

MICA ALTERATION REACTIONS IN JURASSIC RESERVOIR SANDSTONES FROM THE HALTENBANKEN AREA, OFFSHORE NORWAY

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Abstract—Petrographic observations indicate that dolomite, siderite, pyrite, Ti oxides, quartz, and K-feldspar formed as by-products of mica alteration during diagenesis of Jurassic reservoir sandstones of the Haltenbanken area (offshore central Norway). These minerals precipitated on a mica-grain scale or a thin-section scale. Modal analyses and mass-balance calculations of muscovite alteration to kaolinite and of biotite to kaolinite, illite, and chlorite suggest limited elemental mobility during sandstone diagenesis. The alteration of mica to kaolinite occurred in sandstones buried <2200 m deep (present temperature <70°C), whereas illitization and chloritization of biotite occurred during burial to depths >3000 m (present temperature >95°C).

Key Words—Alteration, Burial diagenesis, Chlorite, Illite, Kaolinite, Mica, Sandstone.

INTRODUCTION

Quantification of mica alteration reactions by use of mass-balance calculations can reveal the extent of material transfer in diagenetic systems and elucidate the role of mica in sandstone cementation. In this paper, such mass-balance calculations are presented for mica alteration in Jurassic sandstones from the Haltenbanken area, offshore of central Norway (Figure 1).

Detrital biotite and muscovite are common in clastic rocks of the North Sea and other offshore reservoirs. Many minerals result from alteration of these micas, and some, particularly clay minerals, can significantly lower the permeability of the reservoir rocks (Pallat *et al.*, 1984; Hurst and Archer, 1986). Karlsson (1984) observed that in Jurassic sandstones of the Haltenbanken area, muscovite is “expanded” and illitized, whereas biotite is replaced by siderite. Bjørlykke *et al.* (1979) concluded that alteration of mica in Jurassic sandstones from the Statfjord Field retarded silica cementation, whereas growth of carbonates and feldspar along cleavage planes of mica was enhanced due to the high pH of this microchemical environment. Microprobe analyses revealed a gradual transition in chemical composition between the original mica and the replacive illite. Morad (1986b) and Morad and AlDahan (1986) suggested that such chemical trends were due to variable proportions of mica and clay minerals analyzed by the electron beam. Gjelsvik and Bjørkum (1984) suggested that increased pH at the mica surfaces enhanced the dissolution of detrital quartz in sandstones of the North Sea. Bjørlykke and Brendsdal (1986) and Bjørlykke *et al.* (1986) concluded that alteration of mica is the most important factor controlling the porosity and permeability in Jurassic reservoir sandstones of offshore Norway. Potassium released during

the kaolinitization of mica buffered the pore waters and enhanced the precipitation of K-feldspar. Simultaneous formation of kaolinite and K-feldspar by muscovite breakdown in a closed system (<50°C) was discussed on a thermodynamic basis by Bjørkum and Gjelsvik (1988) for Jurassic North Sea sandstones. Mica alteration to clay and other minerals has been described for several sandstone sequences from different parts of the North Sea and other basins of the world (see, e.g., Burley, 1984; Huggett, 1984; Morad, 1986a; Boles, 1987; Warren, 1987).

GEOLOGICAL SETTING

The Haltenbanken area of the Norwegian Sea (Figure 1) is part of a passive continental margin between the Møre Basin and the Trøndelag Platform and represents a southern extension of the Nordland Ridge (Jørgensen and Navrestad, 1981). The shallowest (1500–2000 m below seafloor) reservoir sandstones (Upper Jurassic; Early Kimmeridgian to Early Portlandian) occur in the Draugen Field in southeast Haltenbanken (Figures 1 and 2). These sandstones are a shallow-marine facies near the edge of the Trøndelag Platform. The Middle Jurassic sandstones of the Garn Formation in the Midgard Field occur at depths between 2000 and 3000 m, with marginal marine deposits in the south and open marine deposits in the north. In the Tyrihans Field, these sandstones occur between 3000 and 4000 m (a marginal marine facies) and in the Smørbull Field, between 4000 and 5000 m. Reservoir rocks of the Lower Jurassic Tilt Formation lie between 2100 and 3100 m near the Midgard area, whereas in northwest Haltenbanken they occur at 4200 to 4600 m. The primary hydrocarbon source rocks are the shales of the Upper Jurassic Spekk Formation, which is structurally lower

