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Reply to comments by T. F. D. Nielsen on 'The Tertiary Kærven syenite complex, Kangerdlugssuaq, East Greenland: Mineral Chemistry and Geochemistry'

Introduction

THE Kærven syenite complex (KSC) in the Kangerdlugssuaq region of East Greenland is a Lower Tertiary syenite–granite multiple intrusion. We have recently given an account of the mineralogy and geochemistry of the complex (Holm and Prægel, 1988). From our analytical data we were able to substantiate the co-magmatism and mantle signature of the syenite–granite suite of rocks constituting the bulk of the KSC. We furthermore demonstrated that, whereas the main Kærven suite was not geochemically influenced by its passage through the Precambrian basement, a small number of plagioclase-rich granites in the complex have been contaminated by crustal melts. We suggested an internally consistent mixing model capable of accounting for most of the geochemical features observed. Nielsen (1989) criticises our interpretation of the data from the KSC and attempts to make our data fit a model of a different intrusive complex in the region. We will in the following demonstrate the failure of this attempt and generally that Nielsen's (1989) scepticism of our interpretation of the KSC is unwarranted.

The Kærven paper by Holm and Prægel (1988) is a first presentation of aspects of this felsic complex which has proven to be of some importance to the understanding of the magmatic evolution of the Kangerdlugssuaq area. The limited field work carried out when writing our paper made it premature to set the KSC into a larger frame including every other syenite in the area. For instance, the syenites at Bagnæsset (see Fig. 1 in Holm and Prægel, 1988; and references in Nielsen, 1989) are quite distant to Kærven and only very limited accounts have been published. Instead, we preferred to present the basic petrographical and geochemical data for the complex by itself and to evaluate them in comparison with the adjacent part of the largest felsic complex of the province, the Kangerdlugssuaq Intrusion, which intrudes and is intimately related to the KSC.

Age of the complex

Holm and Prægel (1988) stated that parts of the Kærven syenite complex were intruded at 58 Ma. Nielsen casts some doubt on this age information.

Detailed radiometric analyses of the Kærven rocks have revealed that some of them, after initial cooling, were reheated to rather high temperatures, which disturbed the isotope systems (Holm, in prep.). Both K/Ar, $^{40}Ar/^{39}Ar$ and Rb/Sr techniques have been used on whole rocks and mineral separates. Partial isotopic homogenization, argon loss and excess argon complicate the interpretation of the data. However, parts of the complex were not reheated. Identical $^{40}Ar/^{39}Ar$ plateau ages of 58 ± 1 Ma were produced by the stepwise heating of K-feldspar and amphibole separates from the same rock sample (#40160). Also other results indicate ages higher than 55 Ma for parts of the complex. Nielsen (1989) refers to a fission track dating of zircon yielding 51 ± 3 Ma. A similar age is also indicated by the $^{40}Ar/^{39}Ar$ age of 51 Ma of a three-step plateau in the age spectrum of a feldspar from a syenite dyke in the Kærven gabbro. However, this age is thought to be a cooling age significantly later than the time of intrusion of large parts of the complex. Finally, felsic magmatism at Kærven resulted in numerous intrusions from 58 ± 1 Ma onwards and was succeeded by the Kangerdlugssuaq intrusion at 50 Ma.

We were rather confident in our citing of the age of the Kærven complex. Absolute dating is rather scarce in the Kangerdlugssuaq area, due in part to the complexity and number of intrusions, and the ages of many felsic and mafic complexes are not known. The age of the flood basalts is not well constrained, being based on the dating of magnetic anomalies 24 and 25 (e.g. Tarling *et al.*, 1988). Only a crude concept of the timing of the Tertiary magmatic evolution in the Kangerdlugssuaq area has hitherto been published (Brooks and Gleadow, 1977; Pankhurst *et al.*, 1976; Gleadow and Brooks, 1979). In the light of this incompleteness of knowledge we do not think it is wise to consider, as Nielsen appears to do (Nielsen and Brooks, 1981; Brooks and Nielsen, 1982; Nielsen, 1989), all the syenite complexes more or less contemporaneous at 50 Ma. The older age of Kærven is therefore important in relation both to the syenites and to the refinement of the concept of the overall evolution of the province.

