Chemical variations in members of the fergusonite–formanite series.

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[Read 28 January 1960.]

Summary. Attention is drawn to anomalies in the nomenclature of the niobate-tantalates, and the fergusonite series as used by Dana is renamed the fergusonite–formanite series. Chemical variations in this series are discussed with particular reference to H_2O, Ca, Ti, Yt, individual lanthanons, Th, and U. Members of the series usually show heavy lanthanons exceeding light lanthanons but one specimen shows high Gd+Tb+Dy.

Nomenclature.

THE compositional vagaries of the niobate-tantalates have, not surprisingly, led to numerous difficulties in their nomenclature. For example, the adoption of the term *series* to include minerals varying in composition between two end members is no indication that solid solution is complete or continuous in that series; and usually synthetic work is lacking. However, in the columbite–tantalite series wide variation in the Nb:Ta ratio is well established and it is reasonable to assume that Nb and Ta can similarly replace each other in a variety of minerals—indeed perhaps in all niobate-tantalates. Nevertheless, samarskites are generally assumed to have high Nb:Ta ratios whereas yttrotantalites can be held to differ compositionally from samarskites only in having low Nb:Ta ratios (although lanthanon distribution may be relevant). Mineral series in which the Nb:Ta ratios are the principal variant include the pyrochlore–microlite series as well as the columbite–tantalite series. However, the fergusonite series (Dana, 1955) includes fergusonite (Nb-rich) and the variety formanite (Ta-rich) whereas the tapiolite series includes tapiolite (Ta-rich) and the variety mossite (Nb-rich). It would be better to refer to these series respectively as the fergusonite–formanite series and the mossite–tapiolite series, with mention of the Nb-rich member first. Minerals of the former series will be referred to in this paper as fergusonite-formanites when the atomic ratio Nb:Ta is unknown, fergusonites when Nb $>$ Ta and formanites when Nb $<$ Ta. A minor difficulty can be anticipated for a mineral in which the determined atomic ratio Nb:Ta is, for example, 1·00±0·04, where 0·04 represents the standard deviation of the analytical method employed. Such a mineral could be described as 'fergusonite (Nb:Ta = 1·00±0·04)' or possibly as fergusonite/formanite.

Minerals for which the given ratio for Nb:Ta differs from 1 by the standard deviation or less could be referred to as fergusonites or formanites followed by a statement of the relevant data, e.g. 'fergusonite (Nb:Ta = 1·03±0·05)' and 'formanite (Nb:Ta = 0·98±0·03)'. Such examples are not likely to be common.

General chemical characteristics.

Members of the fergusonite–formanite series are chemically the least complex among the rare-earth niobate-tantalates; if only the essential elements Nb, Ta, Yt, Ln, and O are considered then they correspond to isomorphous mixtures of the two end members $Nb(Yt,Ln)O_4$ or fergusonite and $Ta(Yt,Ln)O_4$ or formanite. Analyses of typical members of the series show $(Yt,Ln)_2O_3$ and $(Nb,Ta)_2O_5$ totalling 85 % or more and prominent elements accounting for the remainder include H, Ca, U, Th, and Ti. Thus H, reported as H_2O or ignition loss, often exceeds 2 % (H_2O) and may reach 8 % in what can be regarded as slightly altered specimens. Ca is usually between 1 and 3 % CaO and doubtless substitutes for the rare-earth group, which has long been known to be rich in Yt-earths and poor in the Ce-earths (Goldschmidt and Thomassen, 1924; and Bjørlykke, 1935). U is often between 1 and 4 % but on occasions exceeds 8 %; the atomic ratio $(Yt,Ln)^{3+}:U^{4+}$ rarely falls below 8 and is generally above 15, and these moderate amounts of U may be assumed to occupy positions structurally equivalent to (Yt,Ln) positions in the original non-metamict mineral. Th varies from below 0·5 % ThO_2 to about 5 % ThO_2 but is generally up to 2 %; it substitutes for the rare earths and in Th-rich specimens the atomic ratio $(Yt,Ln)^{3+}:Th^{4+}$ may be as low as 10. Ti, substituting for Nb and Ta, is normally below 2 % TiO_2, when the atomic ratio (Nb+Ta)/Ti is 10 or more. It is possible that there are graduations between members of the fergusonite–formanite series and the variety risörite, which contains about 6 % TiO_2 and has the atomic ratio (Nb+Ta)/Ti approximately equal to 4. The type risörite contains nearly 2 % CaO and scarcely any U so the substitution of Ti might have been limited by the over-all charge conditions arising from the differing valencies between 4-valent Ti and 5-valent Nb and Ta. Nevertheless limited substitution of Ti is a characteristic not only of members of the fergusonite–formanite series but also of samarskites and yttrotantalites where the possible additional change $Fe^{2+} \rightarrow Fe^{3+}$ might be held to favour more substantial substitution of Ti for Nb and Ta. In Ti-rich niobate-tantalates the atomic ratio (Nb+Ta)/Ti is generally below 2 and the few multiple oxide minerals containing Ti, Nb, and Ta that have values of this ratio between 2 and 4 are not confined to the same mineral species. Ti is thus only partially able to fulfil the role of Nb or Ta despite close ionic radius similarities. Synthetic studies in the system TiO_2–Yt_2O_3–$(Nb,Ta)_2O_5$ would be of particular interest in deciding the behaviour and influence of Ti.

