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A discussion of Hunter and Sparks (Contrib Mineral Petrol 95:451–461)

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Introduction

Hunter and Sparks (1987) have revived the old debate between Fenner and Bowen about iron enrichment versus silica enrichment in basaltic fractionation. For some, this debate was resolved by Wager and Deer’s discovery of very iron-rich rocks at Skaergaard, and further illuminated by understandings about the interaction of oxygen and silica activities in magmas due to Kennedy and later Osborn. In addition, there is now firm evidence for the former existence of silica-poor, iron-rich plutonic liquids in other settings, as we shall see.

Volcanology and plutonology

The Hunter-Sparks argument is fundamentally a complaint that since we don’t see Icelandic lavas like the postulated Fe-rich, silica-poor Skaergaard liquids, why should we believe such liquids can exist? One could just as well ask why one should expect such liquids in an eruptive edifice at a hotspot such as Iceland as well as in a closed magma chamber at a passive margin, such as Skaergaard. The application of volcanology to plutonic processes is fraught with opportunity for error, in particular circularity of argument. The apparent requirement that the only real liquids are those that erupt is a self-fulfilling prophecy that impedes our understanding of the Earth’s interior.

The volcanic processes at Iceland certainly include oxidation and hydration, and very probably include back-mixing of evolved acid liquids (e.g. McBirney et al. 1986; Morse 1987; Helz 1987). The very act of eruption involves volatile propellants (Wilson et al. 1978) which can have affected the course of magma evolution. From the work of Kennedy (1955) and Osborn (1959), we understand that hydration of common mantle magmas (assumed here to start life at or below FMQ) causes oxidation, which in turn causes earlier precipitation of magnetite, and silica enrichment. In short, the Bowen trend can be produced or at least aided by oxidation. The Fenner trend is characteristic of reduced magmas. Iron enrichment and a low volatile content make such magmas so dense that they have a low probability of eruption, as remarked by Hunter and Sparks. The princi-

ples governing Bowen versus Fenner trends are reviewed by Morse (1980a).

Hunter and Sparks would have the observed mafic cumulates deposited from siliceous magmas now absent from view. They evidently prefer to trade unseen rocks for the ones seen. Ockham’s razor would suggest that the rocks we see should carry more weight than those not seen. The original and still reasonable basis for estimating liquid compositions at Skaergaard has been summation over the exposed rocks, assuming no serious differential loss. The Skaergaard problem is difficult because of the relatively large border zones, but it is nevertheless tractable in a semi-quantitative way (McBirney and Naslund, this issue). A more straightforward summation procedure has been used with some success at Kiglapait, where chilled margin rocks match the summed bulk composition quite closely (Nolan and Morse 1986). We return to this example after discussing volcanic processes in a lava lake.

Lessons from Kilauea

The study of lava lakes has added greatly to our understanding of volcanic processes. A recent summary (Helz 1987) is particularly relevant to the present discussion of differences that might be expected between volcanic liquids and those produced by slow fractionation in a layered intrusion. One pertinent observation is that resorption of olivine suppresses iron enrichment, whereas the efficient removal of olivine enhances iron enrichment at the expense of silica, alumina, alkalis and phosphorus. A Fennér mechanism is therefore at work in the same place as a Bowen mechanism. In general, we may speak of fast (volcanic) processes in which reaction is enhanced by continuous contact of crystals and liquid, and slow (plutonic) processes that lead to efficient fractionation by closing the cumulate to the main magma. Inevitably, volcanic processes will tend to enhance the Bowen trend at the expense of the Fenner trend, so one should expect lavas to differ from plutonic liquids.

