points representing Sr versus An in these feldspars is in the field or band occupied by those representing other feldspars; this is well seen in fig. 4.

TABLE II. Anorthite and Sr contents of plagioclases from Rakdasafaka layered series. The arrangement is in order of layering. See appendix for the quality of the data. Localities shown in fig. 3.

Unit number, code, and description of host rock.			Plagioclase composition.		
			An (opt.)	An (chem.).	Sr (p.p.m.).
5	SR51	Troctolite	67	67	1650
4	SR76	Olivine-gabbro	62	65	2200
	SR69	Olivine-leucogabbro	60	62	2100
	SR66	Olivine-gabbro	62	61	2100
3	SR64	Anorthositic troctolite	57	56	2200
	SR45	Uralite-gabbro	62	59	2350
	SR44	Uralite-gabbro	62	64	1950
2	SR43	Anorthositic troctolite	55	56	2200
	SR40	Olivine-gabbro	59	$61\frac{1}{2}$	2000
	SR30	Layered olivine-gabbro	70	73	1850
	SR83	Layered olivine-gabbro	73–75	74	1800
1	SR88	Troctolite	65	69	1750
	SR92	Layered olivine-gabbro	70	$70\frac{1}{2}$	1850
	SR93	Layered olivine-gabbro	75	—	1800

It seems an almost inescapable conclusion that rocks now in the Rakdasafaka area were not originally part of the same layered intrusion as those from any of the three other areas. Thus the Rakdasafaka and Hamar layered intrusions are thought to have been derived from independent magmas. As the ferromagnesian minerals take up insignificant amounts of Sr in the Dudub, Hamar, and Gul Sakar masses, a simple explanation for the higher Sr content in the Rakdasafaka feldspars compared with those from the other areas is that the parent magmas contained different concentrations of Sr. It would be satisfactory to be able to demonstrate this. However, although there is a sympathetic relationship between Sr and decreasing An in feldspars between the An limits shown in fig. 1, there is no evidence for a quantitative or qualitative relationship between Sr and An for feldspars more basic than An_{75} or more acid than An_{52}. Rocks from Rakdasafaka and Hamar could have been produced from a similar parent magma with the same Sr content in a variety of ways. Feldspars more basic than An_{75} and genetically related to the Rakdasafaka mass might conceivably show a lower Sr content than feldspars (with An exceeding An_{75}) related to the Hamar mass; on the other hand (or additionally), feldspars more acid than An_{56} and genetically connected to the Rakdasafaka mass might show Sr decreasing with decreasing An (cf. Wager and Mitchell), whereas those related to the Hamar mass might continue to show Sr increasing with An decreasing below An_{50}. Such speculative alternatives would involve drastically different conditions of cooling, etc.

Wholesale assimilation of Sr-rich material by that magma giving the Rakdasafaka mass is regarded as a weak possibility as rocks from Rakdasafaka are mineralogically very similar to those from the three other areas.

The petrogenetic use of Sr–An relationships in this area is clear. It is hoped to extend this use by analysing feldspars, when available, from isolated basic and ultrabasic rocks in the general area here described.

Sr in plagioclase from sheared rocks.

The two rocks SD13 and SD14 from Dudub are sheared gabbros. The feldspars therein are relatively large (2×3 mm) and have not been recrystallized during the shearing. Plagioclase from SD13 is $An_{63\frac{1}{2}}$ with 1350 p.p.m. Sr; that from SD14 is An_{61} with 1250 p.p.m. Sr. The sheared gabbro SD23 (fig. 1) is in the same shear zone as SD13 and SD14 but the plagioclase therein has been completely crushed and recrystallized to give granular crystals ($0{\cdot}1 \times 0{\cdot}1$ mm). The composition is An_{38} and is clearly not the original one; during the recrystallization of the feldspar part of the anorthite has been lost (to give epidote) and the plagioclase has become appreciably more acid. Almost all the Sr, however, has been retained in the recrystallized plagioclase. Thus an original plagioclase like that from SD13 could assume a composition of An_{38} by losing anorthite to the extent of 41% of its original weight. If all the Sr is retained in the plagioclase the concentration would be 2300 p.p.m. Sr in An_{38}. A similar calculation for the plagioclase from SD14 gives 2000 p.p.m. Sr in An_{38} by the loss of 37% anorthite on the original weight. In fact, the plagioclase from SD23 is An_{38} with 1950 p.p.m. Sr, and it is completely plausible that it has recrystallized from a plagioclase of An and Sr composition similar to those in SD13 and SD14 by the loss of appropriate anorthite and the nearly complete retention of Sr.

Feldspars from the Hamar rocks SH1 and SH5 pose rather different problems; neither of the rocks is sheared and original feldspar has not been recrystallized. SH1 is amphibole-gabbro with brown hornblende, plagioclase, and monoclinic pyroxene as principal constituents. It is in an area where marginal contamination is a possibility. The adjacent country rock is a pelite with approximately 200 p.p.m. Sr and any mixture of this pelite and gabbro magma would lower the Sr concentration in the magma. This may partly explain the low Sr content of 1300 p.p.m. in the An_{41} feldspar. Sr in the associated hornblende is below 50 p.p.m.

However, if assimilation of pelites is a partial explanation for the low Sr in the plagioclase from SH1 it cannot also be an explanation for the very high Sr (2650 p.p.m.) in the plagioclase (An_{35}) from SH5. The rock SH5 is an amphibole-gabbro similar to SH1 and with brown hornblende. It is a tentative suggestion that SH5 is higher in the layered sequence than so far suspected on field evidence. Any relatively acid feldspar might be expected to contain more Sr than found in feldspars from SH106 (An_{48}) or SH129 (An_{50}).

Nevertheless, the marginal rocks including contaminated and uralitized types need to be further studied both in the field and laboratory before tentative conclusions become acceptable.

Appendix.

Plagioclase was determined optically on cleavage fragments by the Tsuboi method. Na was determined on the same material by the usual flame photometric method. K is low throughout and does not exceed the equivalent of Or 1 to 2. Ab contents were calculated from the Na contents and An values derived by subtracting from 100 and, therefore, ignoring the small Or contents. An values are, therefore, less accurate than Ab values but An values are given in the tables and figure as An is most often quoted in the relevant literature. Sr was determined using an A.R.L. Production X-ray Quantometer (40 kV, 30 mA, W-target tube OEG-60; integration time 300 sec with an argon-filled proportional counter); the method is similar to that described by Lucchesi (1957). 100 mg feldspar were mixed with 10 mg of a Yt_2O_3–Al_2O_3 mixture to give an approximate concentration of 2000 p.p.m. Yt in the total. The resulting finely-ground powder was inset into a cellulose disk compressed at 10 000 lb/in.^{2} Integrated Yt–Kα irradiation was used as an internal standard to integrated Sr–Kα irradiation; background corrections were made from the average of integrated intensities $\pm 0{\cdot}025$ Å from either line. Synthetic standard of Specpure $SrCO_3$ in a plagioclase-like base made of quartz, Specpure $CaCO_3$, Na_2CO_3, and Al_2O_3 were employed. The standard deviation of the Sr result is calculated to be ± 100 p.p.m.

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