Albitized feldspars in granites and their bearing on the recognition of diagenetic vs detrital origin of albitized feldspars in sandstones

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AlDahan, A.A. 1991 03 01: Albitized feldspars in granite and their bearing on diagenetic vs detrital origin of albitized feldspars in sandstones. *Bulletin of the Geological Institutions of the University of Uppsala,* N.S. Vol. 16, pp. 47–60. Uppsala. ISSN 0302-2749.

Microscopic (light, SEM and cathodoluminescence) and electron microprobe data of albitized feldspars from the Proterozoic Dala granites in central Sweden reveal many similarities to features of albitized feldspars in sandstones. Secondary albite ($Ab_{>98}Or_{<0.3}An_{<1.5}$) has replaced partly or completely primary plagioclase and K-feldspar. Almost completely albitized grains commonly have a clouded appearance; they are untwinned, and consist mainly of fine (<20μm) subhedral to euhedral, tabular to compact and pseudorhombic-rhombic albite. Epidote, sericite, chlorite, fluorite and apatite are associated with these albitized feldspars. Both the occurrence of these minerals and the generally low intercrystalline porosity make the albitized feldspar in the Dala granites partly different from the diagenetically albitized feldspars in sandstones. A dissolution-crystallization model explains albitization of feldspars at temperatures <300°C and thus applies for low-temperature albitization in granites and sandstones.

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Introduction

The origin of secondary feldspars, especially albite, in rocks has received much attention during the last few decades. This is due to, among others: 1) many mineralization zones being associated with sodic (albitization) alterations (e.g. Eugster & Wilson, 1985; Kinnaird et al., 1985; Carten, 1986) 2) diagenetic albitization of detrital feldspars appearing to be a common process in hydrocarbon-associated sandstones (e.g. Land & Milliken, 1981; Boles, 1982; Walker, 1984; Saigal et al., 1988). This importance of secondary albite encouraged the author to investigate in detail the textural and chemical features of albitized feldspars in granite and to compare them with those in sandstones. This approach seemed useful because granitic rocks constitute a major source of detritus in many parts of the world. A better understanding of the features of their albitized feldspars thus will help elucidating the diagenetic vs detrital origin of albitized feldspars in sandstones. Although the data presented in this paper refer to granitic rocks from the Siljan impact area, the features described are expected to occur in other granitic rocks worldwide.

Samples and methods

Outcrops, cores and cuttings of granites were used in this study. The cores (3 samples) and cuttings (30 samples) cover about 3000 m of the deep borehole (Gravberg-1 well) in the Siljan Ring structure, central Sweden (Fig. 1). All the samples were thin sectioned and stained for the identification of feldspars. Selected thin sections were carbon-coated and used for backscatter imaging and analysis of element distribution in the feldspars by using a Cameca Camebax SX-50 electron microprobe. SEM examinations were made on 1–2 cm large samples by using a Philips SEM 525 equiped with a Link system.

Brief geology and petrology of the Dala granites

The rocks studied are 1.63–1.7 Ga old granites formed after the Svecokarelian orogeny (2–1.7 Ga). They occur within and around the eroded impact crater (about 52 km in diameter) of a 362–368

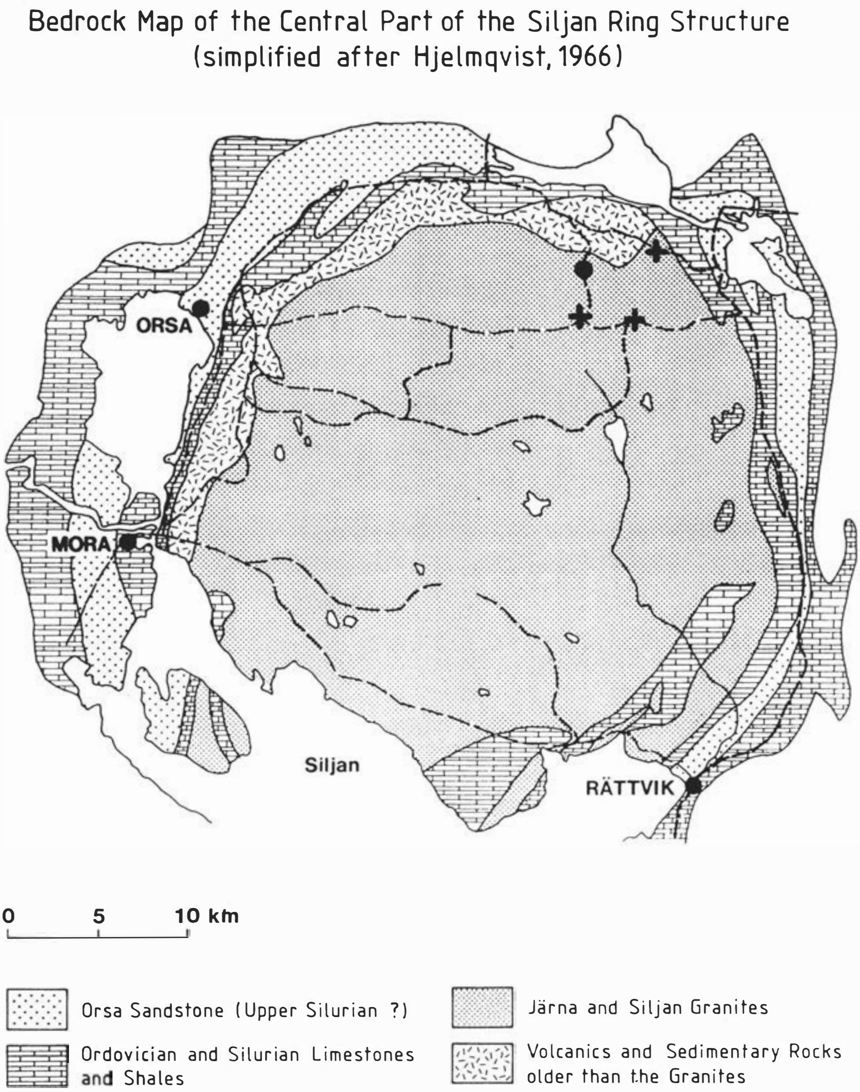


Figure 1. Location of the Gravberg-1 well (●) and outcrops (+) used in this study.

Ma old meteorite (e.g. Åberg & Fredriksson, 1984; Grieve, 1987, 1988). These granites show three main alteration styles: 1) deuteric (sericitization, saussuritization and albitization); 2) pre-impact burial metamorphism (in the prehnite-pumpellyite facies) and 3) impact and post-impact modifications (including extensive fracturing and alteration at <300°C). The third alteration is characterized by the formation of abundant secondary albite (up to 40%, estimated, of total feldspars), which dominates down to a depth of about 2000 m in the borehole section.

