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Geochemical Constraints on the Genesis of the Tellnes Ilmenite Deposit, Southwest Norway

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Abstract

The ilmenite norite of the Tellnes Fe-Ti deposit in the Åna-Sira massif-type anorthosite is connected to a main dike which varies in composition from monzonorite to quartz mangerite. Fine-grained satellite dikes also occur in the vicinity of the main dike.

A number of rock samples have been analyzed for 36 major and trace elements. An Rb-Sr whole-rock isochron (12 samples) gives an age of 930 Ma. Initial Sr isotope compositions of the ilmenite norite, the main dike, and the satellite dikes are 0.7050, 0.7069, and 0.7100, respectively, thus precluding a comagmatic origin without invoking contamination.

The evolution of the main dike can be accounted for by a closed-system fractional crystallization of a monzonoritic magma (that is, without progressive contamination) which gave rise to a series of liquids prior to intrusion. Mass balance calculation permits a two-stage process in which noritic cumulates were subtracted. Trace element behavior is also consistent with such a model.

The satellite dikes represent undifferentiated monzonorites, with trace elements and isotopic ratios implying a source material quite different from that of the main dike monzonorite.

The orebody is made up of ilmenite norite and small amounts of more plagioclase-rich rocks, which plot on linear trends in variation diagrams. It is interpreted as a noritic cumulate which was enriched in dense, oxide-rich magma before being emplaced as a crystal mush. The parental magma was noritic in composition, unsaturated in apatite, and probably derived from the crystallization of the enclosing massif anorthosite. It is not precluded either that it could have given rise to the main dike monzonoritic liquid after being contaminated by lower crustal material. Nevertheless, as an alternative, it is not possible to reject two distinct parental magmas for the orebody and the main dike. They would have evolved in two separated magma chambers, before the tapping of these chambers and simultaneous injection of their contents in the dike.

The main dike illustrates the process by which a quartz mangerite can derive from a monzonoritic magma, and gives support to a comagmatic origin of charnockitic and monzonoritic rocks.

Introduction

THE Tellnes orebody is an ilmenite norite lens emplaced in the Åna-Sira massif-type anorthosite which belongs to the Rogaland anorthosite province (SW Norway; Fig. 1). It accounts for more than 13 percent of the world supply of TiO_2 pigment. The orebody has been extensively studied by Dybdahl (1960) and Krause and coworkers (Gierth and Krause, 1973; Krause and Pedall, 1980; Krause et al., 1985) who provided detailed maps of the area and petrographic data. The major points that emerge from these studies are the following:

1. The ilmenite norite is intrusive into the surrounding anorthosite, as evidenced by sharp contacts, numerous apophyses cutting the host rocks, intrusive breccias, and xenoliths of anorthosite.
2. The mineralogical and chemical composition of the body is rather uniform, though some detailed variation, such as modal enrichment in plagioclase, is observed in some apophyses or along the contact.
3. The sickle-shaped outcrop of the orebody, more than 2.5 km long and 400 m thick, extends on both ends into a dike, called here the "main dike," 5 to 10 m thick and ranging from monzonorite (hypersthene diorite) to quartz mangerite (hypersthene quartz monzonite). The main dike is connected to the northwestern tip of the orebody in perfect geomet-

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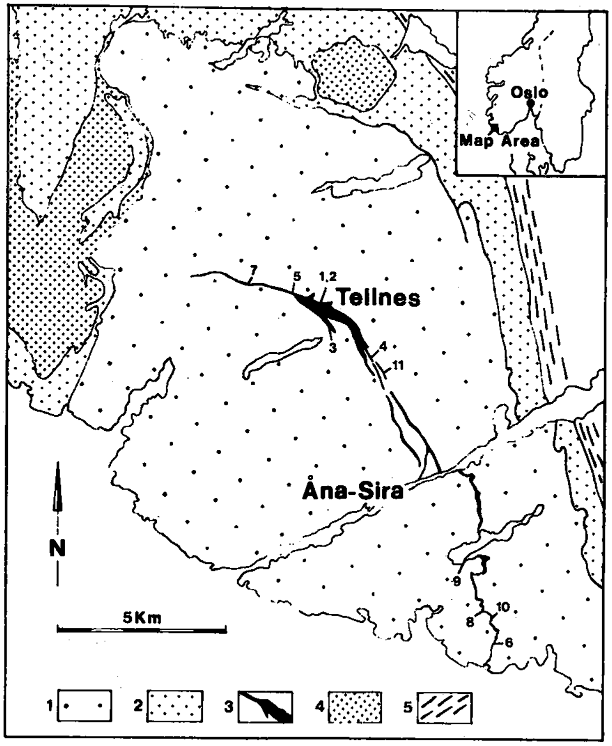

FIG. 1. Schematic geologic map of the Åna-Sira anorthosite massif (after Krause et al., 1985). 1 = anorthosite and leuconorite; 2 = monzonorite, mangerite, and quartz mangerite of the Bjerkreim-Sokndal massif (on the west and north) and of the Apophysis (on the east); 3 = Tellnes orebody and related dikes; 4 = layered norites of the Bjerkreim-Sokndal massif; 5 = metamorphic envelope. The numbers refer to rock numbers in Table 1.

rical continuity and cuts across the surrounding anorthosite for 4 km. In the southwest, it extends more than 10 km.

A fractional crystallization mechanism similar to that prevailing in the neighboring Bjerkreim-Sokndal layered lopolith (Michot, 1965) has been put forward by Krause and Pedall (1980) to explain the occurrence of ilmenite norite together with more evolved products of intermediate and acidic composition in the same simple geologic unit.