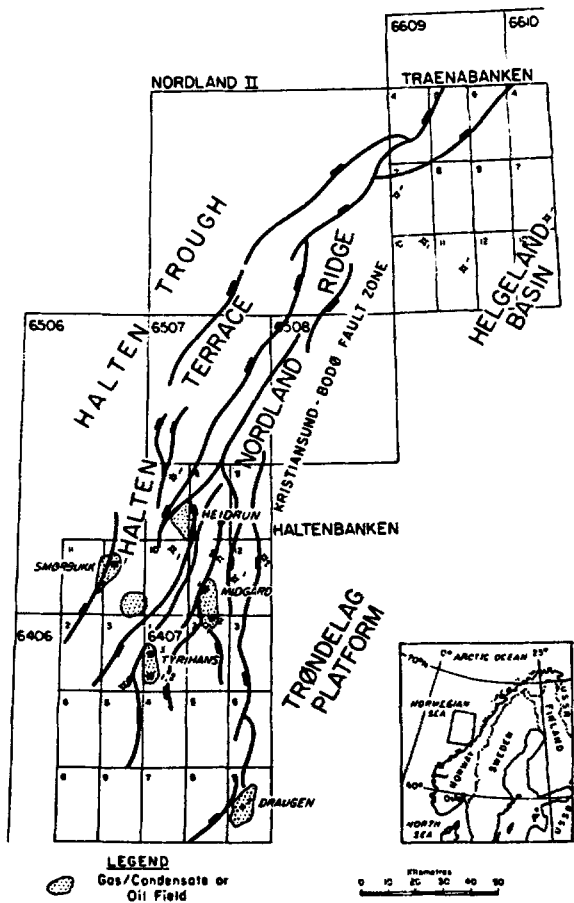


Figure 1. Map of the Haltenbanken area, offshore central Norway, showing location of the wells studied.

than the main reservoir sandstones of the Garn and Tiltle Formations.

The burial history of the Jurassic sandstones is characterized by three events: (1) slow burial from Jurassic to earliest Cretaceous, (2) moderately slow burial from Early Cretaceous to Early Pliocene, and (3) rapid burial from Early Pliocene to Recent. The final stage involved accumulation of 1000–1500 m of sediment. Therefore, source rock maturation and hydrocarbon migration have occurred relatively recently in many parts of the Haltenbanken area (Bjørlykke *et al.*, 1986) and have retarded diagenetic processes in the sandstones.

The pattern of diagenesis can be broadly related to two burial depths (modified after Bjørlykke *et al.*, 1986 and Saigal *et al.*, 1988): (1) moderate-burial diagenesis (1600–2200 m) encompassing the formation of kaolinite, K-feldspar overgrowths, minor quartz, Ti oxides, pyrite, siderite, and calcite, and (2) deep-burial diagenesis (>2200–5000 m), including the precipitation of quartz overgrowths, chlorite, and Fe-dolomite-ankerite, the albitization of detrital K-feldspar, and the