The granites studied vary between medium and coarse grained with some porphyritic parts. Besides quartz, microcline, albite, oligoclase and andesine, there are variable amounts (3−10 vol.%) of biotite, chlorite and hornblende. Epidote, magnetite, ilmenite, hematite and titanite are common minor minerals (1−3 vol.%). Traces (<1 vol.%) of zircon, fluorite, apatite, monazite, tourmaline and pyrite occur. In the upper 2000 m of the borehole section, most biotite and hornblende were altered into chlorite, sericite, hematite and titanium oxides. The feldspars were also partly altered to sericite, chlorite and epidote. The fractures are mainly filled up by quartz, albite, calcite, chlorite and epidote in addition to minor amounts of hematite and smectite.

Feldspars in the samples examined exhibit variable textures (Figs. 2 and 3). Their shapes vary from euhedral to anhedral, they are either twinned or untwinned, clouded or clear, zoned and/or mantled, extensively replaced by secondary minerals or fresh. Apart from these general textures, there appears to be a relationship of some of the features with depth. For example, occurrence of either clouded or clear crystals of untwinned albite is common in the upper 2000 m of the borehole. A change from twinned to untwinned crystals is found in several samples (Figs. 2 B and C). The cloudiness of untwinned albite seems to result from the presence of fine hematite and titanium oxide pigmentations, submicroscopic porosity and vacuoles or fluid bubbles (Figs. 4 A and B; cf. AlDahan et al. 1987). Untwinned albites showing irregular boundaries are observed in the upper 2000 m of the borehole (Fig. 3 C):

Microscopic and chemical features of albitized feldspars

In thin sections, albitized feldspars (particularly the plagioclases) are dominantly untwinned and clouded (Figs. 4 A and 4 B). The secondary albite in such grains appears as patches which either partly or completely replace the primary feldspar (Figs. 5–8). The albite patches may be randomly distributed (Fig. 8) or arranged along the traces of cleavage and twin composition planes (Figs. 5 and 7). In both cases, destruction of these primary crystallographic features occurs. SEM examination of the albite patches revealed densely packed subhedral crystals (Figs. 5 C and D), losely packed euhedral crystals (Fig. 8 B and C) or a combination of both types. Their relation with respect to the primary cleavages and twinnings vary between well oriented (Figs. 5 C–D and 7 B–C) and random (Figs. 8 B and C).

Intercrystalline (mainly dissolution) porosity is generally low in most albitized feldspars examined, but local variations may occur. For example, the grains in figure 8 show the highest intercrystalline porosity compared to those in figures 5 and 7. Albitization of the oligoclase in figure 7 has resulted in comparatively very low intercrystalline porosity.

Other, less frequent, textures of albitized feldspars are the occurrence of chessboard-like twinned grains showing pseudo- and antiperthitic habits. In the chessboard-like texture, the albite appears as relatively coarse crystals which are aligned in parallel orientation with the primary K-feldspar twinnings. These albite crystals are commonly euhedral,

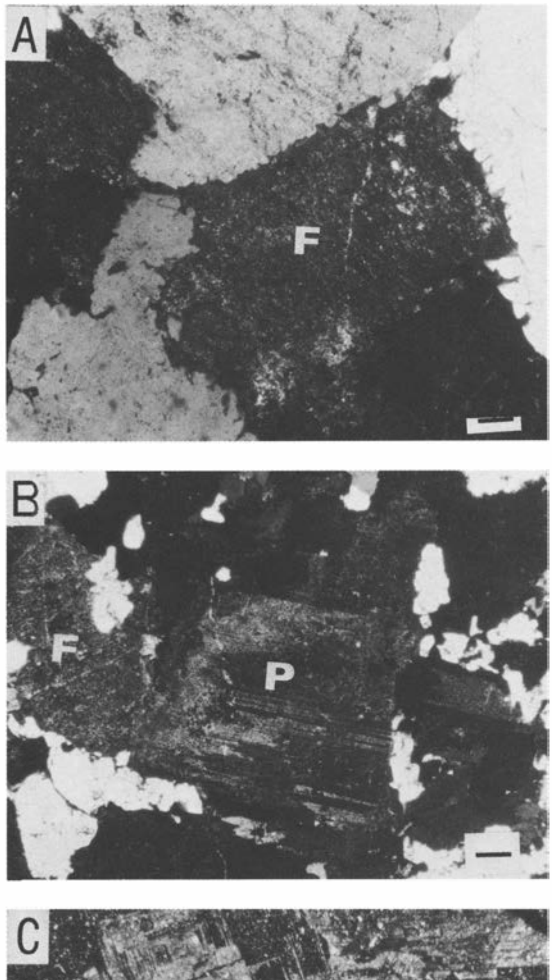


Figure 2. A. Untwinned and clouded feldspar grain (F). Crossed nicols (bar scale = 0.25 mm).
B. A transition from twinned-clear to untwinned-clouded parts in a plagioclase (P), F is clouded microcline. Crossed nicols (bar scale = 0.25 mm).
C. An early stage in plagioclase atteration showing the extensive minute pigments of sericite-albite-hematite and vacuoles. Crossed nicols; bar scale = 50 μm.