Assuming that Yt-earths dominate throughout the fergusonite–formanite series, total rare earths are lower in formanites than in fergusonites owing to the higher atomic number of Ta. Fergusonites frequently contain over 40 % $(Yt,Ln)_2O_3$ but in the type formanite $(Yt,Ln)_2O_3$ sinks to 32 % (Simpson, 1909). Such low percentages compare with those from certain samarskites but a distinction is, perhaps, possible on consideration of the Fe contents—scarcely above a few per cent. in fergusonite-formanites and approaching 10 % or more in samarskites (and yttrotantalites).

Analytical methods and identification.

The following methods were used to obtain the data in tables I and II. Total rare-earth plus thorium oxides were determined via fluorides, perchlorates, and oxalates as previously described (Gordon *et al.*, 1949; and Butler, 1957*a*); individual rare earths were determined on the separated $(Yt,Ln)_2O_3+ThO_2$ mixtures using an optical spectrographic method (Butler, 1957*b*), and it was confirmed from the spectrograms, using Th 4412·74 Å., that Th was below about 1–2 % in the oxides from nos. 3, 5, 7, 8 and 10, but somewhat richer in oxides from nos. 2, 6, and 9. In specimen no. 1 ThO_2 was determined by the method of Meyer and Speter (1910) and TiO_2 by the peroxide method. Oxides of Nb+Ta together were determined chromatographically (Mercer and Wells, 1954) and checked for absence of W and Ti using optical spectrographic methods; individual Nb and Ta oxides were determined on the separated $(Nb,Ta)_2O_5$ using an A.R.L. Production X-ray Quantometer and calibrating against mixed oxide standards. Optical spectrograms were recorded of minerals nos. 2–10 (and of numerous other rare-earth niobate-tantalates) using operating conditions as for individual rare-earth determination but using Ilford N. 30 photographic plates 10″×4″ and recording in the range 3600–2500 Å. with a Hilger large quartz prism spectrograph (E742) giving a plate separation of 1 mm. for lines differing in wave number by 40. Chemically analysed minerals including type specimens were used as standards and the following additional semi-quantitative data were obtained: CaO was below 2 % throughout; Fe was below 1 % for nos. 2–6 and 8–10 but a little above 1 % for no. 7; TiO_2 was below 3 % for nos. 2–5 and 8–10, and between 3 % and 6 % for nos. 6 and 7; Al_2O_3 was below 1 % throughout; SiO_2 was below 2 % for nos. 2–6, 8, and 10, but appreciably above 2 % in nos. 7 and 9; U was highest in no. 7 which contained approximately $3\frac{1}{2}$ % U (anal. Mountain, 1935); Zr was below 1 % in all specimens except for no. 7, which contains major quantities of Zr. Table I shows analytical data for ten members of the fergusonite–formanite series arranged in order of decreasing $(Yt,Ln)_2O_3+ThO_2$. All the minerals except no. 10 give X-ray diffraction patterns closely similar to each other after suitable heat-treatment (Berman, 1955). That for the Ta-rich specimen no. 10 gave a pattern difficult to correlate with the others but with affinities to those of a heated yttrotantalite from Ceylon and a Ta-rich samarskite (or an yttrotantalite with marked Gd+Tb+Dy enrichment in the lanthanons) from Mtoko district, Southern Rhodesia. Specimen no. 10 is considered to be formanite rather than yttrotantalite on account of its chemical composition, especially its low Fe content (below 1 %).

It is considered that the data in table I together with subsidiary X-ray and optical spectrographic data are sufficient to confirm that all the specimens nos. 1–10 are members of the fergusonite–formanite series. The low partial total in table I for sample no. 6 is due to appreciable Ti and that for no. 9 is due to silicate contamination (which will not affect rare-earth distribution or the Nb:Ta ratio). Specimen no. 7 is part of that collected by Prof. E. Mountain (1935) and described as embedded in 'grey or greyish brown matrix which on analysis proves to be a form of zircon'; we have confirmed the high Zr and Si content but see no lines of zircon in the X-ray photograph.

Niobium and tantalum variations.