The present geochemical study was undertaken in order better to constrain the formation of the orebody and the differentiation mechanism. Moreover, the Tellnes dike appears to be one of the rare cases in which four members of the anorthosite suite (see the reviews of Emslie, 1978, 1985; Morse, 1982; Duchesne, 1984)—i.e., norite, monzonorite, mangerite, and quartz mangerite—unambiguously occur together in a simple geologic structure. Its study can therefore also throw some light on the evolution of anorthosites and related rocks.

Petrography

The ilmenite norite is medium grained (ca. 0.5 mm) and equigranular. Euhedral plagioclases (An_{45-42}), commonly slightly bent and locally granulated, and euhedral bronzite (En_{77-75}) with subordinate olivine (Fo_{80}) are enclosed by an interstitial hemo-ilmenite ($Hem_{13}Ilm_{87}$). Clinopyroxene, apatite, biotite, magnetite, and complex Fe-Ni-(Co)-Cu sulfides are present in minor amounts. Exsolutions of hematite are observed in the ilmenite; the magnetite contains coarse lamellae of zinciferous aluminous spinel which can also form external granules. Subsolidus reequilibration of the two oxides is evidenced by a decrease of the hematite content in the ilmenite toward the contact and by the development of a thin rim of spinelliferous ilmenite at the ilmenite-magnetite contact (Duchesne, 1973). Olivine is rimmed by pyroxene or has broken down to a symplectic intergrowth of orthopyroxene and opaque minerals. Clinopyroxene occurs as granules adjacent to bronzite; subordinate titanian biotite flakes are present in the interstices as a late magmatic phase. Plagioclase and bronzite embedded in ilmenite commonly show a parallel orientation, indicative of cumulate or fluidal processes. None of the minerals are zoned. The contact between the grains is finely interlobate, reflecting late crystallization of the oxide or postcumulus grain boundary adjustment. The average modal composition (in vol %) is plagioclase, 53; ilmenite, 29; orthopyroxene, 10; biotite, 4; magnetite, 0.7 (up to 2.5); and accessories, 3 (Krause et al., 1985). Chemical composition of the minerals shows limited variation between the ilmenite norite and the plagioclase-enriched varieties (e.g., the plagioclase goes down to An_{39}; the Mg number of the pyroxenes is from 0.77 to 0.60).

The monzonorite (= hypersthene monzodiorite; Streckeisen, 1974) from the main dike is a medium-grained, equigranular rock. Antiperthitic plagioclase (An_{28}) and lesser K feldspar (microperthite) form a regular mosaic in which inverted pigeonite develops poikilitic crystals. Apatite (6 wt %) is approximately as abundant as ilmenite and magnetite. Zircon and Fe-Ni sulfides are accessories.

The mangerite (= hypersthene monzonite) has the same texture but contains more K feldspar and mesoperthite-rimmed plagioclase.

The quartz mangerite (=hypersthene quartz monzonite) presents a more heterogranular structure with quartz and mesoperthite of a somewhat larger size than the other minerals. Inverted pigeonite is poikilitic and primary clinopyroxene is more abundant than in more basic rocks. Zircon, apatite, Fe-Ti oxides, and sulfides are accessories. A progressive and continuous variation from monzonorite to quartz mangerite is observed in the dike connected to the northwestern tip of the orebody as well as in many places in the southern dike (e.g., Slottheiknuten; see the sample locations in Fig. 1).

Fine-grained monzonorites (ca. 30 μm) can locally be found either at the 2- to 5-cm-thick margin of the main dike or as dikelets (10 cm–1 m thick)—called here "satellite dikes"—closely associated with the main dike with which they locally show crosscutting relationships. The structure is similar to the coarser grained monzonorite, except that apatite is more acicular, elongated parallel to the wall and dispersed, together with the Fe-Ti oxides, in all other minerals. This structure strongly suggests that the fine-grained monzonorites were aphyric magmas, chilled against the walls.

The granular (mosaic) texture in these rocks is a normal feature of monzonoritic dike rocks in the province (Duchesne et al., 1985b) and is interpreted as a primary magmatic structure.

Geochemical Data

Sixty samples from both the orebody and the dike rocks have been analyzed for major and trace elements. Representative analyses are given in Table 1. The main dike rocks grading from monzonorite to quartz mangerite show geochemical features of the monzonoritic family (Emslie, 1978; Duchesne et al., 1985b): high Ti and P contents, as well as high Fe/Fe + Mg and K_2O/SiO_2 ratios. Some pertinent features are high K/Rb ratios (1,150–600), which fall with increasing SiO_2; chondrite-normalized values for light rare earth elements between 150 and 180 (Fig. 2) with $(La/Yb)_N$ ratios between 5 and 9 and positive Eu anomalies (Eu/Eu* from 1.2 in monzonorite to 1.7 in quartz mangerite); very low U and Th contents, little variation in Zn, and relatively high amounts of Sc compared to Cr and Ni. In variation diagrams, the main dike rocks plot on smooth trends as illustrated by Figure 3. As for the ilmenite norite, the high concentration in ilmenite and sulfides is reflected in the transition element contents; the average rare earth element distribution is similar to that of the monzonorite, with $(La/Yb)_N$ around 8, but is lower by a factor of 7. It shows a distinct positive Eu anomaly (Eu/Eu* = 1.7). A linear trend can be observed toward more plagioclase-rich rocks in all variation diagrams (Fig. 3). Fine-grained satellite dikes differ distinctly from the main dike monzonorites in their high Zr, Hf, and rare earth element contents and in a strong negative Eu anomaly (Eu/Eu* = 0.38). They are, however, depleted in K, Rb, and Ba.