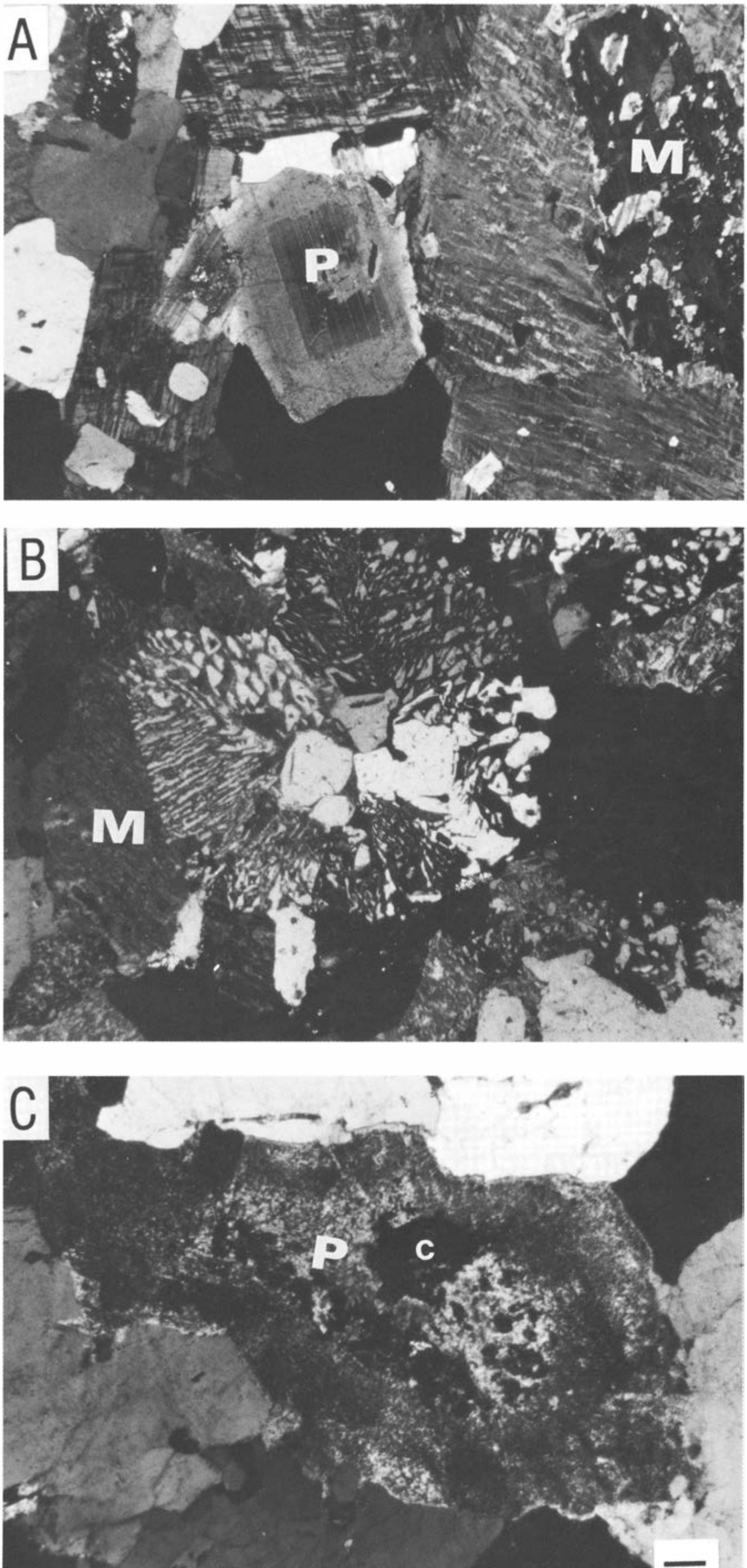


Figure 3. A. Mantled (overgrown) plagioclase (P) associated with mantled microcline (M). B. Myrmekitic intergrowth partly outlined by clouded microcline (M). C. Irregular and clouded plagioclase (P) in between quartz grains, c is chlorite. Crossed nicols; bar scale = 0.25 mm.

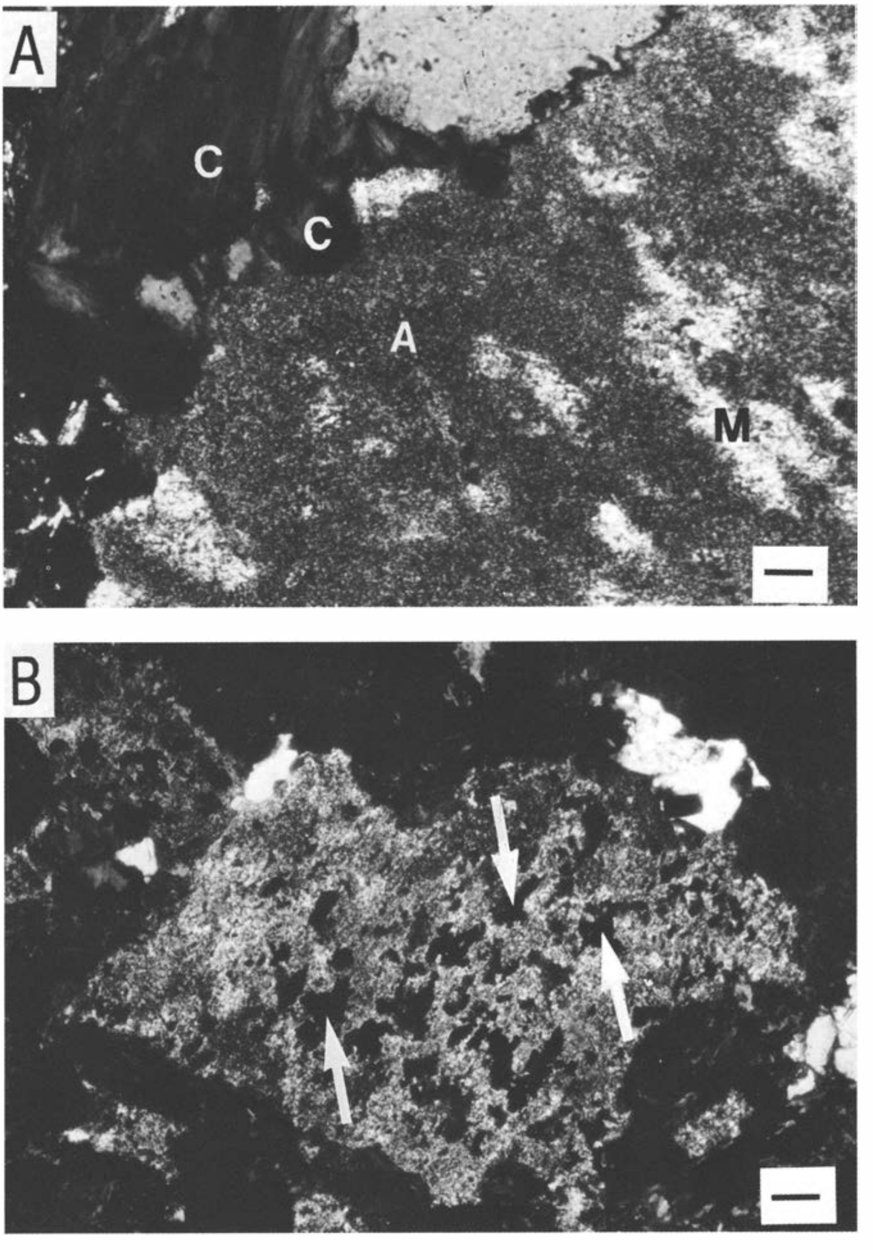


Figure 4. A. Clouded and untwinned albite (A) replacing microcline (M); C is chlorite. Crossed nicols; bar scale = 50 μm. B. Albitized plagioclase heavily clouded by hematite (arrows). Crossed nicols; bar scale = 0.1 mm.

tabular to compact and show pseudorhombic to rhombic sections (Figs. 9 B and C).

Preliminary examination with a high voltage cathodoluminescence microscope (at the Institute of Geology, Bern University) indicated that most secondary albite lacks luminescence or shows a dark brownish colour. The luminescence colours of the primary plagioclases are bright yellow and pink whereas the K-feldspar is bright blue.