Even without documentation of the absolute age of the Kærven complex, the relative ages of the intrusions at Kærven prior to and at Bagnæsset, posterior to the Kangerdlugssuaq intrusion, which has not been disputed by Nielsen (1989), is highly significant, because of the emplacement of very large quantities of magma in the immediate vicinity in the time interval between emplacement of the two satellites. Around 50 Ma the crust was probably heavily intruded by magmas at different levels and stages of solidification in notable parts of the Kangerdlugssuaq area. It is likely that both large-scale anatexis and reaction between magmas took place at this mature state in the process of continental break-up. The scenario for the early magmas at Kærven might have been very different. The crust was probably quite brittle during the emplacement of the Kærven syenites relatively distant from the zone of upwelling of penecontemporaneous basaltic magmas along the coast. This is evidenced by the dyke-like intrusive forms and by the lack of field evidence for crustal interaction with the Kærven syenites, except in rare instances. These field relations are in sharp contrast to the geology at Bagnæsset (Nielsen, 1989; Brooks and Nielsen, in press). Thus, it may be possible that most Kærven magmas were emplaced without notable crustal influence. In Nielsen's opinion several indications of the opposite are detectable. These will now be examined.

Discussion of the petrological comments

The main conclusion of our paper is that the magmas at Kærven rarely interacted significantly with the upper crustal rocks (Holm and Prægel, 1988). Nielsen (1989) disputes this conclusion based on a number of arguments, on which we comment below:

Comagmatism. Nielsen incorrectly classifies the Kærven rocks as coarse grained, and thereby places the use of rock samples as representative of liquids in doubt. We clearly stated that the rocks are medium grained.

Nielsen argues that a syenite group of hybrids and a granitic group of anatectic melts exist. He then focuses on the fact that 4 out of 24 analyses of rocks from the main Kærven suite have lower Zr/Nb ratios than the narrow interval of the bulk. On the other hand, he also notes that these four rocks are not grouped exclusively in his hybrid (syenite) or anatectic (granite) group. The existence of these four outliers, therefore, does not in any way support Nielsen's grouping. Their low Zr abundances were probably caused by the fractionation of zircon. We commented on these four rocks in our paper and conclude that they have no influence on the present discussion of a common parental mantle heritage versus a crustal origin heavily influenced by anatexis and hybridization.

In view of the suspected multiple intrusion at Kærven, we did not expect perfect correlation in a plot of incompatible elements. A rather nicely trending cluster in a diagram of Th versus Ce (Fig. 7, Holm and Prægel, 1989) is, however, a necessary premise for comagmatism. If the rather large analytical uncertainty on the low concentration results, acquired by X-ray fluorescence analyses ($\pm 10\%$ at the 10 ppm level, $\pm 25\%$ around 3 ppm; J. Bailey, pers. comm.), is taken into account, the correlation is quite significant. The Ce/Th ratio is constrained well; all samples except two being within 19 ± 5 for this ratio.

Unfortunately Nielsen does not discuss much of the evidence against crustal contamination displayed by the incompatible elements. The very clear difference between the basement-influenced rocks and the main Kærven suite of rocks is demonstrated most clearly in incompatible element ratio plots, where the contrast is much more evident than in the element–element plots of Nielsen. These differences between basement geochemistry and the granites Nielsen explains as a result of partial melting of basement accompanied by incongruent melting of biotite, without any specification of the process. Our calculations demonstrate that these processes cannot explain either the observed ratios or the patterns of the incompatible elements. Nb displays a striking difference between basement (1–5 ppm) and Nielsen's postulated anatectic granitic melts from the Kærven main suite (100–120 ppm; Table 1 of Holm and Prægel, 1988), a level which would be impossible to achieve by a granitic mobile magma during any plausible anatexis. Moreover, the lower abundance of Nb in the less evolved syenites are in conflict with the predictions of the hybridization/diffusion/anatexis model of Nielsen. We note that in Fig. 4 of Holm and Prægel (1988) the tie mark labelling of the Nb ordinate axis is 20 ppm too low.