Sr isotope ratios measured on 17 samples (Table 2) are plotted in an $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ diagram (Fig. 4). Three important points should be emphasized:

1. The 12 samples from the main dike are consistent with an isochron giving an age of 930 ± 21 Ma (2 σ) and an Sr isotope initial ratio (I_{Sr}) of 0.70686 ± 0.00018 (2 σ). Although the MSWD value is rather large (ca. 12), this age is quite consistent with the U-Pb zircon age of 940 to 950 Ma obtained by Pasteels et al. (1979) on other monzonoritic dikes in the same province.
2. The four samples from the orebody give an I_{Sr} ratio close to 0.7050, in agreement with the values found in the Åna-Sira anorthosite (Duchesne and Demaiffe, 1978) but significantly lower than that of the main monzonoritic dike.
3. The samples from two fine-grained satellite dikes on the contrary give ratios close to 0.710, which represents the maximum value found in the area for monzonorites.

Discussion

The variation diagrams and the isotopic data clearly indicate that the main dike, the orebody, and the satellite dikes are not comagmatic. We will discuss separately the formation of these various units and then envisage the process of emplacement and the source of the magmas.

The main dike

The Rb-Sr whole-rock isochron for the main dike rocks gives the correct age; the linear relationship observed in the isochron plot cannot be interpreted as a mixing line. The differentiation mechanism can thus be considered, as a first-order approximation, to have taken place in a closed system, without progressive contamination. (We interpret the small scatter of points around the isochron as due to small and erratic degrees of contamination or later alteration. Interestingly, Rb also displays a larger scattering than the other elements in the variation diagram (Fig. 3). These second-order variations are neglected).

Petrographically, the rock textures are equigranular and aphyric. Their compositions plot on smooth trends in variation diagrams (Fig. 3). Fine-grained varieties with chilled textures, locally found at the walls, plot on the same trends as coarser grained rocks from more central parts of the dike. All dike rocks are thus considered to represent a series of liquids, unladen with crystals.

In bilogarithmic diagrams, pairs of trace elements plot on linear arrays, which indicates that fractional crystallization is the prevailing mechanism of differentiation. A two-stage model has been calculated by least-squares regression to account for the major element variation from the less evolved liquid—the monzonorite—to the quartz mangerite. The compositions of the cumulate minerals were constrained by using the approach of Ford et al. (1983) based on

TABLE 1. Major and Trace Element Composition of Representative Samples

Rock no.	Orebody				Main dike					Satellite dikes	
	1	2	3	4	5	6	7	8	9	10	11
Sample no.[1]	64.145	78.27.1B	79.27.5	T21	72.52	84.4	78.28	84.1	78.32	84.2	T20.1
Wt percent											
SiO_2	31.69	33.09	49.37	54.84	47.32	52.94	56.38	62.66	65.71	48.32	49.56
TiO_2	17.57	18.06	3.60	1.52	3.60	2.79	1.90	1.29	0.99	2.54	2.18
Al_2O_3	12.06	11.10	20.43	22.24	12.80	13.28	14.00	14.53	13.31	16.62	16.26
Fe_2O_3	7.37	8.09	8.86[2]	3.10	4.53	2.06	4.42	2.95	2.72	6.45	7.92
FeO	15.95	14.92		2.44	11.96	11.61	7.87	6.15	5.09	9.37	7.47
MnO	0.15	0.12	0.07	0.05	0.21	0.25	0.16	0.15	0.11	0.28	0.18
MgO	7.73	8.25	2.84	1.27	3.44	2.44	1.69	0.84	0.65	2.50	2.51
CaO	4.34	3.46	8.38	8.47	7.43	4.89	4.66	2.93	2.56	7.87	7.89
Na_2O	2.99	2.47	4.86	4.71	3.53	3.71	3.31	3.72	3.07	4.14	3.81
K_2O	0.44	0.70	1.15	1.41	2.28	3.87	3.60	4.68	5.04	0.90	1.32
P_2O_5	0.16	0.46	0.66	0.56	2.74	1.94	1.04	0.57	0.51	1.15	1.01
Tot	100.45	100.72	100.22	100.61	99.82	99.78	99.03	100.47	99.76	100.14	100.11
Parts per million											
U	0.10	0.18	0.42	0.14	0.32	0.36	0.18	0.26	0.20	0.76	0.62
Th	0.41	0.57	1.36	0.57	0.79	0.93	0.59	0.63	0.66	2.69	5.00
Zr	166	265	223	144	442	454	717	1,184	1,387	1,683	2,533
Hf	4.6	5.9	4.5	3.9	11.0	13.1	17.3	30.1	32.5	57.3	57.7
Nb	20		12	8	27	28	26	26	18	26	28
Ta	1.93	1.96	0.89	0.62	1.68	1.82	1.27	1.36	0.94	0.92	0.86
Th/U	4.1	3.2	3.2	4.1	2.5	2.6	3.3	2.4	3.3	3.5	8.1
Zr/Hf	36	45	50	37	40	35	41	39	43	33	44
Nb/Ta	10		13	13	16	15	20	19	19	28	33
Ba	180	226	449	523	1,212	1,389	1,533	1,749	1,842	562	883
Rb	6.4	10.1	17.0	12.4	17.0	44.0	33.9	62.0	71.0	3.7	6.2
Sr	509	563	913	889	354	286	272	223	128	532	476
K/Rb	568	556	559	939	1,108	727	877	623	586	2,009	1,759
K/Ba	20	26	21	22	15	23	19	22	28	13	12
Cr	208	285	77		22	38	34	25	21	62	17
V	667	923	147	41	128	138	35	48	72	157	72
Sc	52.8	49.8	15.1	8.15	26.3	23.0	21.1	17.9	16.0	34.3	30.8
Ni	416	451	65	14.1	6.6	4.5	1.4	2.7		51.5	8.5
Co	105	110	31	13	36	30	17	9.9	7.2	27	21
Zn	118	137	84	71	197	187	186	230	151	280	279
Mo	0.61			0.4	0.6	1.8	2.5	2.4	3.5	4.1	4.6
La	6.1	10.0	20.4	20.3	54.7	61.3	47.5	45.8	33.7	164	190
Ce	14	24	46	46	138	141	113	105	77	412	452
Nd	8	14	29		106	108	83	73	57	296	
Sm	1.7	3.1	6.2	5.9	20.4	16.9	16.2	15.8	11.7	58.1	52.7
Eu	0.8	1.2	2.4	2.6	7.4	6.9	6.4	6.7	5.7	6.0	6.8
Tb	0.20	0.37	0.75	0.71	2.40	2.20	2.11	2.22	1.68	7.53	7.12
Yb	0.50	0.70	1.00	1.78	3.80	3.60	3.90	5.10	4.00	16.30	22.50
Y	8	17	19	21	79	92	78	85	52	295	271
$(La/Yb)_N$	7.2	8.4	12.0	6.7	8.5	10.0	7.2	5.3	5.0	5.9	5.0
Eu/Eu*	1.48	1.21	1.22	1.36	1.15	1.26	1.22	1.29	1.47	0.32	0.40