Several minerals other than albite were found in the albitized feldspars. Sericite, hematite, Ti-oxides, titanite, chlorite and epidote are common. The albitized K-feldspars contain commonly quartz, hematite and sometimes epidote. Some albitized plagioclase and K-feldspar grains contain calcite, fluorite and apatite. The latter two minerals occur as anhedral crystals which are commonly randomly distributed within the altered feldspar grains.

Microprobe analysis of secondary albite in the albitized feldspars indicates variation in composition from almost pure end-member (up to 99 mol.) to composition containing up to 1.6 and 0.3 mol.% orthoclase and anorthite, respectively (Table 1). The contents of anorthite in the primary plagioclase generally vary between 10 and 40 mol.%.

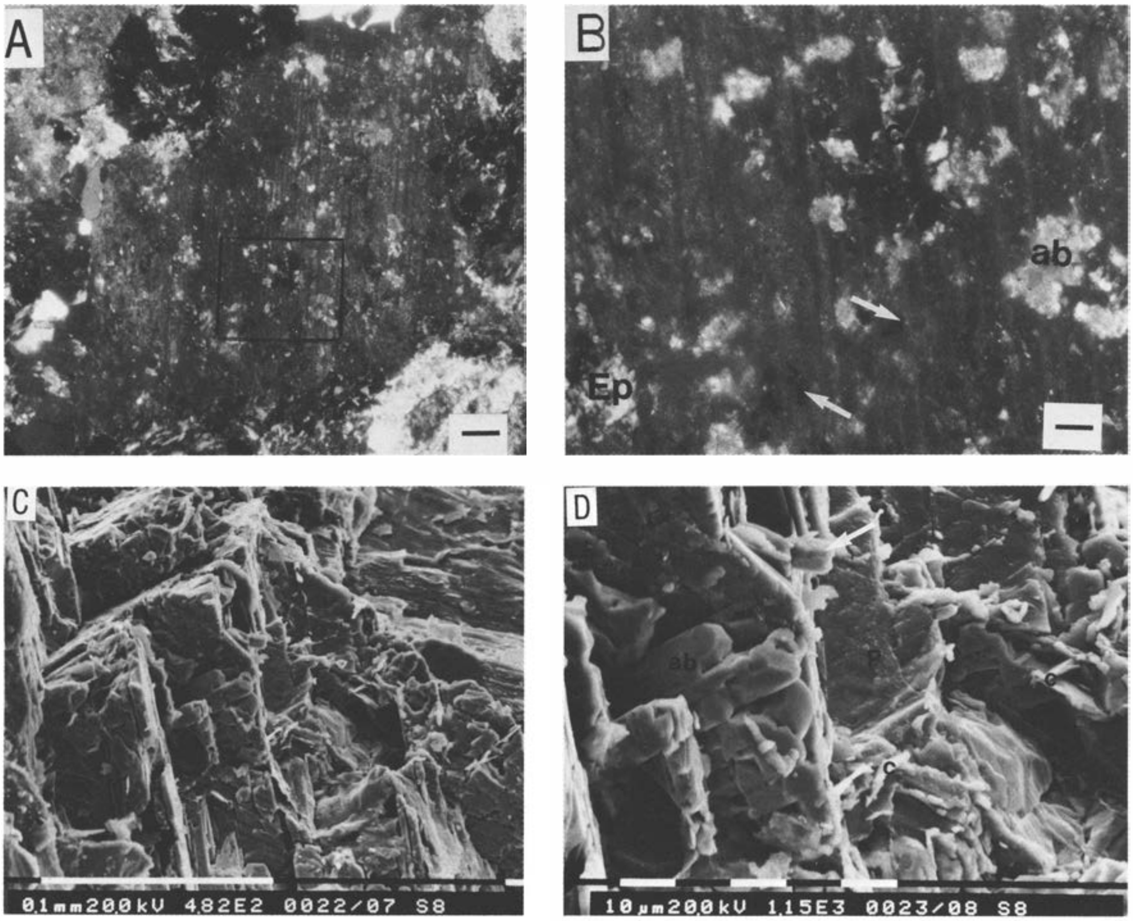


Figure 5. A. An oligoclase grain showing patchy replacement by albite, chlorite, epidote and hematite. Crossed nicols: bar scale = 0.25 mm.
B. Part of fig. 5 A (delineated area) at higher magnification showing the albite (ab), chlorite (c), epidote (Ep) and hematite (arrows). Observe the distortion of twinning features due to replacement. Crossed nicols; bar scale = 50 µm.
C. SEM photograph of a grain showing similar features to that of fig. 5 A.
D. Higher magnification of the middle part of fig. 5 C showing the albite (ab), chlorite (c) and epidote (arrows). P is a primary oligoclase.

Table 1. Representative microprobe analyses of secondary albite (1 and 2) and primary plagioclase (3 and 4) in the granite studied.

Wt.%	1	2	3	4
SiO_2	67.54	68.20	63.51	66.21
Al_2O_3	19.83	19.84	21.49	20.61
TiO_2	0.01	0.00	0.01	0.02
FeO	0.08	0.06	0.31	0,11
MgO	0.00	0.00	0.01	0.01
MnO	0.00	0.01	0.01	0.01
CaO	0.20	0.08	4.76	3.01
Na_2O	11.24	11.18	8.92	9.88
K_2O	0.10	0.07	0.01	0.08
total	99.01	99.08	99.02	99.94
Numbers of cations on the basis of 32(0)				
Si	11.93	12.02	11.37	11.66
Al	4.13	4.04	4.53	4.28
Fe	0.00	0.00	0.04	0.01
Ca	0.03	0.01	0.91	0.56
Na	3.86	3.83	3.09	3.37
K	0.01	0.00	0.00	0.01
Mol.%				
An	1.53	0.52	37.07	24.89
Ab	98.22	99.48	62.93	74.89
Or	0.25	0.00	0.00	0.22