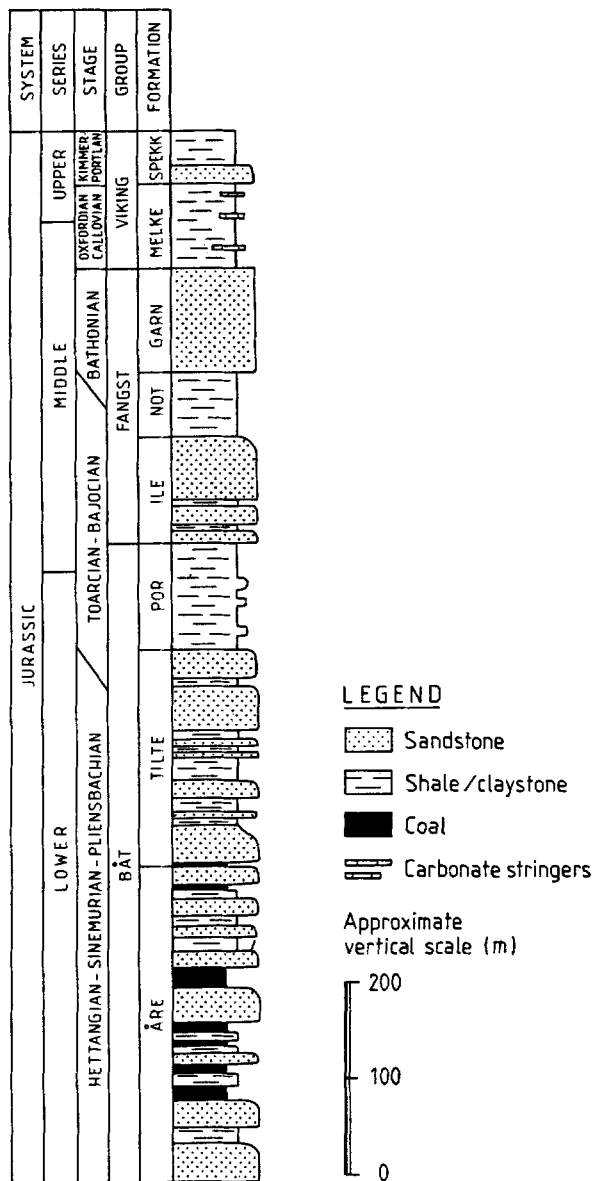


Figure 2. Jurassic stratigraphy in the Haltenbanken area.

illitization of kaolinite. The intensity of these processes increases systematically with depth.

SAMPLES AND METHODS

About 80 sandstone core samples were obtained from depths between 1700 and 5000 m. These samples were thin sectioned and examined with a standard petrographic light microscope. Twenty-four representative sections were coated with a thin layer of carbon and examined using the backscattered electron detector (BSE) of a JEOL JSM 840 scanning electron microscope (SEM). Small sample chips were coated with a

Table 1. Formulae of minerals used in construction of mass-balance reactions.¹

Mineral	Average formula ²
Biotite	$K_{0.89}Na_{0.11}(Fe_{1.21}Mg_{1.00}Al_{0.33}Ti_{0.19})(Al_{1.12}Si_{2.88})O_{10}(OH)_2$
Muscovite	$K_{0.85}Na_{0.03}(Fe_{0.10}Mg_{0.09}Al_{1.88})(Al_{0.87}Si_{3.13})O_{10}(OH)_2$
Illite	$K_{0.61}(Fe_{0.16}Mg_{0.21}Al_{1.78})(Al_{0.66}Si_{3.34})O_{10}(OH)_2$
Chlorite	$(Fe_{2.52}Mg_{1.21}Al_{1.85})(Al_{0.97}Si_{3.03})O_{10}(OH)_8$
Siderite	$(Fe_{0.74}Mg_{0.18}Ca_{0.08})CO_3$
Dolomite	$Ca_{1.01}Mg_{0.86}Fe_{0.13}(CO_3)_2$

¹ Based on average microprobe analyses of at least 15 grains.

² Iron was assumed to be only as Fe(II).

thin layer of gold and examined using the secondary electron detector of the SEM in order to observe textural relations between mica and alteration products. Some thin sections were analyzed with a Cameca Camebax SX-50 electron microprobe, employing an acceleration voltage of 15 keV and a beam diameter of 1 μ m. The standards used were wollastonite (Ca and Si, 20 s), orthoclase (K, 5 s), corundum (Al, 20 s), MgO (Mg, 20 s), MnTiO₃ (Mn, 20 s), albite (Na, 5 s), and hematite (Fe, 20 s).