A second process of great interest is the diapiric rise of evolved melt from basal olivine cumulates, as document-

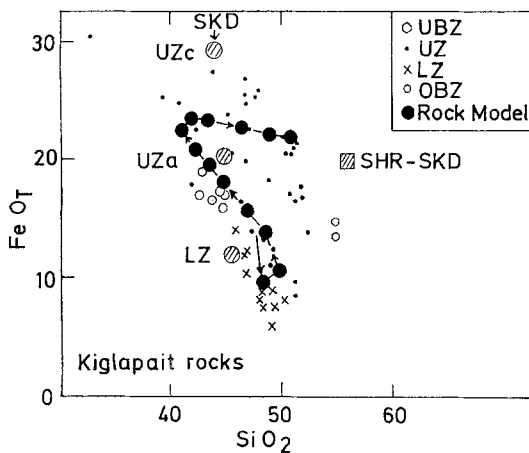


Fig. 1. Total iron as FeO versus silica for cumulate rocks of the Kiglapait Intrusion, from Morse (1981). The *hachured* symbols are Skaergaard zone averages and the Sandwich Horizon Rock (SHR) from Wager and Brown (1967). The Kiglapait rock model shows the trend of average rock composition upstratigraphy as indicated by the *arrows*. The diagram establishes the fact that the Skaergaard rocks are not unique, and are similar to the products of demonstrably silica-poor Kiglapait liquids

ed by Helz. This melt is of minimum density, just at the point of plagioclase saturation, and it rises rapidly to contaminate the overlying magma and promote differentiation. The compositional details of the diapiric melt are not yet known to us, but we can assume that alkalis and silica are concentrated in it. The direct production of oceanic rhyolite by such a process was recently suggested (Morse 1987) and would be enhanced by a modest content of water in the melt, which scavenges silica even when in contact with olivine (Kushiro et al. 1968). It appears likely that Icelandic lavas have been affected by such diapiric rise and mixing of evolved (Bowen-trend) melt, whereas the slower-formed Skaergaard liquids were not so affected.

Yet another lesson from Kilauea is that iron-rich sills of ferrobasalt are formed, and that rhyolitic segregations, attributed to gas filter-pressing, are tiny in amount. The evidence would not suggest a trend toward voluminous siliceous residual liquids in the very small magma chamber at Kilauea, or indeed at Skaergaard.

Comparison with Kiglapait and Nain

The Skaergaard Intrusion should not be viewed in isolation. Other layered intrusions show strong iron enrichment; the most extreme of these known to date is probably the Kiglapait Intrusion (Morse 1981), which occurs in a petrographic province containing other examples of Fe-rich intrusions and dikes. Data for FeO (total) versus silica for the Kiglapait Intrusion are shown in Fig. 1, where several Skaergaard zone averages and the Sandwich Horizon Rock (SHR) are shown for comparison. The data are clearly comparable to those from Skaergaard. The SHR is somewhat more silica-rich than the last Kiglapait rock, but new estimates based on more samples show appreciably lower silica, as shown by McBirney and Naslund (this issue, accompanying discussion). The Kiglapait data are relevant for several reasons.

1. The Kiglapait Intrusion shows no olivine hiatus, nor any low-Ca pyroxene except as trace rims in some samples. It is, therefore, clearly not the product of a siliceous magma.

Table 1. Composition of chilled dioritic pillows from the Proterozoic Nain Plutonic Suite (Wiebe 1979; average of first 3 columns of Table 3) compared to the calculated Skaergaard liquid LUZA of Wager and Brown (1967, Table 10). Critical comparisons are emphasized by horizontal lines

	Nain Pillows (3)	Skaergaard LUZA
SiO ₂	47.26	47.18
TiO ₂	3.51	2.19
Al ₂ O ₃	12.75	12.42
Fe ₂ O ₃	2.62)	3.77)
FeO	17.60) 20.01	17.18) 20.72
MnO	0.26	0.28
MgO	2.75	2.48
CaO	8.40	9.44
Na ₂ O	2.89	3.20
K ₂ O	0.85	0.65
P ₂ O ₅	1.11	1.24
Sum	100.00	100.00

2. The intrusion was emplaced and contained in a tight envelope at ~2.3 Kbar (Berg and Docka 1983). It has a well-defined contact aureole against supracrustal rocks along one edge, but elsewhere is in contact with refractory anorthosite that afforded little opportunity for contamination. Oxygen isotopes are consistent with closed-system fractionation (Kalamarides 1984, 1986).