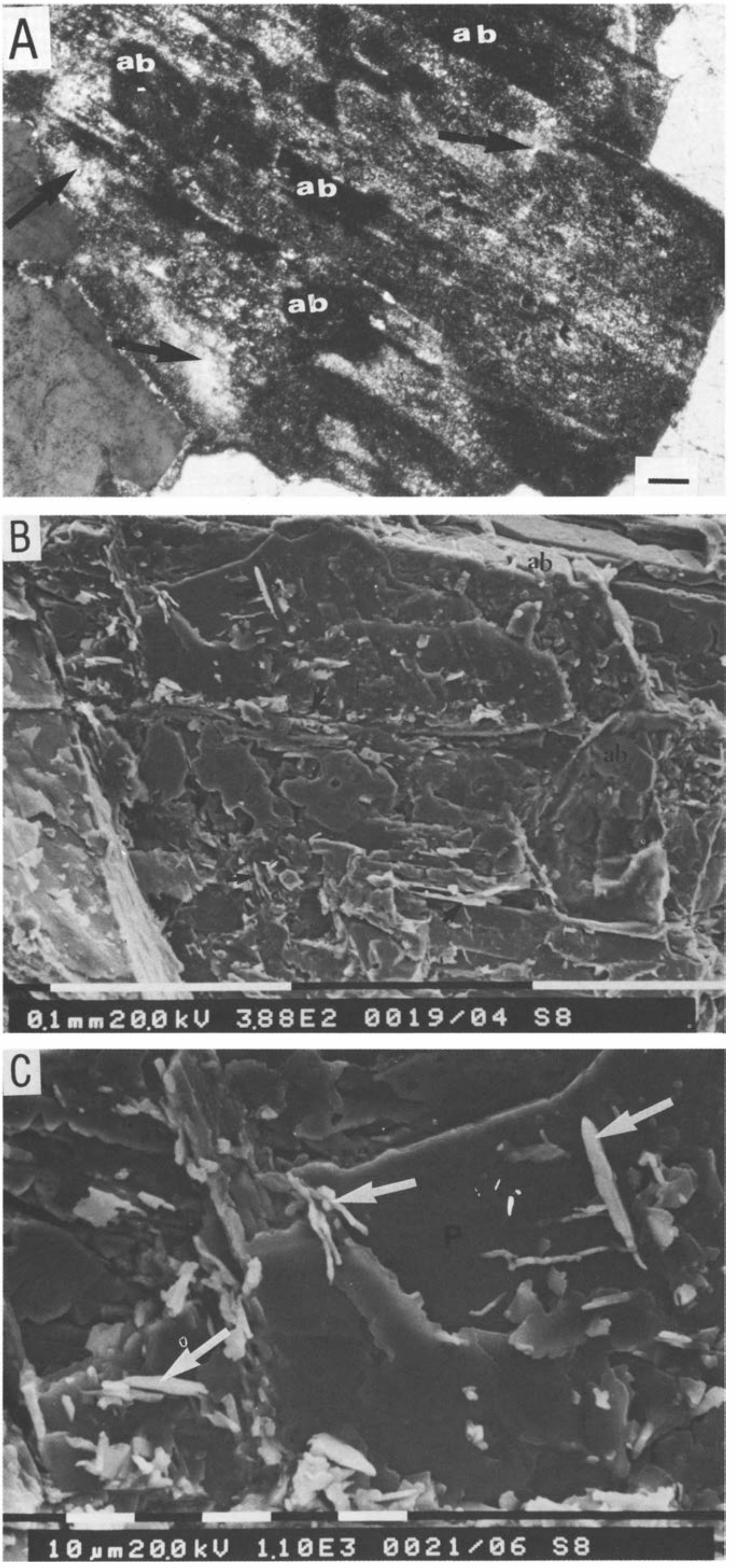


Figure 6. A. A partly albitized (ab) and sericitized (arrows) oligoclase. Crossed nicols; bar scale = 0.1 mm.
B. Part of a grain similar to fig. 6 A as shown by SEM; ab is albite and arrows is sericite.
C. Higher magnification of the left upper part of fig. 6 B showing sericite flakes; P is oligoclase.

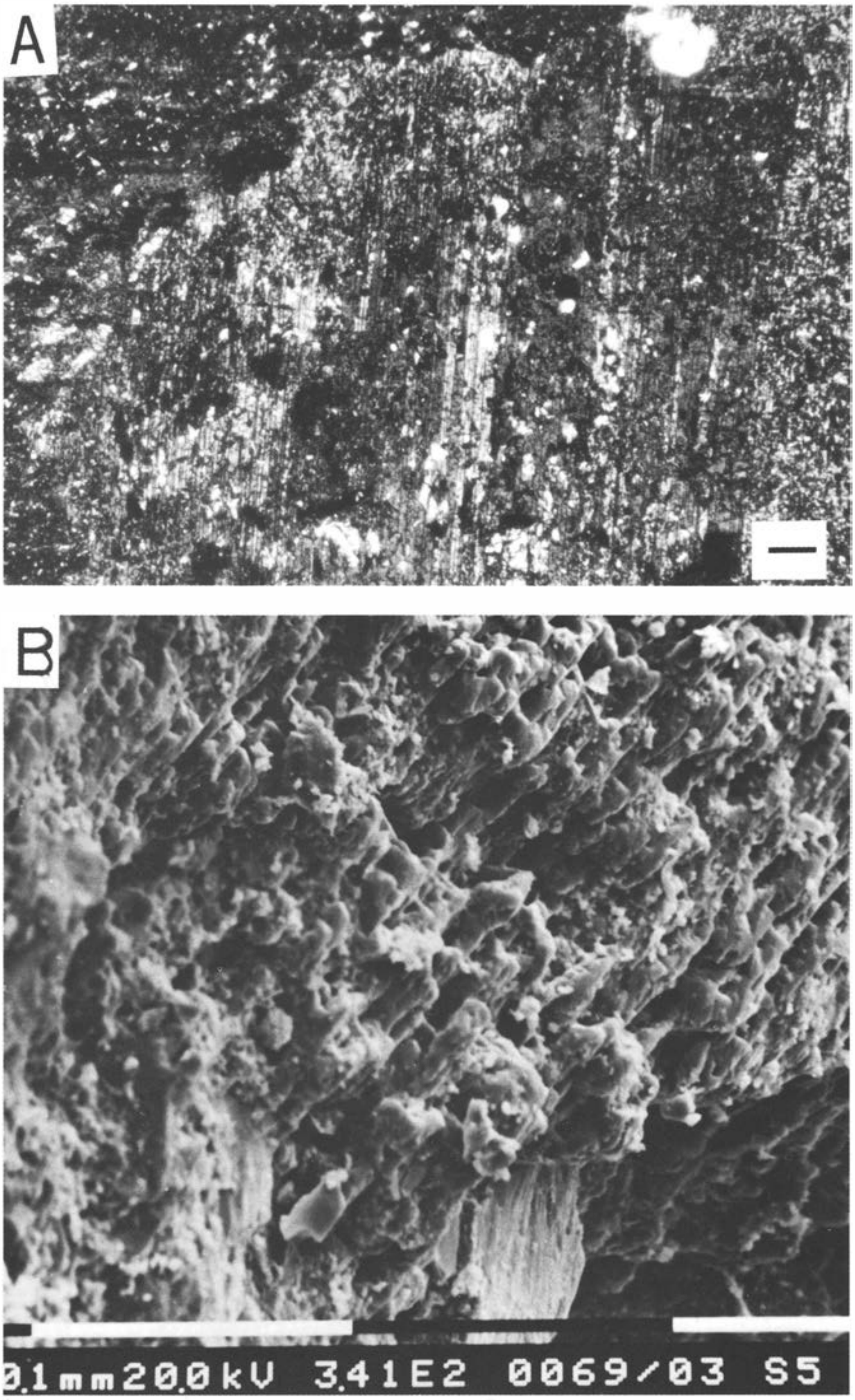
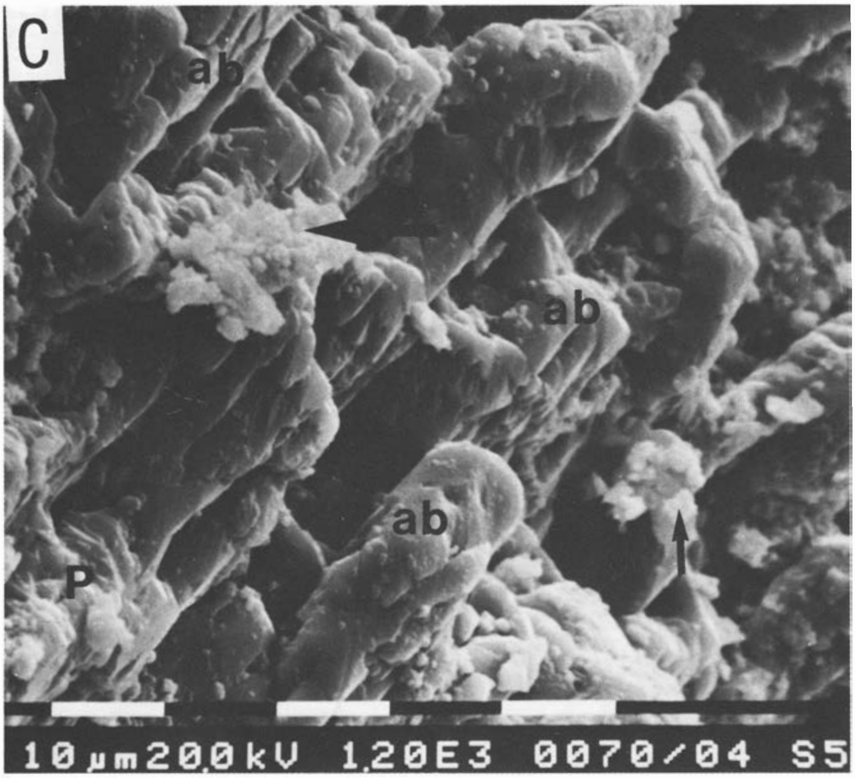