RESULTS

Petrography

The sandstones are fine- to medium-grained, moderately sorted to well-sorted subarkoses and arkoses, in which the framework materials are quartz (35–60%), feldspars (5–20%), micas (3–10%), rock fragments (2–7%), and traces of heavy minerals (garnet, zircon, apatite, rutile, and altered Fe-Ti oxides). The feldspars are predominantly albitized K-feldspar grains, although the original K-feldspar is preserved in sandstones heavily cemented by carbonates. The cements are mainly clay minerals (kaolinite, illite, and, less commonly, chlorite), carbonates (calcite, siderite, dolomite, and Fe-dolomite-ankerite), and quartz. Small amounts of authigenic pyrite, Ti oxides, phosphate, and feldspar overgrowths are common. The thin-section porosity of the sandstones ranges between 3% and 23% and clearly decreases with depth.

Mica alteration

Microprobe analyses of detrital muscovite (Table 1) revealed that the tetrahedral Si content is about 3.0 of 4 sites and that octahedral sites are occupied by Al and small amounts of Fe and Mg. Detrital biotite was found to be rich in tetrahedral Si and octahedral Ti, and to have a greater Fe than Mg content. The biotite is therefore considered to be Fe-biotite (Foster, 1960).

The kaolinitization of mica was noted in sandstones buried at depths of less than 2200 m (present temperature < 70°C). At this depth, replacement was common

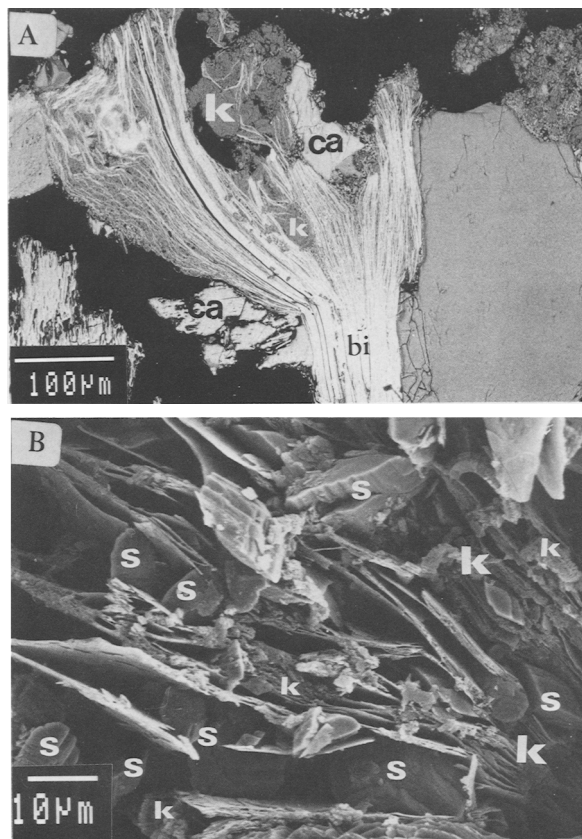


Figure 3. (A) Backscattered electron image (BSE) of biotite (bi and bright areas) replaced by kaolinite (k and grey areas). Calcite (ca), which does not occur in surrounding pores, was probably stabilized by the kaolinitization of biotite. Depth = 2000.3 m. (B) Scanning electron micrograph of biotite sheets partly replaced by kaolinite (k) and siderite (s). Depth = 2000.3 m.

in micas deformed between the rigid quartz and feldspar grains (Figure 3A). Variable amounts of siderite ($Fe_{0.74}Mg_{0.18}Ca_{0.08}CO_3$), dolomite ($Ca_{1.02}Mg_{0.93}Fe_{0.05}(CO_3)_2$), Ti oxides, and pyrite were noted in the immediate vicinity of or between the cleavage planes of kaolinitized micas (Figures 3A and 3B). Authigenic K-feldspar was not observed between sheets of kaolinitized micas, but was noted as overgrowths on detrital K-feldspar (cf. Bjørlykke *et al.*, 1986).