Major elements and Rb, Sr, Ba, Y, Zr, V, Ni, and Zn by XRF; other elements by NAA (Jaffrezic et al., 1980)

[1] See Table 2 for locations of samples

[2] Total Fe as Fe_2O_3

Fe-Mg partition coefficients between olivine and liquid, to determine the composition of the liquidus olivine in equilibrium with each liquid. An association of cumulus minerals containing an olivine of this composition or a corresponding orthopyroxene was then selected among the sequence of cumulates (Du-

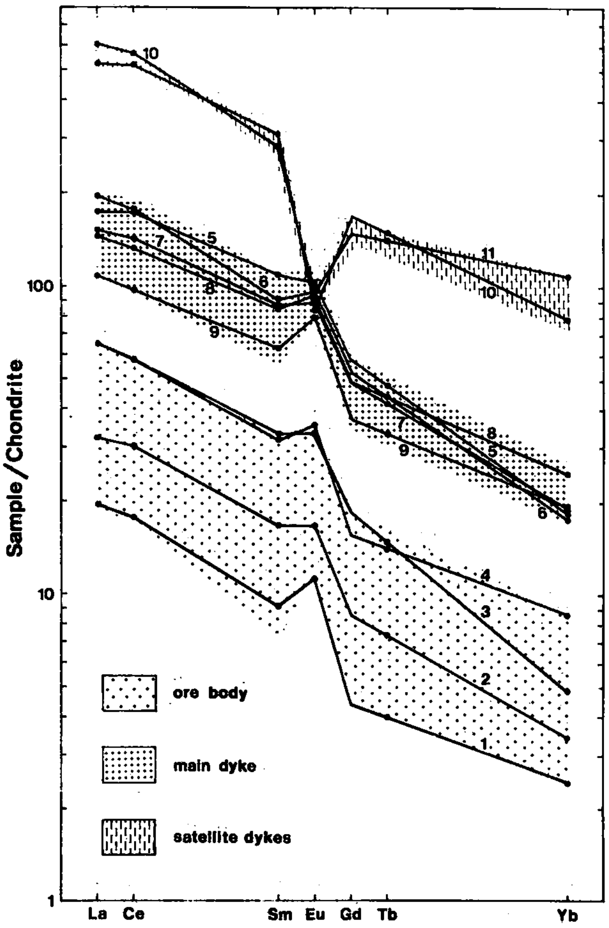

FIG. 2. Chondrite-normalized rare earth element distributions in representative rocks of the orebody, the main dike, and the satellite dikes. The numbers refer to rock numbers in Table 1.

chesne, 1987; Duchesne et al., 1987) occurring in the Bjerkreim-Sokndal lopolith, which also crystallized from a monzonoritic liquid under roughly the same pressure and temperature conditions (Duchesne and Hertogen, 1988). A cumulate made up of 42 percent plagioclase (An$_{38}$) + 23 percent orthopyroxene (En$_{56}$) + 4 percent clinopyroxene (Wo$_{44}$En$_{37}$Fs$_{19}$) + 9 percent ilmenite (Hem$_4$) + 11 percent magnetite (5% TiO$_2$) + 11 percent apatite subtracted from the less evolved monzonorite (sample 5, Table 1) leads the liquid to a mangeritic composition (sample 7). The subtraction of a second cumulate of 58 percent plagioclase (An$_{37}$) + 13 percent olivine (Fo$_{50}$) + 4 percent clinopyroxene (Wo$_{44}$En$_{38}$Fs$_{18}$) + 4 percent ilmenite (Hem$_3$) + 15 percent Ti magnetite (11% TiO$_2$) + 6 percent apatite yields quartz mangerite (sample 9). The fractions of residual liquid at the end of stages 1 and 2 are 0.49 and 0.32, respectively.

When extended to trace elements, the model gives very consistent results. The Rayleigh equation applied to the two stages of the evolution permits the calculation of two sets of mineral-melt bulk partition coefficients (Wilmart, 1988). For a number of elements, values of the partition coefficients for individual minerals can be deduced and compared to experimental values. For instance, Rb, Ba, Zr, and Hf display clearly incompatible behavior. Rare earth elements which are mainly controlled by the crystallization of apatite, show apatite-melt partition coefficients around 10, close to those experimentally determined at 950°C for similar magma compositions (Watson and Green, 1981) and to those calculated for other cases of differentiation of monzonoritic magmas (Duchesne et al., 1985b).