The difference between the rocks of the Kærven and Kangerdlugssuaq intrusions. Nielsen (1989) doubts the existence of a significant difference between the two intrusions. A major point is the evidence presented by Deer and Kempe (1976). They discuss mainly two rocks sampled at Kærven mountain. Unfortunately, one of these (#EG3683) is a nordmarkite of the Kangerdlugssuaq intrusion which at this place intrudes into parts of the Kærven complex. This is unequivocally documented by out recent field work. The petrography of this sample, with its ægerine, is thus not a feature of the Kærven syenites. Comparison of analyses nos. 9 and 10 (Table 1 of Deer and Kempe, 1976) with Table 1 (Holm and Prægel, 1988) illustrates the unrepresentative nature of their samples. The chevkinite, which according to Nielsen (1989) links Kærven to other satellite intrusions and the Kangerdlugssuaq intrusion, was reported by Deer and Kempe (1976) from hybrid rocks from the contact zone to the earlier Kærven gabbro and not from the typical Kærven syenites.

In our paper we have noted a number of very significant differences between the rocks of the two adjacent intrusions, which Nielsen does not dispute in his comment. Nielsen (1989) would have preferred us to compare Kærven rocks to the quartz nordmarkites of the Kangerdlugssuaq intrusion. There are several reasons not to do this, principally: (1) the closest 30 km^2 of the Kangerdlugssuaq intrusion are nordmarkites; (2) the late intrusive rocks in Kærven extending from the main Kangerdlugssuaq intrusion are nordmarkites; (3) should the Kangerdlugssuaq intrusion turn out to be multiple, caution should be taken when comparing geographically distant rocks; (4) in the mentioned geological evolution at Kærven, the Kangerdlugssuaq nordmarkites located to the west of Kærven would be the successors to the KSC.

Interaction with the crust. We agree with Nielsen that the plagioclase-rich granitic xenoliths from Kærven are closely related to the basement, as already stated in our paper. Also, clearcut crustal interaction is seen in relation to the Kærven gabbro, but is notably absent from the main suite of rocks. However, we cannot conform to Nielsen's line of argument, that the mere position in an AFM-diagram of the actinolitic amphiboles of the granitic xenoliths near to that of the magnesiohornblendes of the least-evolved syenites makes it reasonable to suggest that the latter, completely different amphiboles, were inherited from the basement. Our Table 3 (Holm and Prægel, 1988) in fact clearly demonstrated the different chemistries of the amphibole populations. Also the petrography is totally inconsistent with such an interpretation. The amphiboles in the main suite rocks crystallized as the last interstitial, often poikilitic, phase. By the detailed identification of the characteristic evidence for crustal influence on the granitic xenoliths it was possible to eliminate these rocks from the main suite. The contrasting lack of these characteristics of crustal influence in the Kærven main suite rocks really leaves no room for Nielsen's hypothesis that the two distinct groups of rocks should have nearly the same petrogenesis. On the contrary, we have pointed out the primary geochemical features which are likely to be inherited from the ultimate mantle source and preserved in these rocks despite an extensive magmatic evolution.

The kink in the Harker diagrams. Several times in our paper we drew attention to a kink appearing in a few of more than twenty Harker diagrams. It was the major item explicitly left unexplained. Nielsen (1989) suggests that these kinks are inconsistent with a fractional crystallization and mixing model. The redrawing by Nielsen (1989) of our Fig. 4, accompanied by contours limiting subpopulations of analyses, in our opinion only adds a deceiving visual effect which is not very helpful in the interpretation.