Specimens nos. 1–9 inclusive are all Nb rich (table I) with the fergusonites from Nedenäs (no. 6) and Boksput (no. 7) nearest to the theoretical Nb-pure end member in the series. The atomic ratio Nb:Ta remains above 23 for specimens nos. 2, 3, and 9 but drops below 9·0 for the remaining fergusonites. The latter may be regarded as fergusonites containing moderate amounts of Ta. No mineral shows Nb:Ta between, say, 5 and $\frac{1}{5}$ and there is no example here of a formanite

TABLE I. Analytical data for members of the fergusonite–formanite series. Total rare-earth oxides (of formula shown) plus thoria, niobium plus tantalum oxides, and ignition loss determined chemically as wt. % on mineral basis. Individual rare earths were determined spectrographically in and on the basis of chemically separated rare earth plus thorium oxides for nos. 1–10 (Sc_2O_3 and Eu_2O_3 below 0·1 % throughout, La_2O_3 below 0·1 %, and Pr_6O_{11} below 0·3 % where indicated by *. No data for Ho_2O_3). R^{3+}, ionic radii (Å.) of trivalent rare-earth cations. $\hat{\sigma}$, percentage standard deviations of estimate of individual rare earths for duplicate spectrograms (cols. 1–10); for bracketed values $\hat{\sigma}$ is increased by up to √2.

	R^{3+}	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	$\hat{\sigma}$.	11.
$(Yt,Ln)_2O_3+ThO_2$...	—	43·30	42·60	42·42	42·35	41·43	40·33	37·16	35·76	33·91	31·04	—	31·33
$(Nb,Ta)_2O_5$	—	n.d.	42·14	47·44	45·91	44·20	38·88	37·15	51·36	35·19	55·42	—	52·10
Ign. loss	—	n.d.	2·95	1·31	1·77	2·92	3·79	2·71	5·70	5·52	n.d.	—	—
Sum...	—	43·30	87·69	91·17	90·03	88·55	83·00	77·02	92·82	74·62	86·46	—	88·23
Nb:Ta (at.)	—	n.d.	24	28	6·7	8·8	30	33	6·2	26	0·07	—	0·09
Yt_2O_3	0·92	54·1	55·0	59·9	64·4	57·1	58·0	56·3	63·5	47·0	62·0	5	63·8
La_2O_3	1·14	*	0·10	*	0·15	*	*	*	*	0·21	*	7	0·36
CeO_2	1·07	0·83	0·67	0·76	1·60	0·20	0·47	0·71	(0·4)	1·05	0·79	7	0·72
Pr_6O_{11}	1·06	*	*	0·39	0·68	*	*	0·33	*	0·55	0·42	7	0·51
Nd_2O_3	1·04	2·24	1·18	1·90	5·89	1·03	0·96	1·92	0·56	2·67	2·38	5	2·06
Sm_2O_3	1·00	1·90	(1·38)	2·28	6·50	(1·7)	(1·15)	1·86	(0·6)	3·56	2·19	5	3·08
Gd_2O_3	0·97	5·95	4·55	5·50	10·2	5·20	3·62	4·90	2·11	8·17	2·52	6½	3·12
Tb_4O_7	0·93	1·09	1·18	1·27	1·73	1·51	0·90	1·14	(0·7)	1·78	(0·7)	6	0·62
Dy_2O_3	0·92	7·94	6·95	8·65	8·11	10·5	5·56	7·35	4·73	10·5	3·60	5	3·98
Er_2O_3	0·89	7·77	9·46	7·94	1·80	11·6	7·25	8·38	7·50	7·45	4·48	13	5·43
Tm_2O_3	0·87	1·01	1·18	1·00	(0·16)	1·07	0·90	1·02	1·10	0·77	0·88	7	1·45
Yb_2O_3	0·86	(14·4)	10·1	6·83	1·30	7·35	12·5	10·7	15·9	8·58	15·8	5	9·77
Lu_2O_3	0·85	0·86	1·29	0·82	(0·24)	0·93	1·05	1·28	1·55	0·83	1·7	20	2·06
ThO_2	—	6·10	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	—	—
Sum...	—	104·19	93·04	97·24	102·76	98·19	92·36	95·89	98·65	93·12	97·46	—	—

containing moderate amounts of Nb—both the Cooglegong (no. 10) and Marble Bar (no. 11) formanites have Ta exceeding Nb by at least 10 to 1 on an atomic basis. There is a large range in Nb:Ta ratios not met with in these or other members of the fergusonite–formanite series recorded in the literature. This is in contrast to the reasonably wide variation for the atomic ratio Nb:Ta recorded in samarskites: for example, from Mt. Painter, South Australia, 31 (Kleeman, 1946); from Ta-fang-Shên, south Manchuria, 11 (Takubo, 1952); and from Ryujomen, Korea, 3·4 and 1·2 (Imori and Hata, 1938). Moreover, typical atomic ratios Nb:Ta for yttrotantalites are 0·86 from Berg, Norway (Brøgger, 1906); 0·50 from Sweden (the authors, unpublished); and 0·35 from Minas Gerais, Brazil (Peixota and Guimarães, 1953). These data suggest that it will be worth while comparing Nb:Ta ratios from associated fergusonite and samarskite. It would also be useful to know comparative ratios for the associated pairs fergusonite–columbite and formanite–tanteuxenite.