The illitization of biotite was observed in sandstones buried at depths greater than 3000 m (present temperature > 95°C). The illitization appears to have initiated along cleavage planes (Figure 4A) and continued outwards to result in almost complete replacement of the biotite grains (Figure 4B). Crystals of quartz, anatase, pyrite, dolomite ($Ca_{1.01}Mg_{0.86}Fe_{0.13}(CO_3)_2$), and siderite were noted intimately mixed with illitized biotite (Figure 4C); chlorite was also observed (Figure 4D). Microprobe analyses revealed that small amounts of

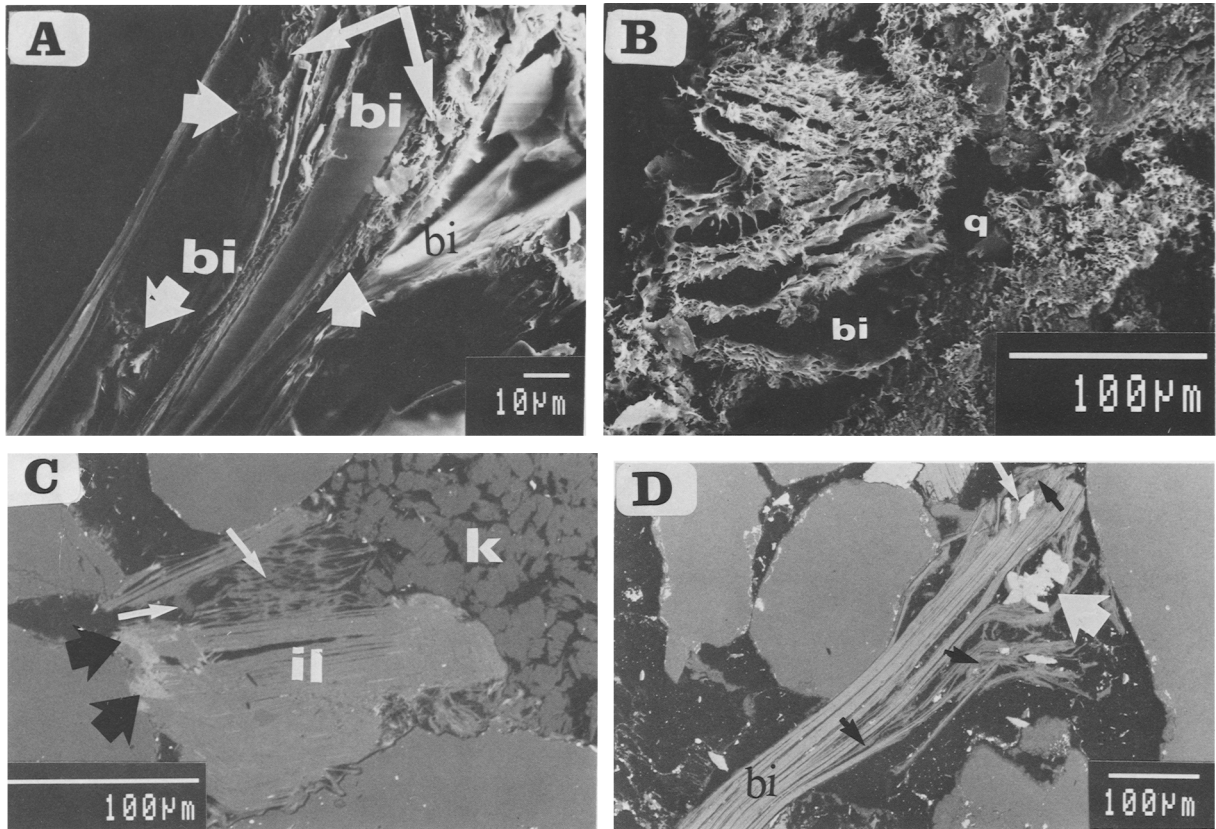


Figure 4. (A) Scanning electron micrograph (SEM) showing the replacement of biotite (bi) by illite (arrows) along traces of cleavage planes. Depth = 3802.9 m. (B) SEM showing a biotite grain (bi) extensively replaced by illite. Note authigenic quartz (q). Depth = 4297.2 m. (C) Backscattered electron (BSE) image showing replacement of biotite (bi) by illite (il) and siderite (white arrows). Depth = 4255.5 m. (D) BSE image showing replacement of biotite by illite (il) and small amounts of chlorite (black arrows) and kaolinite (white arrows). Biotite occurs as tiny relicts within the illite. Note abundant kaolinite cement (k) close to the altered biotite. Depth = 2000.3 m.

Table 2. Mass-balance reactions of mica alteration related to petrographic observations.

2.07 Biotite + 6.87 H ⁺ + 3.37 HCO ₃ ⁻ + 0.27 Ca ²⁺ = 1.00 Kaolinite +	
(149.3 cm ³)	(99.5 cm ³)
+ 1.00 K-feldspar + 0.93 Quartz + 3.37 Siderite + 0.39 Ti oxides +	
(100.7 cm ³) (22.7 cm ³) (29.6 cm ³) (20.5 cm ³)	