Fractional crystallization exempt from progressive contamination thus gives a consistent picture of the geochemical record. A possible mechanism by which a series of liquids can be obtained is sidewall crystallization and upward migration of the light residual liquid as described by McBirney (1980). This mechanism has possibly operated in a magma chamber prior to emplacement in the fault zone. The observation of continuous gradations in composition along the strike of the dike points to little perturbations of the compositional gradient in the liquid during the injection.

The Tellnes dike thus gives unambiguous evidence that acidic rocks (quartz mangerite) can derive from a monzonoritic magma by fractional crystallization without progressive contamination.

The satellite dikes

The small variation in chemical composition, as illustrated in Figure 3, indicates that the satellite dike liquids are rather homogeneous and have not differentiated in situ. Considering their major element contents, they are roughly at the same degree of evolution as the main dike monzonorite. The variation diagrams and the high Sr isotope ratio value (0.710) preclude any direct relationship through fractional crystallization or immiscibility with the main dike, the orebody, or the enclosing anorthosite. It does not seem that contamination of the main dike monzonoritic liquid by crustal material—which would account for the high I_{Sr} in the satellite dikes—is acceptable (unless a selective contamination by radiogenic ^{87}Sr alone is postulated); the K, Rb, and Ba contents are indeed distinctly lower than those in the main dike. It is therefore suggested that the satellite dike liquids are produced from quite different source rocks than those for the main dike or the orebody.

The orebody: a sorted cumulate

The orebody cannot result from the crystallization of an immiscible liquid unmixed from the monzonoritic liquid or of any liquid from the main dike because, if so, both liquids should have the same Sr isotope ratio. An immiscibility process, in a liquid distinct

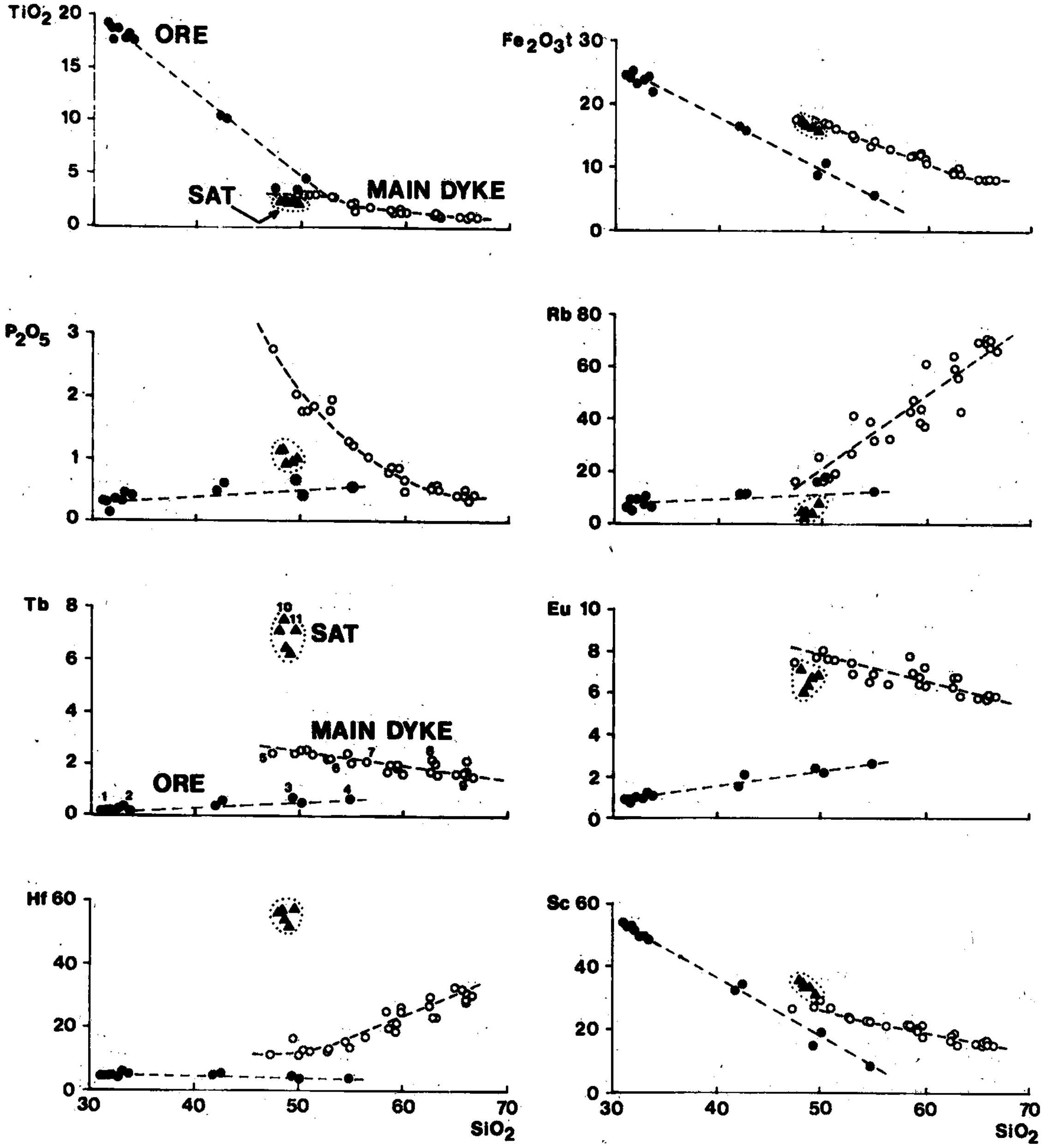

FIG. 3. Variation diagrams of some elements versus SiO_2 (wt % for the major elements, ppm for the trace elements). Symbols: filled circle = orebody; open circle = main dike; filled triangle = satellite dikes. The numbers indicated in the Tb vs SiO_2 diagram refer to rock numbers in Table 1.