Figure 7. A. Extensively altered plagioclase by minute crystals of albite, sericite, epidote and quartz. Crossed nicols; bar scale = 0.1 mm.
B. SEM photograph of a grain similar to fig. 7 A showing the strongly altered surface of the plagioclase.
C. Higher magnification of part of fig. 7 B showing the minute crystals of albite (ab), sericite (arrows) and microvoids.



Discussion

Similarity between the features of detrital albitized feldspars and those formed during diagenesis is a known problem for sedimentary petrologists. Indeed this fact repeats itself when comparing features of albitized feldspars in the granite studied (AFG) with those reported for diagenetically albitized feldspars (DAF) (e.g. Middleton, 1972; Boles, 1982; Walker, 1984; Morad, 1986; Gold, 1987; Saigal et al., 1988). Both types of albitization share features such as cloudiness (also referred to as dusty, dirty, turbid), occurrence of chessboard-like twinning, lack of luminescence, a high purity albite composition and less commonly lack of polysynthetic twinning. In spite of these shared characters, some differences were observed in this study. One such difference is the commonly low intercrystalline porosity of AFG relative to that of DAF. Although data on intercrystalline porosity are not available on the DAF in most literature on the subject, the results of e.g. Morad (1986) indicate up to 100 µm across pores in the DAF of the Visingsö sandstones. This size of the intercrystalline pores is ten times larger than that encountered in the AFG (Figs. 6–8). This low intercrystalline porosity of the AFG together with the generally low total rock porosity is a major hindrance during detailed SEM examinations of granites. Neverthless another textural difference between the AFG and DAF is in the ratio and arrangement of the secondary albite crystals and patches. In sandstones, these commonly dominate and mostly overprint the primary feldspar phase and are usually equally scattered (e.g. Walker, 1984; Morad, 1986) whereas random scattering and local minor replacement is common in AFG (Figs. 4 A and 5 A). An additional difference between the AFG and DAF is the type of associating minerals. Epidote, titanite, sericite, chlorite and occasionally apatite and fluorite are common in the AFG. Documentation of minerals other than the feldspars in the DAF includes: 1) calcite in the Frio sandstones (Tertiary; Boles, 1982); 2) anhydrite and dolomite in the Fountain Formation (Pennsylvanian; Walker, 1984), 3) illite, calcite, quartz and Fe-oxides in the Visingsö Group (Upper Proterozoic; Morad, 1986) and 4) phengite, ankerite and quartz in the Brøttum Formation (Upper Proter-