3. The petrographic province (Nain Plutonic Suite) is devoid of contemporaneous normal tholeiitic intrusions or dikes, but contains numerous very Fe-rich intrusions, and chilled pillows (e.g. Wiebe 1979). Extreme chilled pillow compositions reach 20% FeO_T and 3.8% TiO₂ at 45.6% SiO₂ (Wiebe 1979, Table 3). This liquid composition is close to the contested Skaergaard UZa zone average of Wager and Brown (1967, Table 6), but higher in Ti. The average of three extreme chilled pillows is remarkably close to the calculated liquid UZa of Wager and Brown (see Table 1). There is no question that such plutonic liquids can occur.

4. The Kiglapait Intrusion has a complete, inverted UBZ meeting the UZ in a sandwich horizon. The UBZ is mafic where the layered group is mafic (Allison 1984), and it also has Ti-rich titanomagnetite consistent with a low oxygen fugacity (Morse 1980b). The roof chill therefore reflects the presence of liquids similar to those that formed the floor cumulates.

5. The uppermost rocks of the Kiglapait layered group are closed off against the UBZ in the sandwich horizon, from which there is no field evidence of departing liquids. The sandwich rocks are exhausted of Mg and hence are the products of extreme fractionation of mafic silicates.

6. In hundreds of thin sections examined, traces of quartz are recorded in only three, at the 99.978, 99.98, and 99.99 percent solidified (PCS) levels (Morse, unpublished data).

7. The Kiglapait Main Ore Band is about a meter thick and accompanied by many lesser magnetite-rich layers. Even though the starting liquid was more Fe-rich, the oxide minerals precipitated at a later stage (lower Mg No.) than at Skaergaard, and they precipitated more abundantly. They are Ti-rich and crystallized at low oxygen fugacity. Their abundance requires their high concentration in the liquid, which was therefore low in silica.

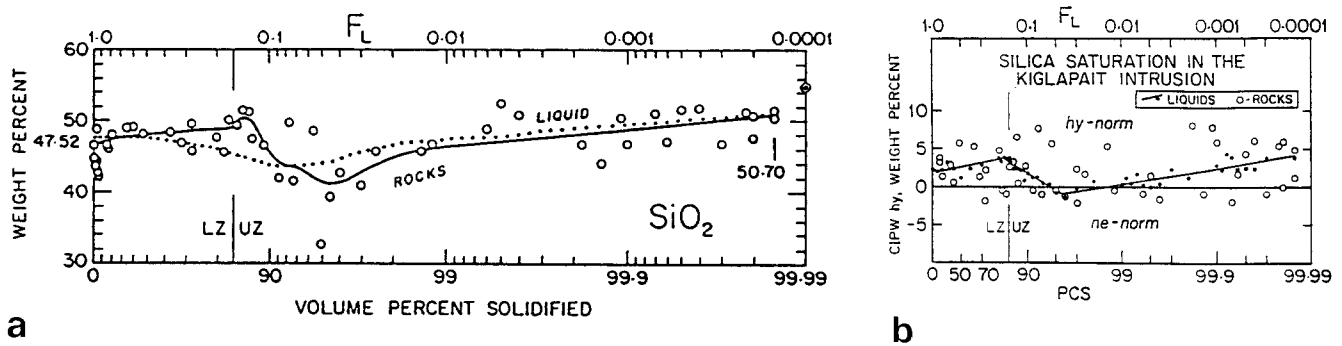


Fig. 2a, b. Silica concentration (a) (Morse, 1981) and saturation (b) as a function of stratigraphic height in Kiglapait rocks and calculated liquids. Both silica and excess silica rise very little in the late-stage residual liquids because the rocks are very similar in composition to the liquids themselves except near the Main Ore Band at 93.5 PCS. At the same time, the liquids are undergoing extreme fractionation in Mg ratio

8. The summed bulk composition of the intrusion closely resembles the chilled margin of the nearby Hettasch Intrusion (Morse 1981) and is even more closely matched in major and trace element composition by newly discovered chilled rocks at the South Margin (Nolan and Morse 1986). The slight differences between the chilled margin and the summed bulk composition are now interpreted as the result of selective thermal migration during chilling (Leshner and Walker 1988). The intrusion therefore appears to be an excellent example of closed-system fractionation, with the possible exception of some minor contamination indicated by radiogenic strontium (DePaolo 1985).