Kinks in the variation diagrams for comagmatic rocks are often a consequence of the change in phase relations of the evolving magma. They are thus compatible with a fractional crystallization model, and they should not in themselves bring about complicated theories for the magmatic evolution as proposed for Kærven by Nielsen (1989). For Kærven, however, we found that we could not model the kinks numerically when using the information available to us at that stage. We have previously presented the numerous indications for magma mixing (Holm and Prægel, 1988) which is not substantially opposed by Nielsen (1989). Nielsen (1989) fails to comprehend our presentation of the relationship between mineralogy and whole-rock geochemistry and also omits acknowledging the implications of the Fe/Mg systematics. Nielsen (1989) states that our observation of the coherence between amphibole Fe/Mg and host-rock Fe/Mg does not support mixing. We are, however, dealing with mixing of magmas and are therefore not disturbed by the fact that the explicitly stated late crystallizing amphiboles reflect the chemistry of the bulk rocks. Hybridism of the syenites, as advocated by Nielsen (1989), is contradicted by the overall equilibrium mineral chemistry.

Rejection of Nielsen's model for Kærven

The geochemical data for the model of Nielsen for the Bagnæsset feature at Astrophyllite Bay are not published. The earlier field and petrographic descriptions (Brooks and Nielsen, 1982; Nielsen, 1987; Nielsen and Brooks, 1987) are very short with only sparse information and no discussion at all. Submitted at the same time as Nielsen's comments, Brooks and Nielsen (in press) are now publishing an extended abstract including most of the data cited in his comments. We found it impossible to relate the model for Bagnæsset to KSC before the relevant data were published. However, if they had been published it would have been clear that there is only a small resemblance between the two complexes.

From Fig. 1 of Nielsen (1989) it is evident that his model cannot explain the variation of the granitic end of the Kærven main suite, which is not at all like that of the crustally derived melt at Astrophyllite Bay: Al, Ti, Fe, Ca, Na, Th, Ba and Nb are in striking contrast to the analysis of basement melt presented by Nielsen (1989) for ABC as well as to any compositions between this and the basement itself even allowing for diffusional processes. We have already discussed that anatectic basement melts cannot explain the data (Holm and Prægel, 1988). Moreover, no petrographical evidence is present in the Kærven rocks to support Nielsen's (1989) complicated model which involves anatexis, reequilibration, metasomatism, incorporations of restites, mixing and incongruent melting of biotite. Nielsen suggests that the syenite part of the Kærven main suite is related by hybridization, but admits that fractional crystallization is another possibility. No evidence has been presented to substantiate the hybridization hypothesis and based on our previous work we obviously prefer the fractional crystallization model.

As an example of the many conflicts between the model proposed by Nielsen (1989) and the Kærven data, we present a diagram (Fig. 1) of the ratio of Th/Nb versus the Nb abundance. The basement of the area and most mantle-derived melts from rifting regimes display contrasting Th–Nb geochemistry. Further, these elements are incompatible during the anatectic processes mentioned by Nielsen (1989) and should not preferentially enter the high-silica component in diffusion-controlled equilibration (Watson, 1976; Lesher, 1986). Interaction between basement/basement-derived melts and mantle-derived magmas should therefore be easily detectable in a diagram such as Fig. 1 by an enhancement of the Th/Nb ratio. No interaction with the crust is evident from this diagram and the Kærven data are much in contrast to the ABC data.

Nielsen (1989) presents Sr isotopic data for ABC, which support the idea of mixing between basement-derived melts and andesite magmas.