Theoretically the ratio $(Nb,Ta)_2O_5$:$(Yt,Ln)_2O_3$ should widen as the Nb:Ta ratio increases (provided Yt remains the dominant rare earth) but such a correlation is difficult to see for minerals nos. 1–9 even allowing for approximate ThO_2 estimates. Nor is there any clear trend for the ratio Nb:Ta with changing Yt content as, for example, Yt in total rare earths.

Rare-earth variations.

Table I shows the individual rare earths (determined spectrographically) in the total rare earth plus thorium oxides separated from the

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1. Fergusonite–formanite, North Carolina, U.S.A. (ThO_2 = 2·77 %, TiO_2 = 2·20 %).
2. Fergusonite, var. risörite, Gryting, near Risør, Norway.
3. Fergusonite, Ceylon.
4. Fergusonite, Julianehaab, Greenland (B.M. 26899).
5. Fergusonite, Rullandsdalen, nr. Risør, Norway (G.M., Oslo; T. Tørjesen, Nov. 1923).
6. Fergusonite, var. risörite, Nedenäs, Norway (B.M. 1911, 198).
7. Fergusonite, intimately mixed with a form of zircon, Boksput farm, south-west corner of Gordonia, South Africa (B.M. 1931, 448, pres. E. D. *Mountain*).
8. Fergusonite, Rakwana, Ceylon (B.M. 67650 g.).
9. Fergusonite, var. tyrite, Helle, Arendal, Norway (B.M. 55162).
10. Formanite, Cooglegong, Western Australia.
11. Formanite, Marble Bar district, Western Australia. Anal. Wylie (1954); sum includes TiO_2 = 2·50 % and U_3O_8 = 0·30 %; ThO_2 = 0·13 % and Fe_2O_3 < 0·1 %; Ho_2O_3 = 1·12 %, La, Gd, Tb, and Lu values are approximate and Eu_2O_3 = tr.

minerals nos. 1–10. It will be seen that the totals vary between 92 and 104 %; this is owing to lack of data for Ho (possibly 1 % and above throughout) and Th, which lead to low summations, and to errors in the spectrographic analysis, which lead to either high or low summations. Yt is the dominant rare earth throughout and on an atomic basis varies between 63 % (no. 9) and 75 % (nos. 8 and 10) in the total rare earths, excluding Ho. This variation is small and there is no indication of any correlation between the Yt content and that of any other constituent.

TABLE II. Atomic percentages of lanthanons in total lanthanons. Nos. 1–10 on an Ho-free basis; no. 11 Ho = 3·23 % (Wylie, 1954). Localities as in table I (*Z*, atomic number).

	Z.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
La	57	—	0·30	—	0·43	—	—	—	—	0·52	—	1·21
Ce	58	2·04	1·93	2·20	4·35	0·53	1·52	1·88	1·27	2·45	2·46	2·41
Pr	59	—	—	1·14	1·87	—	—	0·88	—	1·30	1·31	1·53
Nd	60	5·70	3·48	5·60	16·4	2·80	3·17	5·20	1·82	6·40	7·57	6·70
Sm	62	4·67	3·96	6·50	17·5	4·5	3·38	5·33	1·88	8·25	6·72	9·62
Gd	64	14·1	12·3	15·8	26·4	13·2	11·1	12·3	6·39	18·2	7·52	9·39
Tb	65	2·49	3·12	3·37	4·32	3·69	2·66	2·77	2·04	3·82	2·0	1·84
Dy	66	18·3	18·5	23·0	20·4	25·8	16·5	17·9	13·9	22·6	10·3	11·7
Er	68	17·4	24·6	20·6	4·41	27·8	21·0	24·3	21·4	15·7	12·5	15·3
Tm	69	2·22	3·03	2·56	0·39	2·53	2·58	2·40	3·10	1·60	2·42	4·38
Yb	70	31·3	25·4	17·2	3·00	17·0	35·1	24·7	44·0	17·5	42·6	27·1
Lu	71	1·85	3·19	2·02	0·56	2·14	2·92	2·34	4·25	1·68	4·55	5·55

Variation amongst the lanthanons is, however, appreciable as seen in table II showing the atomic percentage of lanthanons in total lanthanons excluding Ho. The variation is greatest towards the ends of the lanthanon series and least for Gd, Tb, and Dy. The small variation in Dy, with an identical ionic radius to that of Yt, is to be expected in view of the narrow Yt variation. The total of Gd+Tb+Dy also varies modestly from 20 % in no. 10 to 51 % in no. 4 and, therefore, the minerals as a group are not particularly enriched in the middle lanthanons. Eu is below sensitivity (0·1 % Eu_2O_3 in the oxides) throughout, concurring with the low content found for Eu in fergusonites by Semenov and Barinsky (1958). Wylie (1954), however, originally reported 5·7 % Eu in lanthanons from a Western Australian formanite but has later amended his figure, as an ion exchange separation confirmed the general trends of the rare-earth distribution given, but showed the spectrophotometric values for Eu and La to be in error; preferred values are Eu = tr. and La = approx. 1 % (Dr. Wylie, personal communication). Wylie's amended data are given in table II, col. 11, and it will be observed that reasonable agreement obtains for lanthanon distribution and values in this formanite and in the one analysed here (table II, col. 10) which has a similar Ta content and also comes from Western Australia.