from those of the main dike, is also unlikely, because the ilmenite norite is depleted in P, rare earth elements, Zr, and Ba. In agreement with theoretical considerations (Ryerson and Hess, 1978), experimental data on pairs of unmixed liquids (Watson, 1976) predict enrichment factors in the Fe-rich liquid of about 10 for P_2O_5, 3 for Zr, and 5 for rare earth elements. This would imply a complementary SiO_2-rich liquid extremely depleted in incompatible elements, down to or even less than midocean ridge basalt values (MORB). Such liquids are unknown in the area and more generally in plutonic rocks.

The association of ilmenite norite with more plagioclase-rich rocks (such as samples 3 and 4, Table 1) is a feature which constrains the genetic process of the orebody. All rocks virtually plot on straight lines in all variation diagrams (Fig. 3). This strongly points to a mixing mechanism as the main controlling process. Inspection of the variation diagrams shows that the variation in rock composition can be explained

TABLE 2. Rb and Sr Analytical Data

Sample no.	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	2 sigma (×10^{-5})
Orebody					
64.145(1)(1)	6.4	509	0.0364	0.70498	1
66.262	4.5	645	0.0202	0.70487	4
78.27.1B(2)	10.1	563	0.0519	0.70510	4
79.27.5(3)	17.0	913	0.0539	0.70498	11
Main dike					
72.52(5)	17.0	354	0.1390	0.70872	2
T8.2	40.2	315	0.3694	0.71121	6
78.28(7)	33.9	272	0.3608	0.71244	5
84.4(6)	44	286	0.4453	0.71271	7
T6.1	48	224	0.6204	0.71539	6
T8.1	63	242	0.7538	0.71537	28
84.1(8)	62	223	0.8052	0.71789	25
T18	65	178	1.0579	0.72141	27
T17	62	139	1.3134	0.72406	6
84.3	74	149	1.4395	0.72619	2
78.32(9)	71	128	1.6080	0.72780	3
84.9	78	132	1.7133	0.72975	3
Satellite dikes					
84.2(10)	3.7	532	0.0201	0.70969	4
T11	2.1	453	0.0134	0.70995	30
T20.1(11)	6.2	476	0.0377	0.71162	3

[1] The numbers in brackets refer to rock numbers in Table 1 and Figs. 3 and 4

Sample location and description: 64.145(1): ilmenite norite, open pit of the Tellnes mine; 66.262: ilmenite norite, open pit of the Tellnes mine; 78.27.1B(2): ilmenite norite, open pit of the Tellnes mine; 79.27.5(3): leuconorite, small apophysis of the orebody; T21: anorthosite, southern tip of the orebody; 72.52: monzonorite, northern tip of the orebody; T8.2: fine-grained mangerite, SE Eikeli; 78.28(7): mangerite, road to the mine, 1.2 km W of 72.52; 84.4(6): mangerite, E Bykjeheia; T6.1: fine-grained quartz mangerite, NE Eikeli; T8.1: quartz mangerite, SE Eikeli; 84.1(8): quartz mangerite, Slottheiknuten; T18: leucocharnockite, Slottheiknuten; T17: leucocharnockite, Slottheiknuten; 84.3: quartz mangerite, ENE Bykjeheia; 78.32(9): quartz mangerite, Road N44, Botnevatnet; 84.9: quartz mangerite, Lundevatnet; 84.2(10): fine-grained monzonorite, SE Slottheiknuten; T.11: fine-grained monzonorite, SE Slottheiknuten; T20.1(11): fine-grained monzonorite, N Tarravatnet

by the mixing of two end members, ilmenite norite and anorthosite (samples 1 and 4, Fig. 3). It should be recalled that though there is a negligible variation in the mineral composition of the ilmenite norite, a small but significant decrease in the anorthite content of the plagioclase and in the Mg number of the pyroxenes has been observed in plagioclase-enriched rocks. Some differentiation due to solid-liquid fractionation thus seems to have played a role. The change induced in mineral composition is, however, not large enough to appear in bilog diagrams or to alter the linear trends in variation diagrams.

A first model to envisage is the mixing of an ilmenite-norite cumulate with an interstitial anorthositic liquid, the latter being squeezed out in the apophyses and along the contact during emplacement to form the plagioclase-rich rocks. Hyperfeldspathic liquids have been considered to play a major role in the formation of massif-type anorthosite in deep-seated magma chambers (Wiebe, 1980; Morse, 1982). It is, however, rather difficult to believe that a decrease in the stability field of plagioclase with increasing pressure, invoked by these authors, could be efficient enough to produce a liquid with less than 10 percent mafics, even if it had taken place at a greater depth than the level of final emplacement. In the Rogaland province, field evidence, moreover, favors anorthositic crystal mush instead of anorthositic liquids (Duchesne et al., 1985a). This model thus appears unlikely.

As an alternative, we suggest that the plagioclase-rich rocks of the orebody were emplaced together with the ilmenite norite as a plagioclase crystal mush and thus that both end members of the mixing process have a cumulate origin. Though plagioclase and bronzite locally show parallel orientations, the cumulate origin of the orebody apparently conflicts with its intrusive character, unless it is accepted that the orebody was emplaced as a crystal mush, as suggested by local bending and protoclastic granulation of the plagioclase.