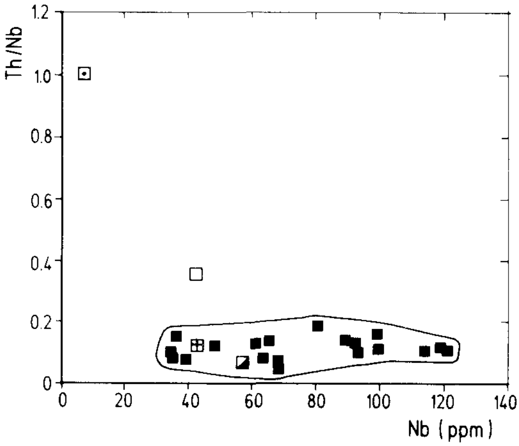

FIG. 1. Comparison of the Kærven main suite of rocks (Holm and Prægel, 1988) with the compositions from Astrophyllite Bay (ABC) suggested by Nielsen (1989) to represent end-members in the petrogenesis of the Kærven syenite complex (KSC). Symbols: Filled square—main suite (KSC); square with cross—trachy-andesite (ABC); half-filled square—hybrid (ABC); open square—crustal-derived melt (ABC); square with dot—metasomatised basement (ABC). The variation of the Kærven samples are consistent with comagmatic evolution by fractional crystallization and show no significant crustal component. In Nielsen's (1989) model, the granitic part of the suite should be crustal-derived liquids variably modified. The low-silica end of the granites should coincide with the crustal-derived syenite from the ABC. The trachy-andesite and the crustal-derived syenite from the ABC should constitute a trend together with the syenites of the main Kærven suite. The trend of the Kærven main suite in this diagram is very much in contrast to the model of Nielsen (1989) and clearly illustrates some shortcomings of his model.

Low values of initial $^{87}Sr/^{88}Sr$ ratios in the most basic rocks and very radiogenic values in the felsic crustal-derived samples are essential to such models. We did not present Sr isotope results for Kærven in our paper. However, such data are now available and lead us to a conclusive rejection of the analogy between ABC and KSC. The most evolved granitic members of the Kærven main suite have the lowest $(^{87}Sr/^{88}Sr)_0$ ratios while the least evolved syenites have the highest. Mixing is suggested by both Sr, Nd and Pb isotope systematics (Holm, in prep.).

Concluding remarks

We feel very much that Nielsen attempts to squeeze the Kærven complex into a model which does not fit at all. Although we find ourselves compelled to reject the major criticism of our previous paper, we would nevertheless thank Troels Nielsen for giving us this opportunity to elaborate our position regarding the petrogenesis of the Kærven syenite complex.

References

Brooks, C. K. and Gleadow, A. J. W. (1977) *Geology* **5**, 539–40.
—— and Nielsen, T. F. D. (1982) *Meddr. Grønland Geosci.* **9**.
———— (in press) *Bull. Geol. Soc. Denmark*.
Deer, W. A. and Kempe, D. R. C. (1976) *Meddr. Grønland*, 1974.
Gleadow, A. J. W. and Brooks, C. K. (1979) *Contrib. Mineral. Petrol.* **71**, 45–60.
Holm, P. M. and Prægel, N.-O. (1988) *Mineral. Mag.* **52**, 435–50.
Lesher, C. E. (1986) *J. Geophys. Res.* **91**/B6, 6123–41.
Nielsen, T. F. D. (1987) *Geol. Soc. Lond. Spec. Publ.* **30**, 489–515.
—— (1989) *Mineral. Mag.* **53** (previous paper).
—— and Brooks, C. K. (1981) *J. Geol. Soc. London* **138**, 559–68.
———— (1987) Abstract in Sødalen Symposium (Rosing, M. T., ed.). Geol. Museum, Copenhagen, April 1987.
Pankhurst, R. J., Beckingsale, R. D. and Brooks, C. K. (1976) *Contrib. Mineral. Petrol.* **54**, 17–42.
Tarling, D. H., Hailwood, E. A. and Løvlie, R. (1988) *Geol. Soc. Lond. Spec. Publ.* **39**, 215–24.
Watson, E. B. (1976) *Contrib. Mineral. Petrol.* **56**, 119–34.

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