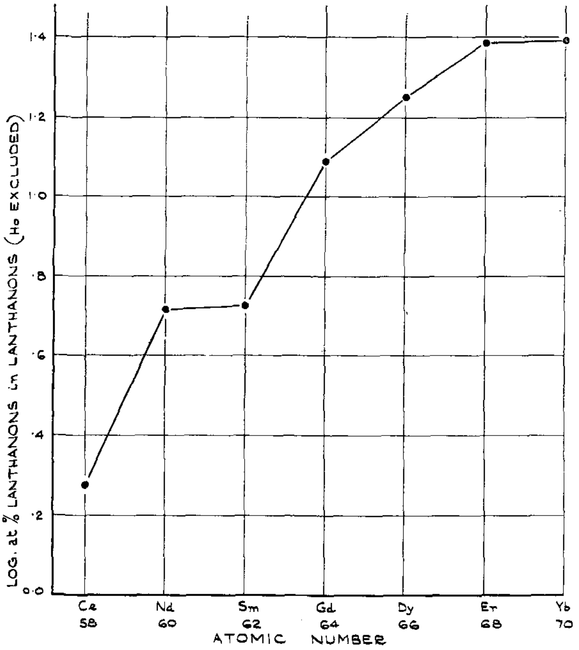

FIG. 1. Lanthanon distribution in fergusonite, Boksput farm, south-west corner of Gordonia, South Africa (B.M. 1931, 448).

Yb is the most abundant lanthanon (on an atomic basis) in minerals nos. 1, 2, 6, 7, and 10; indeed in the latter two samples it is nearly as abundant as all the remaining lanthanons taken together. Fig. 1 shows the relationship between lanthanon concentration and atomic number for the fergusonite from Gordonia, South Africa (no. 7). The distribution pattern shows the impoverishment of Ce and the tenfold concentration build-up to the peak concentration of Yb with Er almost as abundant. The distribution pattern is typical for fergusonites in that a reasonably 'smooth curve' results from the joining of the points representing *Z*-even lanthanon abundance—with the exception of Sm which is known to be nearer Gd than Nd in abundance in the lithosphere. A smooth distribution pattern in itself might not mean very much. A mineral which shows a high degree of intolerance (like samarskite or thortveitite) to lanthanon ions outside a limited size range will give a smooth pattern irrespective of the composition of the fluid from which it crystallized; a mineral able to accept into its lattice the whole ionic size range of the lanthanons (like yttrotungstite or gadolinite) will give a smooth distribution pattern only if that for the lanthanons in the mother fluid is smooth. Members of the fergusonite–formanite series clearly have moderately strong selectivity for the heavier lanthanons (nos. 1, 2, 6, 7, 8, and 10) and it is therefore hazardous to conclude much about the composition of the mother fluids except to suggest that they are not the result of the removal of the middle lanthanons Sm and Gd from a fluid containing lanthanons proportionately abundant as in the average lithosphere. This is brought out in fig. 2, which shows a plot of atomic number against the ratio of the atomic abundance of the Z-even lanthanons in fergusonite no. 7 to that in the lithosphere (Suess and Urey, 1956). When the points are joined a reasonably smooth curve without depressions or minima for Sm or Gd results. Reasonably similar curves are obtained for specimens nos. 1, 2, 6, and 8. Formanite no. 10 shows the

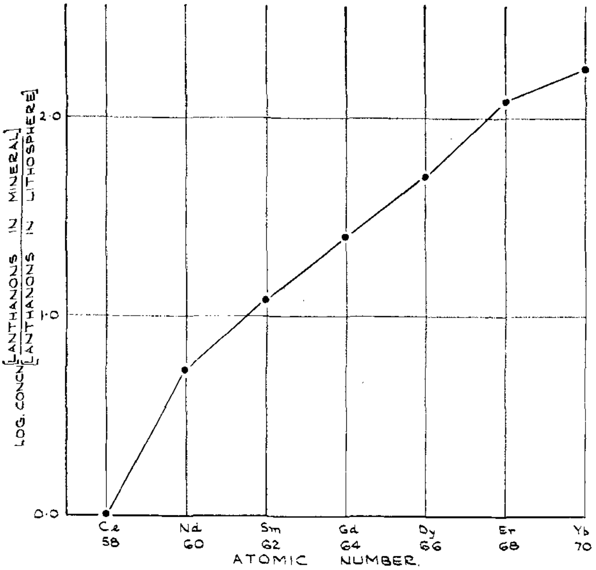

Fig. 2. Lanthanon distribution (Ce ratio taken as 1·00) in fergusonite of fig. 1 compared with that in the lithosphere.