+ 0.84 K ⁺ + 0.23 Na ⁺ + 1.46 Mg ²⁺ + 5.19 H ₂ O	(1)
1.09 Muscovite + 1.56 H ₄ SiO ₄ + 0.07 K ⁺ + 0.28 H ⁺ = 1.00 Kaolinite +	
(140.7 cm ³)	(99.5 cm ³)
+ 1.00 K-feldspar + 0.03 Na ⁺ + 0.11 Fe ²⁺ + 0.09 Mg ²⁺ + 2.35 H ₂ O	(2)
(100.7 cm ³)	
1.68 Biotite + 4.38 H ⁺ + 1.72 Ca ²⁺ + 3.42 HCO ₃ ⁻ = 1.00 Illite +	
(149.3 cm ³)	(140.7 cm ³)
+ 1.71 Dolomite + 1.50 Quartz + 0.29 Ti oxides + 0.88 K ⁺	
(64.2 cm ³) (22.7 cm ³) (20.5 cm ³)	
+ 0.18 Na ⁺ + 1.64 Fe ²⁺ + 4.58 H ₂ O	(3)
2.63 Biotite + 7.7 OH ⁺ = 1.00 Chlorite + 1.00 K-feldspar + 1.54 Quartz +	
(149.3 cm ³) (211.7 cm ³) (100.7 cm ³) (22.7 cm ³)	
+ 0.50 Ti oxides + 1.34 K ⁺ + 0.29 Na ⁺ + 1.42 Mg ²⁺ + 1.48 H ₂ O	(4)
(20.5 cm ³)	

Fe and Mg replaced octahedral Al in these illites. The amount of tetrahedral Si was greater than the stoichiometric value of 3.0 for dioctahedral mica.

Chloritized biotite was noted in sandstones buried at depths greater than 3000 m. Small flakes of chlorite were found partially replacing biotite sheets and filling voids between these sheets (Figure 5A). Biotite grains were also extensively replaced by parallel aligned chlorite flakes (Figure 5B). Authigenic quartz and pure K-feldspar (revealed by microprobe analysis) were found between sheets of chloritized biotite (Figure 5C). Iron was the predominant octahedral cation (44%) in the chlorite, whereas Al and Mg occupied 35% and 21%, respectively, of the octahedral sites. The total octahedral occupancy was <6.0 per formula unit (stoichiometric trioctahedral chlorite), probably due to interstratification with dioctahedral chlorite or smectite.