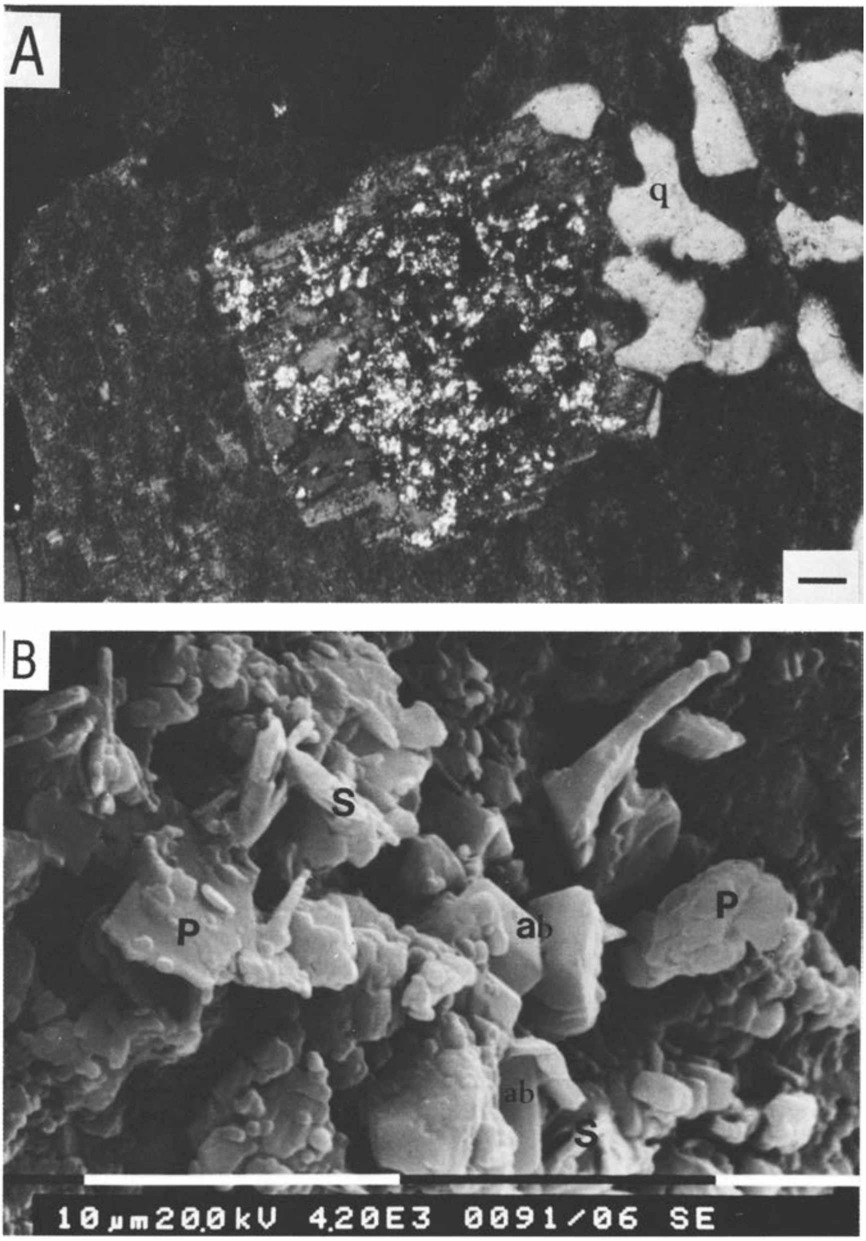
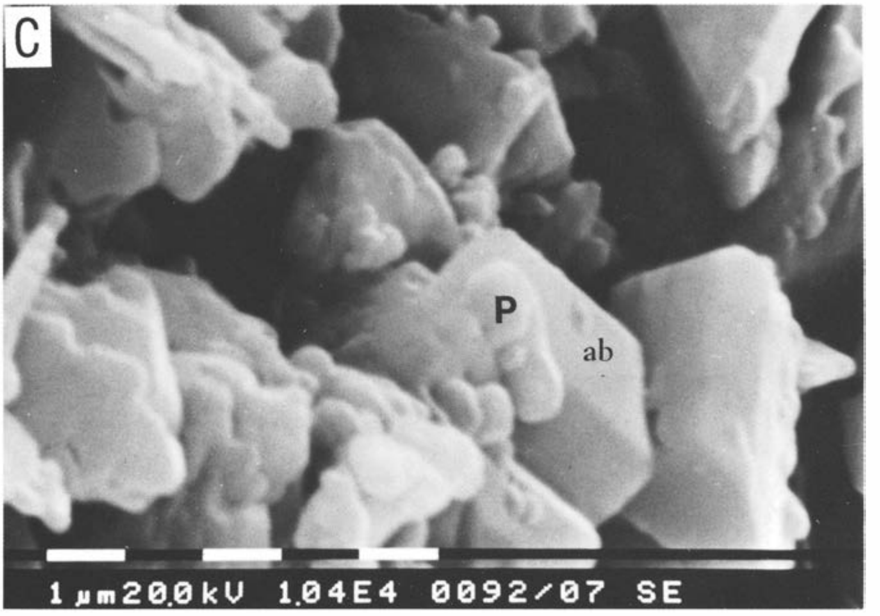


Figure 8. A. Oligoclase selectively replaced by minute albite and sericite crystals; q is quartz. Crossed nicols; bar scale = 0.25 mm.
B. SEM photograph of a grain similar to fig. 8 A showing the remnants of the oligoclase albite (ab) and sericite (S).
C. Higher magnification of part of fig. 8 B showing the rhombic albite (ab). P is oligoclase.

ozoic; Morad 1988). Occurrence of e.g. sericite, chlorite, pumpellyite, prehnite and laumontite were observed in albitized feldspars of sandstones which were affected by high grade diagenesis to very low grade metamorphism (Coombs, 1954; Martini, 1968).

The differences outlined above between the AFG and DAF were based on the occurrence of grains as



single entities outside their matrix (i.e. crystalline and sedimentary, respectively). This was done for the purpose of extending the discussion towards how the features of the AFG will be affected upon weathering and erosion and deposition in a sedimentary basin. My experience with textural evaluation of altered feldspars in sandstones (e.g. AlDahan & Morad, 1987) and observations from the literature (e.g. Berner & Holdren, 1979) indicate difficulty in applying textural criteria given above. This is because most feldspars were highly altered by weathering processes. On the other hand, a check on the minerals associated with the albitized feldspars seems to be very helpful in all cases. In fact none of the documented DAF in the literature indicate the occurrence of epidote, apatite and/or fluorite. Similarly, a careful differentiation between sericite and illite (e.g. by means of microprobe analysis) can also give clue to either origin; sericite contains more K_2O and less H_2O compared to illite. Sericite is a common mineral in most AFG (cf. Ferry, 1985, Klemd & Hallbauer, 1987). Variation in the composition of calcite may help verifying origin of albitization. Calcite in the AFG is found to be pure (99.5 wt.% $CaCO_3$). Available data on the composition of calcite in DAF are scarce. However, data reported by Boles (1982) indicate a pure calcite in DAF, whereas Morad (1986) indicates an Fe-Mg bearing calcite in DAF. The coexistence of incompatible feldspars (e.g. low temperature albite with andesine containing 30–40 mol.% An) does not necessarily prove a diagenetic albitization, because such occurrences are also observed in the AFG studied.