9. The FMA trend for Kiglapait shows even stronger iron enrichment than Skaergaard (Morse 1981).

10. The Kiglapait rocks are low in silica throughout extreme fractionation, and their coexisting liquids, obtained by summation of the rocks from the top down, are also silica-poor (Fig. 2). The rocks waver between *ne* and *hy*-normative, confirming the lack of a siliceous trend.

11. Average rocks in the region 90–99 PCS have silica contents less than 46% and as little as 41%; the calculated liquids in this region dip as low as 43% SiO_2 (Fig. 2) because they are rich in magnetite component. The silica content of rocks and liquids crosses over at 92 PCS, after which the rocks are for a time very mafic; the Main Ore Band occurs at 93.5 PCS. The upper rocks of the layered group have regular exposure, stratigraphy, and structure that allows summations over them to be made with small uncertainty. Combined with the absence of field evidence for leakage, these compositions strengthen the case for low-silica liquids in Fenner-trend differentiation.

12. Activities of silica and oxygen calculated from the cumulus minerals of both intrusions show remarkably systematic differences consistent with their different inferred chemistries and with theory (see below).

Taken together, these features strongly support the conventional interpretation of the differentiation of the Skaergaard Intrusion.

Silica activity

The well-known olivine hiatus is a distinctive feature of the Skaergaard differentiation trend, and it contrasts with the continued crystallization of olivine, in the absence of Ca-poor pyroxene, in the Kiglapait Intrusion (Morse 1980a, 1980b). It is widely appreciated that the olivine hia-

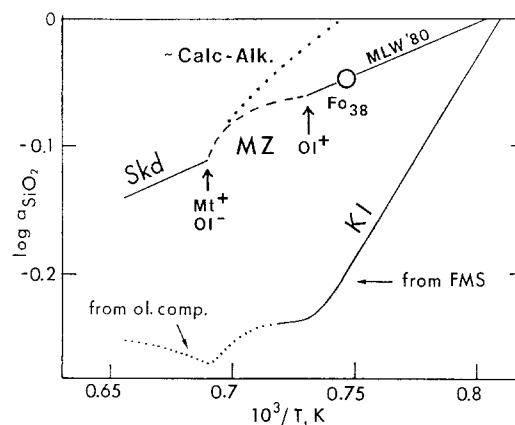


Fig. 3. Silica activities for Skaergaard and Kiglapait liquids, as calculated from the cumulate assemblages by Morse et al. (MLW, 1980) and by Morse (1980b), respectively. The olivine hiatus represented by the Skaergaard Middle Zone (MZ) is succeeded by a return to a silica activity low enough to stabilize olivine of composition Fo_{40} . If instead the liquid became rhyolitic, it would move on some such path as the dotted calc-alkaline line, and fail to produce the observed intermediate olivines. FMS on the Kiglapait curve refers to calculation from the fayalite = magnetite + silica equilibrium

tus represents the destabilization of Mg-olivine owing to a poisoning of the liquid by silica. This poisoning is proximally induced by the crystallization of magnetite, which causes a sharp rise in silica abundance (Morse et al. 1980), as appreciated by Hunter and Sparks. Calculations of the silica activity in the Skaergaard liquid, made from the mineral compositions in the cumulates, nicely illustrate this effect. In particular, they show a return to a slow evolution of silica activity after the crystallization of the Middle Zone. The original curve (from Morse et al. 1980, Fig. 1) is reproduced here in Fig. 3. The activity of silica is estimated to rise overall from about 0.7 in the LZ to 1.0 at the sandwich horizon. Although there is a kick in $a(\text{SiO}_2)$ at Mt^+ , as wanted by Hunter and Sparks, the remarkable feature of the Skaergaard trend is that it returns, at the end of the MZ, to a parallel trend, slightly offset upwards from the LZ trend during the MZ excursion. The olivines that constrain this behavior are the very rare hortonolites (e.g. Fo_{38} , Fig. 3) and ferrohortonolites that do not, as far as I know, characteristically occur in Icelandic lavas.