The nature of the lubricating trapped residual liquid is still speculative. We consider that the interstitial structure of the ilmenite—a habit of Fe-Ti oxide minerals which is the rule in all members of the anorthosite suite of rocks whatever the differentiation mechanism—cannot only result from subsolidus grain boundaries readjustment of cumulus Fe-Ti oxide crystals but from the late crystallization of an interstitial liquid as well. The latter process, referred to

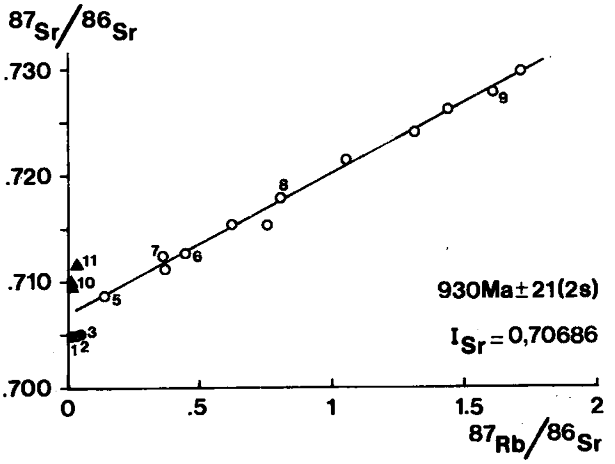

FIG. 4. ^{87}Sr/^{86}Sr versus ^{87}Rb/^{86}Sr diagram. Same symbols as in Figure 3. The numbers refer to rock numbers in Table 1.

by Bateman (1951) as late gravitative liquid enrichment, could contribute to the enrichment in ilmenite at the botton of the cumulate and can also explain the mobility of the crystal mush. Assuming as a rough approximation that the P_2O_5 content of the ilmenite norite (ca. 0.3%; Table 1) entirely results from the crystallization of a trapped liquid of monzonoritic composition (P_2O_5 varying between ca. 1.0%—satellite dike—and ca. 2.7%—main dike), the amount of trapped liquid ranges from 3 to 10 percent of the rock. Part of this intercumulic phase might be still liquid at the time of emplacement and capable of lubricating the crystal mush.

To conclude, the crystallization of a noritic cumulate in a magma chamber appears to be the first step in the formation of the orebody. Due to density differences, it is conceivable that the cumulate could have been modally graded, Fe-Ti oxides tending to concentrate at the bottom, and plagioclase in the upper levels. The magma chamber was then tapped before complete solidification and the bottom layer material injected into the dike together with part of the anorthositic sponge, while the rest of the system—anorthosite, pyroxene-rich cumulate, and residual liquid—was emplaced in a now hidden or eroded part of the dike.

Constraints on the nature of the orebody parental magma

The Sr isotope ratio of the orebody compared to that of the main dike monzonorite precludes the formation of the orebody as a cumulate derived from the monzonorite. This mechanism must also be rejected because the monzonorite is too evolved a liquid to crystallize an olivine similar in composition to the olivine of the ilmenite norite (Fo_{80}). Indeed, using the approach of Ford et al. (1983), it can be calculated that the monzonorite is not capable of crystallizing an olivine more magnesian than Fo_{56}. It has, however, been emphasized that a change in the oxidation conditions of a magma can induce variation in the Mg number of mafic minerals (see Speidel and Nafziger, 1968). In the present case, the oxidation state is actually taken into account in the calculation of Ford and coworkers by considering the Fe^{+3} of the magma.

It is, however, not excluded that the ilmenite-norite is a cumulate derived at a higher temperature from a more basic liquid than the monzonorite, e.g., from a norite with a higher Mg number. The Roeder and Emslie (1970) partition coefficient between olivine and liquid permits the prediction of liquid with an Mg number of 0.54. The absence of cumulus apatite in the orebody further indicates that this liquid was not saturated in apatite at the liquidus temperature. Associations of minerals analogous in composition to those of the orebody and without apatite are found in the Bjerkreim-Sokndal lopolith, e.g., $An_{50} + Fo_{70} + En_{72} + Hem_9Ilm_{81}$ + Mt, at the base of the fourth megacyclic unit (Duchesne, 1972, 1987). They occur at a lower stratigraphical level than apatite-bearing noritic cumulates similar to those calculated here to account for the evolution of the main dike monzonorite. These associations thus point to a higher crystallization temperature for the orebody than for the monzonorite.

The $(La/Yb)_N$ ratio (= 7–8; Table 1), which characterizes the rare earth element distribution in the ilmenite norite, is close to that of the main dike monzonorite (= 8.5) and points to some consanguinity of the parental norite and the monzonorite. The positive Eu anomaly in the ore and in the anorthosite is likely to result from the accumulation and sorting of plagioclase. No clear conclusion can be drawn concerning the Eu anomaly in the parental liquid because the intrusive process has sorted the various components of the crystal mush formed in the magma chamber. The original proportion of the minerals thus cannot be reconstructed. In the most simple model of an equilibrium crystallization in a closed system in which the sum of the various solid parts—i.e., the ilmenite norite, the anorthosite, and the pyroxene-rich cumulate—gives the parental magma distribution, the positive Eu anomalies in the ilmenite norite and in the anorthosite do not imply a positive anomaly in the norite because the pyroxene separated from the ilmenite norite shows a significant negative anomaly (Wilmart, 1988, table 3.7). In the more realistic model of a fractional crystallization for the formation of the Tellnes cumulate, the ignorance of the exact nature and composition of the possible residual liquid prevents any reconstruction.