DISCUSSION

The effects of mica alteration on the chemistry of pore fluids and the mineralogy of the sandstones were evaluated by means of mass-balance reactions. Reactions were constructed from petrographic observations and average microprobe analyses of the different phases (Tables 1 and 2); Al was assumed to be conserved among the solid phases (Ferry, 1979; Veblen and Ferry, 1983). Molar volumes of biotite and chlorite were calculated based on the equations given by Parry and Downey (1982). Molar volumes of other minerals were taken from Robie and Waldbaum (1968).

A significant positive relationship between the calculated and measured amounts of mineral by-products coexisting with altered mica (Tables 2 and 3) suggests a limited amount of net mass transfer in the sandstones. Differences between these two values primarily reflect: (1) errors in point counting caused by the small amounts and fine grain size of the alteration products, and (2) difficulties encountered in differentiating diagenetic minerals of various origins. The measured amount of clay minerals exceeds calculated values, indicating that process other than mica alteration must have been active. Some elements released by mica alteration may have migrated with the pore fluids and precipitated on the thin-section scale, as indicated by a higher calculated/measured ratio for some minerals; for example, K-feldspar produced by reaction 2 (Table 2).

Alteration reactions also resulted in the release of Fe^{2+} , Mg^{2+} , K^+ , and Na^+ to pore fluids, from which authigenic minerals precipitated. Fe^{2+} and Mg^{2+} precipitated as siderite at depths <2200 m and as chlorite and Fe-dolomite-ankerite at depths >3000 m. Some of the Fe^{2+} precipitated as pyrite at all depths. Potassium contributed to K-feldspar overgrowths at shallow depths and to illite growth at greater depths. In shallow-burial environments, K precipitated as K-feldspar overgrowths. Sodium was consumed in the albitization of detrital K-feldspar and, less commonly, in the for-