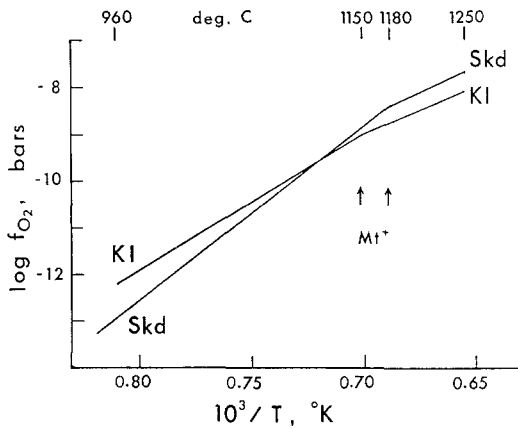


Fig. 4. Oxygen fugacities calculated from the cumulates at Skaergaard and Kiglapait (references as in Fig. 2). The distinctive feature of the comparison is that the earlier higher fugacity of oxygen at Skaergaard yielded an earlier arrival of magnetite, eventually driving the liquid to lower residual oxygen fugacity. Such a low f_{O_2} is inconsistent with production from a silica-rich rhyolite

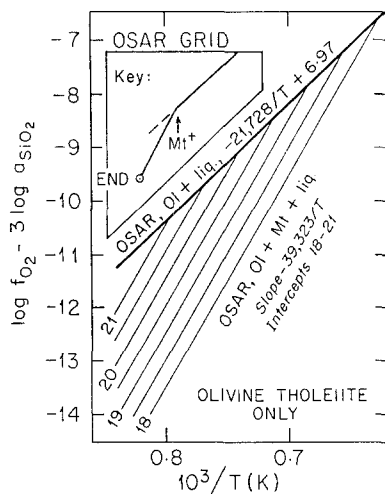


Fig. 5. Oxygen: silica activity ratio (OSAR grid) of olivine tholeiitic liquids. The constants for the curves are taken from Morse (1980b). The Skaergaard UZ trend follows the contour for the 18.5 intercept. The Kiglapait UZ trend lies near the 20 contour. Gas-bearing volcanic residua follow the *heavy line*, as at Makaopuhi. The Skaergaard trend is entirely predicted by the initial conditions in a closed system; it is therefore not part of a venting siliceous trend

By contrast, in the Hunter-Sparks hypothesis, the liquid embarks, at Mt^+ , on a siliceous excursion that must somewhat resemble the dotted "calc-alkaline" path in Fig. 3. Such a path would open the olivine hiatus toward the Fe end, and olivine would not be expected to return until near the fayalite composition, where iron-rich pyroxene becomes unstable at low pressures. The existence of olivines in the range Fo 10–40 in the Skaergaard cumulates strongly constrains the nature of the magma depositing them, in terms of silica activity. It appears incumbent on the proponents of the siliceous residua to show that these olivines can form in equilibrium with such residua; I doubt that such evidence exists.

The activity of silica calculated for the Kiglapait Intrusion ranges from about 0.5 to near 1.0 over the entire course of fractionation, evidently falling somewhat in the LZ and locally in the region of the Main Ore Band (Morse 1980b).

This result is consistent with the absence of an olivine hiatus at Kiglapait.

The estimated oxygen fugacities for Skaergaard and Kiglapait are compared in Fig. 4 (whose temperature scale is reversed from Fig. 3). The Skaergaard was evidently more oxidized at first, hence shed magnetite earlier and became more reduced than Kiglapait at the end of crystallization. These relationships of oxygen and silica are conveniently summarized in a plot of the oxygen: silica activity ratio (OSAR; Morse et al. 1980; Morse 1980b), as shown in Fig. 5. The main line of this grid represents the equilibrium crystallization of lavas in which gas is retained, as at Makaopuhi (Morse 1980b, Fig. 11). This is the line one would expect siliceous residua to follow. Instead, the Skaergaard end-stage falls about on the line representing the intercept 18.5, at a very much lower value of OSAR than the lava. The fact that the two layered intrusions and the lava lake, together with pure end-member reactions, successfully combine to predict these subtle and complexly intertwined relationships of oxygen and silica activities leaves very little room for doubt that all these systems fall in the olivine tholeiite class to which these interactions are intrinsically restricted. In sum, the low oxygen fugacity of the late-stage Skaergaard rocks is inconsistent with expectations for voluminous siliceous residua, but probably not with the minor, conjugate siliceous liquids inferred by McBirney and Naslund (this issue), which may be aided in their formation by gas filter-pressing, as found at Kilauea Iki by Helz (1987).