Norites with Mg ratios and low P contents similar to those predicted for the noritic parental magma of the orebody are commonly found in massif anorthosites (Ashwal, 1982; Emslie, 1985; Duchesne and Maquil, 1987) or as chilled margin to some leuconoritic massifs (Duchesne and Hertogen, 1988). Since the Sr isotope ratio value of the orebody falls within the range of those found for massif-type anorthosites in the area (0.703–0.706; Demaiffe et al., 1986), it is not possible to reject the hypothesis that the orebody parental magma is residual after the formation of enclosing Åna-Sira massif anorthosite.

Origin of the various magmas

It is relevant to consider the possibility that the main dike monzonorite could be initially comagmatic with the orebody and has been affected by a sudden and unique contamination taking place after the crystallization of the orebody cumulate and before the differentiation of the main dike monzonorite. The contamination could indeed have increased the Sr isotope ratio of the magma without modifying that of the already crystallized cumulate.

This hypothesis is not testable because we ignore the composition and the proportion of the contaminant and of the residual magma. It should, however, be noted that this process has eventually maintained a high K/Rb ratio and low Th and U contents in the monzonorite, thus restricting the origin of the contaminant to lower crustal material. Moreover, a possible negative anomaly in the orebody residual liquid must have been completely cancelled by the process, which seems rather unlikely in view of the lack of an Eu anomaly in the average composition of the lower crust (Taylor and McLennan, 1981).

Because of these uncertainties, it is thus necessary to leave open the alternative hypothesis of completely distinct sources for the magmas of the main dike and of the orebody. This hypothesis finds some support in the geochemical characteristics of the satellite dikes: the contrasting high Sr isotope ratios with regard to very low Rb and Ba contents (K/Rb up to 2,000 !) are very difficult to account for by a contamination process. Here again, a different source is a more likely explanation.

The nature of the source of monzonoritic magmas has already been discussed by Duchesne et al. (1985a and b) and Demaiffe et al. (1986) on the basis of trace element and isotope data. It has been concluded that they derive from the partial melting of basic to intermediate rocks in the lower crust, the necessary heat being provided by the anorthosite diapirs during their ascent.

Scenarios of intrusion

If the relationship between the main dike and the orebody is accepted, a simple model can account for the petrogenesis of these two units and for their occurrence in the same dike.

A batch of noritic liquid, primary in origin or residual after the formation of the Åna-Sira anorthosite, is collected in a magma chamber outside the anorthosite, where it crystallizes a noritic cumulate at the bottom of the chamber. The residual liquid of monzonoritic composition is then contaminated by a sudden assimilation of lower crustal rocks from the envelope. The differentiation then proceeds in a closed system to yield a continuous gradient of liquid compositions. Then the magma chamber is tapped and the material emplaced in a fracture zone. The most ilmenite-rich part of the noritic crystal mush gives rise to the ilmenite norite; the plagioclase-rich crystal mush provides the anorthosite along the contact and in the apophyses of the orebody, while the liquid is injected to crystallize the continuous series of rocks from monzonorite to quartz mangerite. Somewhat later the fracture zone is revived and the satellite dike monzonoritic liquid is injected and crystallizes rapidly.

In the alternative model, two different parental magmas evolve within two distinct magma chambers prior to their emplacement in the dike. A noritic liquid crystallizes in the first one to give rise to the ilmenite-rich cumulate, and in the second one, a monzonoritic liquid fractionates into a series of liquids. The intriguing feature of this model is that the two magma chambers empty simultaneously. There is indeed no indication whatsoever—crosscutting relations, inclusions, or hybridization structures—that the orebody was emplaced before or after the main dike, despite the excellent conditions of observation in the field and in the open pit.

Conclusions

Textural evidence and geochemical mixing relationships support an origin of the Tellnes orebody as a sorted noritic cumulate. On the other hand, the Tellnes main dike can be explained by a consistent geochemical model of fractional crystallization without progressive contamination affecting a monzonoritic magma and producing a series of liquids extending in composition to quartz mangerite. As for the satellite dikes, a distinct monzonoritic liquid, coming from a different source, could have been injected into the same fracture zone at the end of the evolution.

Two models can equally account for the formation of these units. In the first one, a noritic magma, possibly residual after the formation of the Åna-Sira massif anorthosite, crystallized a noritic cumulate within a magma chamber. Then a sudden contamination affected the residual liquid and, after that episode, fractional crystallization took place in a closed system. The opening of the fracture led to the emplacement of the cumulate and the series of liquids in a single act of intrusion. The major weakness of the model is that it does not account for the lack of an Eu anomaly in the monzonoritic liquid at the end of the contamination.

In the second model, two magma chambers and two parental magmas are required: the noritic cumulate formed in the first chamber and the gradient of composition in the second one. The two chambers were then emptied simultaneously into the same fracture. The existence of magmas coming from different sources finds good support in the fact that other monzonorites (satellite dikes) with quite different geochemical characters are also found in the same fracture zone. Nevertheless, it remains difficult to envisage the process by which the two magma chambers were tapped together.

Thus the Tellnes case, apparently a geologically simple structure, turns out to be rather complex when viewed in the light of geochemical data. From a more general point of view, the Tellnes main dike, though relatively small in volume with respect to the massif-type anorthosite and the acidic rocks in the area, provides an as yet unique opportunity to unravel the "missing link" between the intermediate and acidic members of the anorthosite suite. It shows that acidic rocks can directly stem from monzonoritic magmas through fractional crystallization, without progressive contamination.

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