highest Yb enrichment of the samples analysed and the distribution pattern is shown in fig. 3; compared with the other samples it could be described as rich in Nd and poor in Sm, Gd, and Dy. Fig. 4, however, shows the concentration of the lanthanons in the mineral relative to that in the average lithosphere and the arrangement of the points suggests that the formanite *may have crystallized from an environment* poor in Gd and Dy (and Er) rather than from one enriched in Nd and Sm relative to Ce. Such a suggestion presupposes that formanite does not tend to concentrate Sm as well as Yb and exclude lanthanons with intermediate sizes (e.g. Gd and Dy); but it seems unlikely that formanites will concentrate lanthanons in a way peculiar to davidite (Dixon and Wylie, 1951, and unpublished work by the authors) whereas fergusonites do not. Also shown in fig. 4 is the plot from the data of Wylie (table II,

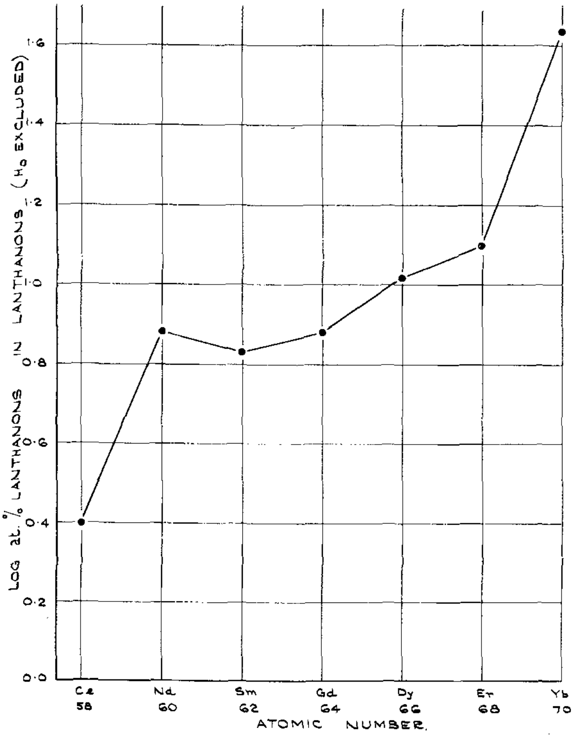

FIG. 3. Lanthanon distribution in formanite, Cooglegong, Western Australia.

col. 11) on formanite from Marble Bar, Western Australia. The curves are strikingly similar and it is suggested that both the Cooglegong and the Marble Bar formanites have a similar paragenesis.

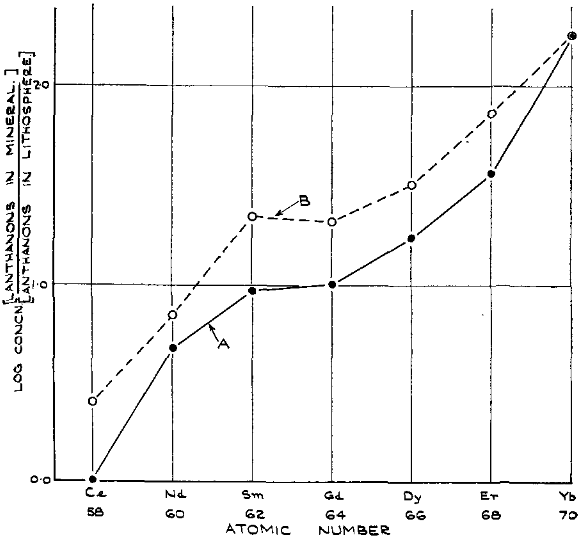

Fig. 4. Lanthanon distribution in formanite of fig. 3 (A with Ce ratio taken as 1·00) and formanite, Marble Bar, Western Australia (B with log Ce ratio taken as 0·20); after Wylie (1954), each compared with that in the lithosphere.

Peak Yb concentration has been observed by Semenov and Barinsky (1958) in their recent informative paper. Using X-ray methods they analysed seven members of the fergusonite–formanite series (all described as fergusonite but without data on Nb or Ta) and found Yb the commonest lanthanon throughout. This is so whether their figures are taken to refer to wt. % or to atomic %. Distribution patterns for their fergusonite–formanite from Iveland, Norway (no. 65), and those for minerals nos. 1, 2, 6, 7, 8, and 10 in this paper are broadly similar; that for their mineral from Sabaragamuwa, Ceylon (no. 71), resembles that for our formanite no. 10. Their remaining minerals, however, show Ce exceeding Nd. In their specimen from Evje, Norway (no. 70), Ce is nearly five times the concentration of Nd (fig. 5), which indicates that either the mother fluids were exceptionally rich in Ce with respect to Nd or that certain members of the fergusonite–formanite series are able to incorporate Ce into the lattice with appreciably greater ease than Nd.