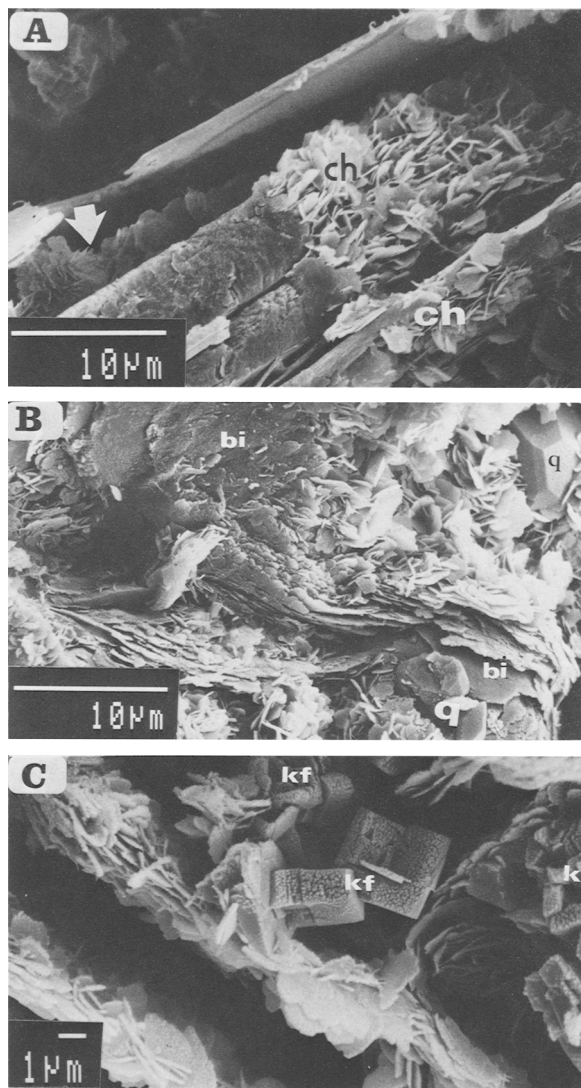


Figure 5. (A) Scanning electron micrograph (SEM) showing the replacement of biotite (bi) by flaky chlorite (ch). Depth = 3802.9 m. (B) SEM showing a biotite grain (bi) extensively replaced by chlorite (ch). Note authigenic quartz (q). Depth = 3802.9 m. (C) SEM showing growth of authigenic K-feldspar (kf) between sheets of chloritized biotite. Depth = 3802.9 m.

mation of albite overgrowths on detrital plagioclase. The release of H_2O from the alteration reactions of Table 2 diluted the pore fluids and therefore enhanced diagenetic reactions, particularly in deep-burial environments where porosity and permeability were low and pore-fluid flow was limited.

The alteration of biotite provided ions and/or created microchemical environments that favored the precipitation of siderite, calcite, dolomite, and Fe-carbonates (Boles, 1987; Bjørlykke and Brendsdal, 1986). Boles and Johnson (1984) related the growth of carbonates between mica sheets to a greater than average pH of the pore fluids due to consumption of H^+ at the

Table 3. Calculated and measured value of volume % of minerals produced as by-products of mica alteration.

Reaction number (Table 2)	Average vol. % altered mica ²	Number of samples	Sample depth (m)	Average volume % mineral by-products (calculated/measured ¹)							ΔV (calc.)	
				Kaolinite	Illite	Chlorite	K-feldspar	Quartz	Siderite	Ti oxides		Dolomite
1	2.3	2	1700-2730	0.75/1.8	—	—	0.82/1.1	0.16/0.3	0.74/0.3	0.06/0.1	—	-0.23
2	2.8	4	1890-2450	1.82/2.2	—	—	1.98/1.1	—	—	—	—	-1.00
3	2.9	5	2690-4780	—	1.64/3.4	—	—	0.40/0.2	—	0.07/0.1	1.28/1.8	-0.49
4	3.8	2	3768-4325	—	—	2.06/3.8	1.06/1.9	0.34/0.5	—	0.10/0.1	—	+0.28

¹ Based on counting 1200 points (per thin section) of minerals occurring within or in pores surrounding altered mica.

² Represents volume % of pseudomorphs formed by alteration of detrital mica.

alteration sites. The chloritization of biotite (Table 2, reaction 4) created microchemical environments having a high a_{K^+}/a_{H^+} and $a_{H_4SiO_4}$ that stabilized authigenic K-feldspar between biotite sheets (Figure 5C), yet detrital K-feldspars in the same sandstone dissolved and/or were albitized. Where the illitized and/or chloritized biotite was embedded in kaolinite cement (Figure 4D), pore fluids within the biotite grains might have provided a microchemical environment suitable for both illite growth (elevated a_{K^+}/a_{H^+}) and chlorite growth (elevated $a_{Fe^{2+},Mg^{2+}}/A_{H^+}$), whereas bulk pore fluids remained in the stability field of kaolinite.

SUMMARY AND CONCLUSIONS

1. Authigenic mineral by-products of mica alteration include siderite, dolomite, K-feldspar, quartz, and Ti oxides. The calculated amounts of these minerals are comparable to those measured by point counting, indicating that cations released by mica alteration precipitated *in situ*, with limited mass transfer during sandstone diagenesis.
2. Variable amounts of cations, including K^+ , Na^+ , Mg^{2+} , and Fe^{2+} , were also liberated as a consequence of mica alteration. These cations precipitated as authigenic minerals on the thin-section scale of the sandstones. The alteration reactions also produced variable amounts of water, which was necessary for the continuation of the reactions, particularly in deep-burial environments.
3. Mica alteration reactions created suitable microchemical environments for the authigenesis of certain minerals, such as K-feldspar, that were unstable elsewhere in the sandstones.

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