Some of the features found in the AFG and DAF appear to originate from the same causes. For example the lack of twinning in the DAF and those of the granite could partly be related to the habit of crystallization and growth mechanism. SEM data (in the Dala granites and in sandstones) indicate that the secondary albite generally appears as fine crystals which may or may not be arranged parallel to the trace of twin composition and/or cleavage planes of the primary grain. Such patterns will both destroy the twin character of the primary grain as well as contribute to the cloudiness. Experimental data on albitized plagioclase (e.g. Moody et al. 1985; Rosenbauer et al. 1988) also support such crystallization habits of the secondary albite and indicate that the dominant morphology of albite is lath-like to tabular albite as also shown by figures 5C and 7C. Occurrence of albite in such modes could be explained by a dissolution-crystallization mechanism (cf. e.g. Boles, 1982; AlDahan & Morad, 1987). By such a model active crystallization of secondary (low-temperature compatible) albite would have been preceded by dissolution of the primary high-temperature (e.g. magmatic) feldspar. The formation mechanism of the secondary albite could be visualized by the following general reaction:

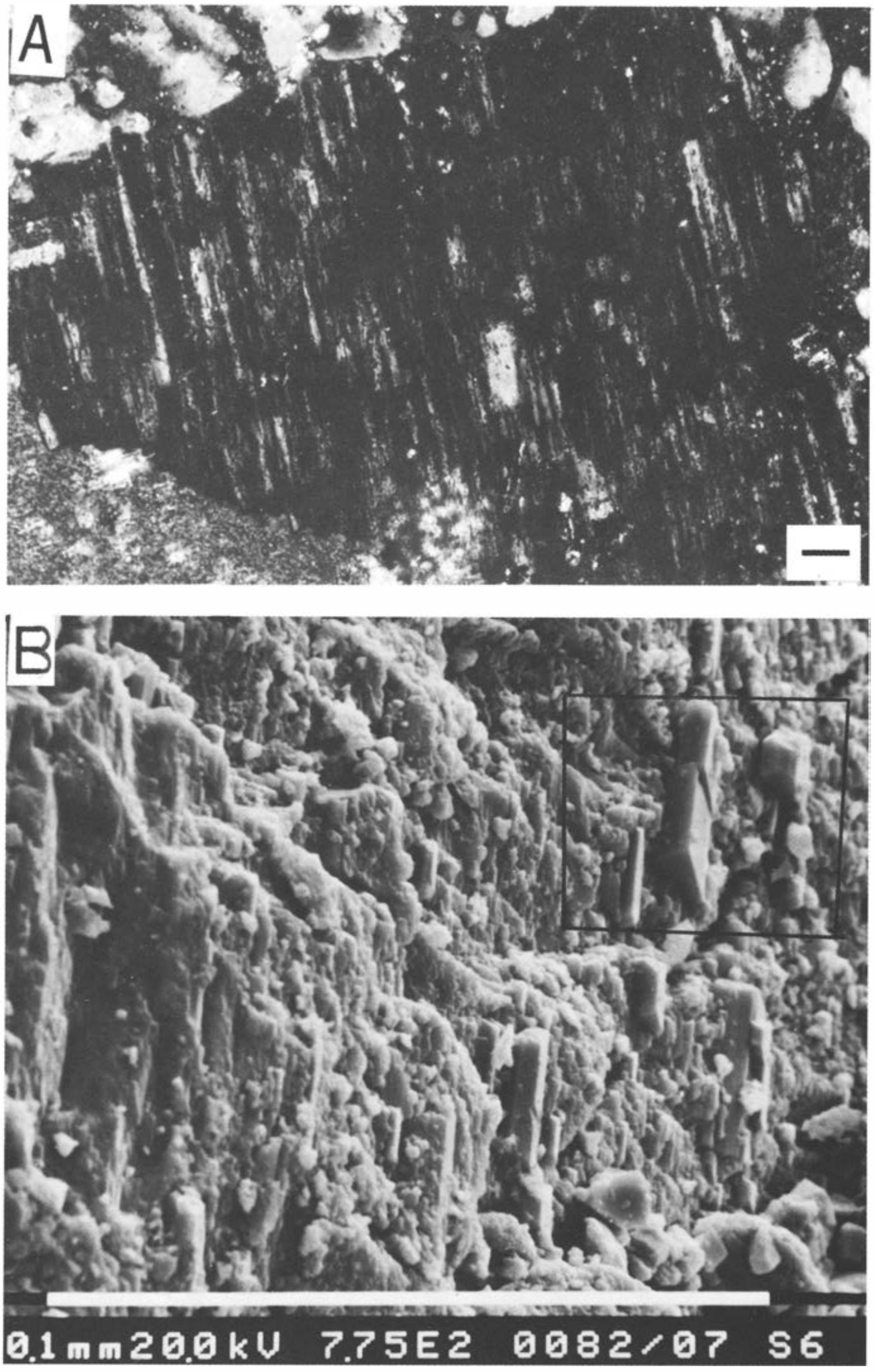


Figure 9. A. Chess-board like (blocky) texture in an albitized microcline grain. Crossed nicols; bar scale = 0.25 mm.
B. SEM photograph of a part of fig. 9 A showing the alignment of albite crystals in a parallel arrangement reflecting primary cleavages of the microcline.
C. Higher magnification of part of Fig. 9 B (delineated area) showing the variable crystal habit of the albite. M is microcline.

Andesine + Microcline + $3H^+$ = Albite + K^+ + Ca^{2+} + $1.5H_2O$ (1)

If we consider the hydrolysis and dissolution model introduced by Helgeson et al. (1984) and the subsequent experimental verifications by Chou & Wollast (1985) and Holdren & Speyer (1985), then reaction (1) should pass through a general subreaction as follows:

Andesine + Microcline + nH^+ = $H_xAlSi_3O_8$ + $n-x(Ca^{2+}, Na^+, K^+)$ hydrogen feldspar (2)

The hydrogen feldspar is unstable and thus rapidly dissociates into different types of Al-Si complexes depending on the pH of the reacting fluids (cf. Chou & Wollast, 1985). These complexes may either precipitate as poorly ordered hydrated Al-silicate phases which inherit the primary feldspar lattice structure (cf. DeVore, 1959 and Tazaki, 1986) or dissociate into simpler forms in reacting fluids. This process depends on the permeability conditions and activity of H_2O which appear to control the texture of the albitized grains. Of course porosity and permeability are different between granites and sandstones, but most observations (e.g. Boles, 1982; Morad, 1986; and this work) suggest that the albitization process is very selective with respect to microenvironment (i.e. on thin section scale). Thus feldspars in granite or sandstone can be exposed to the same conditions. This may also partly explain the similarity in most textures of albitized feldspars in both rock types. For example, when relatively low permeability and activity of H_2O prevail, then the released Na^+ (from reaction (2)) from the unstable high-temperature feldspars rapidly reaches a high enough concentration to react with Al-Si phases and restructuring into a low temperature compatible feldspar (e.g. albite) occurs. Such a mechanism could explain the common parallel growth (i.e. inheriting crystallographic orientation of the primary feldspar) of secondary albite crystals along traces of the primary relic cleavage.

Acknowledgements.– The author thanks S. Morad and D.S. Coombs for valuable comments and K. Ramseyer for the help with the cathodoluminescence microscopy. Samples were kindly provided by the Swedish State Power Board (Vattenfall) and Dala Djupgas Produktions AB. Tord Lindbo is specially acknowledged.

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Printed by Ekenäs Tryckeri Ab, Ekenäs, Finland March 1st, 1991