Iron enrichment, phase equilibria, and residual liquids

The density of evolved silicate melts is a strong function of their approach to saturation with magnetite. The relationships among iron enrichment, silica saturation, oxidation and liquid density are summarized elsewhere (Morse 1988, Fig. 8), but it is of interest here that the density maximum occurs where magnetite crystallizes most abundantly. The earlier this happens, the earlier silica enrichment will begin and the more strongly it is likely to persist, as in the calc-alkaline trend. The phases may be similar over a wide range of conditions, except for the silica-sensitive indicators olivine and low-Ca pyroxene. When phase equilibria are stated only in terms of the mode, a wide degree of freedom exists in the potential abundance of a component such as silica in the liquid, which can be constrained only by intensive parameters. The superficial similarity between cumulate mineralogy in the Skaergaard Intrusion and the phenocryst assemblage of lavas, used by Hunter and Sparks to justify the equivalence of liquids, is a necessary but not sufficient criterion for comparison.

The Hunter-Sparks hypothesis implies that evolved residual liquids can be quite unlike (e.g. much more silica-rich than) the rocks they produce in fractional crystallization. On the contrary, much evidence suggests that late-stage cumulates resemble their parent liquids very closely. This behavior is strikingly shown by the essentially buffered, constant rare-earth element concentrations in the Kiglapait Intrusion after the arrival of apatite (Morse and Nolan 1985), and by the small late-stage variation of many other elements including silica and iron (Morse 1981). The free parameters of chemical variation during such late stages are very few; they include Mg fractionation (until it reaches zero) and the concentration of K until the ternary minimum

feldspar composition is reached. Similarly, granites worldwide are like rhyolites in major respects, even where they are cumulates. It is probably a safe guiding principle that late-stage, multiply-saturated liquids are very like their cumulates instead of unlike them. The postulated existence of fugitive silica-rich liquids at Skaergaard lacks support among the cumulates.

Summary

Silica-poor, iron-rich liquids like those estimated for Skaergaard by Wager and Brown are preserved in Labrador as chilled pillows. Iron-rich rocks in the Kiglapait Intrusion have likewise been produced by liquids poor in silica. There is no reason to expect such liquids in volcanoes, so their absence as lavas means nothing about their possible plutonic occurrence. Successful tests of the siliceous liquid hypothesis would include showing that the proposed rhyolitic liquids can produce the observed olivines in the range Fo 10–40. They would require showing that the observed low- f_{O_2} oxide mineral assemblages can occur at the high silica contents proposed, and that the silicate mineral assemblages and compositions can represent high-silica liquids. I doubt very much that these critical tests can be met.

Acknowledgments. Discussions with A.R. McBirney have been most helpful, and I welcomed the opportunity to preview his manuscript with H.R. Naslund. I thank G.N. Hanson for suggesting the importance of differing tectonic setting between Iceland and Skaergaard in determining differences in magma type and differentiation behavior.

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A discussion of Hunter and Sparks (Contrib Mineral Petrol 95:451–461)

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Introduction

Hunter and Sparks (1987) have argued that the liquids from which the cumulate rocks of the Skaergaard Intrusion formed are quite different from those proposed previously and accepted in countless subsequent publications as well as by all presently active researchers on Skaergaard. Specifically they deny that these liquids differentiated towards ex-

remely iron-rich compositions but instead followed a trend of silica enrichment like those shown by many other extrusive volcanic rocks at other (but distant) sites in the North Atlantic Province. While this proposal is interesting, striking at one of the most widely accepted tenets of igneous petrology, we cannot agree with their conclusions for a number of reasons. Here we confine our comments to those parts of the Hunter and Sparks paper which directly refer