Incidentally Semenov and Barinsky show eight out of twelve members of the euxenite–polycrase series with Ce more abundant than Nd (3 samples from the same locality) and this is also in contrast to the findings of Bjørlykke (1935) and Butler (1958). Curiously, of the thirteen gadolinites analysed only three show Ce more abundant than Nd and yet gadolinite is a complete-assemblage type mineral whilst members of both the fergusonite–formanite series and the euxenite–polycrase series are held to be selective towards the heavier lanthanons.

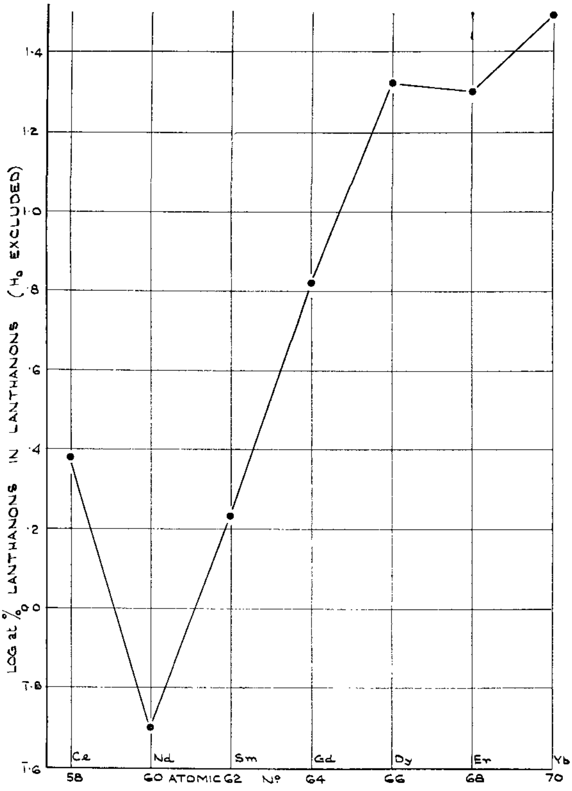

FIG. 5. Lanthanon distribution in fergusonite–formanite, Evje, Norway, after Semenov and Barinsky (1958).

Fig. 6 shows the lanthanon distribution in the fergusonite from Rullandsdalen, Norway (No. 5), and it is seen that Er is more abundant than Yb. Roughly similar distribution curves obtain for fergusonites nos. 3 and 9 except that Dy is the most abundant lanthanon. The peak uptake of Dy and Er may be due to the low availability of the heavier lanthanons. Alternatively or additionally the average ionic size of the most easily admitted lanthanon size range in the lattice may change somewhat with formational temperature of the mineral and restrict Yb uptake accordingly; unfortunately there is rather little data on the temperature range over which fergusonite can crystallize.

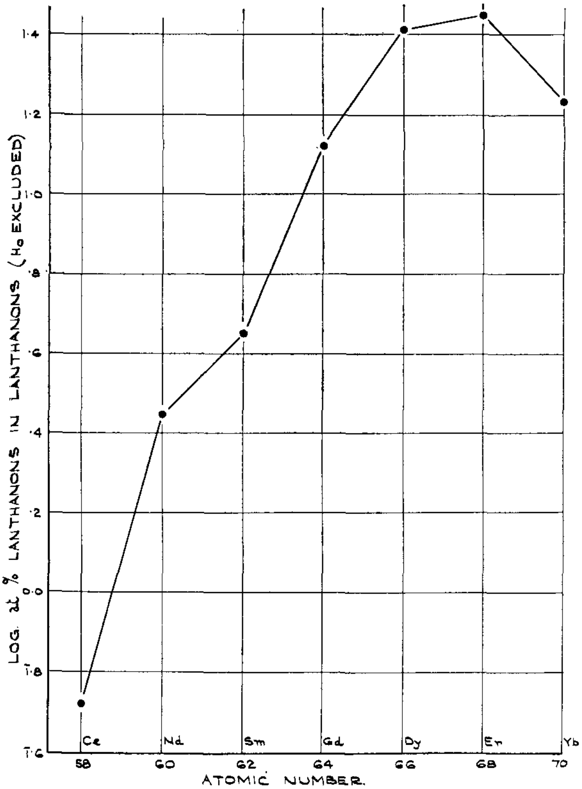

FIG. 6. Lanthanon distribution in fergusonite, Rullansdalen, near Risør, Norway.

Fig. 7 shows the distribution of the *Z*-even lanthanons in the fergusonite from Julianehaab, Greenland (no. 4), and it is at once seen that the pattern is distinct from all those obtained for the other members of the fergusonite–formanite series. Gd is the most abundant lanthanon and even Tb exceeds Yb which is the least abundant *Z*-even lanthanon.

On an atomic basis Gd+Tb+Dy exceed 50 % in the lanthanons (Ho excluded)—a property that has tentatively been ascribed as characteristic of samarskites (Butler, 1958; and Semenov and Barinsky, 1958). Fig. 8 shows the relationship between the atomic number of the *Z*-even lanthanons and the ratio of concentration of the lanthanons in mineral no. 4, compared with that in the lithosphere; comparative data are plotted for a previously described samarskite from Brazil. The two curves are sensibly close even though Dy is at the summit of the curve for the samarskite. A probable explanation for the unusual lanthanon distribution in the Greenland fergusonite is that it crystallized from an environment very depleted of Er and Yb; nevertheless, the fact that fergusonite is formed indicates a tolerance to lanthanons of middle size not suspected in considering data for all the other fergusonites. The problem of the impoverishment of the heaviest lanthanons (e.g. Yb and Er) from a rare-earth assemblage by mineral crystallization remains. Thortveitite seems to be capable of concentrating Yb to an extreme

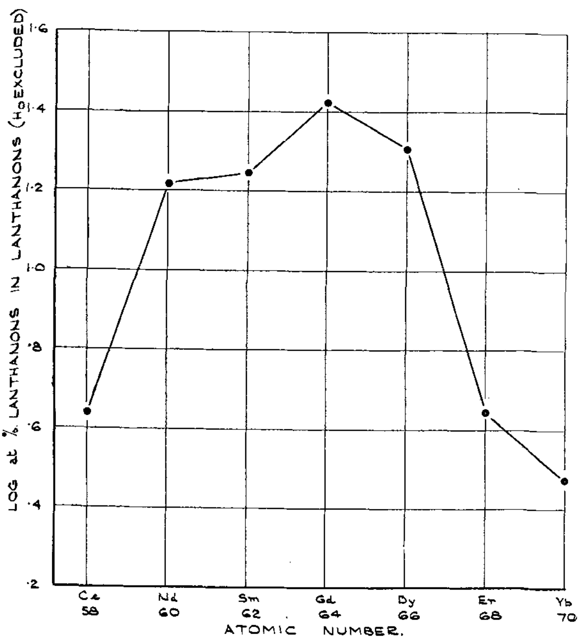

FIG. 7. Lanthanon distribution in fergusonite, Julianehaab, Greenland (B.M. 26899).

degree, but analyses of the mineral are not numerous (Goldschmidt and Thomassen, 1924; Bjørlykke, 1935; and Semenov and Barinsky, 1958). On the basis of more extensive data, xenotime and members of the euxenite–polycrase series are known to favour the heavier rather than the lighter lanthanons (Goldschmidt and Thomassen, 1924; Bjørlykke, 1935; Semenov and Barinsky, 1958; Butler, 1958; and Carron *et al.*, 1958), but their selectivity is on a par with that of the majority of fergusonites and although the concentration ratio Yb:Er is usually above unity it can be substantially less. It is, of course, possible that other fergusonites from the Julianehaab area will show higher Yb contents, in which case mineral no. 4 would be regarded as a very late stage fergusonite crystallizing from an environment low in Yb and Er due to prior crystallization of more 'normal' fergusonites. It would clearly be valuable to study a number of fergusonites occurring in petrogenetically connected pegmatites and this we propose to do in the future.

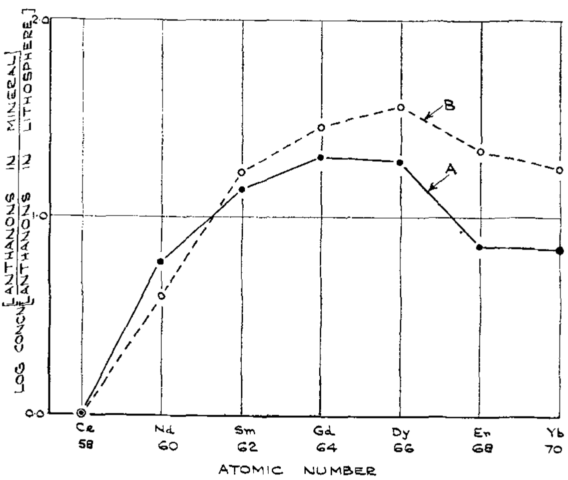

FIG. 8. Lanthanon distribution in fergusonite of fig. 7, (A) and samarskite, Divino Ubá, Minas Gerais, Brazil (B.M. 1926, 296), (B), each compared with that in the lithosphere (Ce ratio taken as 1·00).

Acknowledgements. We wish to thank the curators of H.M. Geological Museum, the British Museum (Natural History), and the Geologisk Museum (Oslo) for providing specimens and the Director of Rothamsted Experimental Station for the loan of the spectrograph used for rare-earth determinations. We have benefited greatly from discussions with J. E. Horne of H.M. Geological Survey (Atomic Division) and would record our thanks.

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