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CONTROLS ON CLAY-MINERAL AUTHIGENESIS IN THE VIKING SANDSTONE, CENTRAL ALBERTA. I. SHALLOW DEPTHS

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ABSTRACT

The Viking Formation of east-central Alberta is a shallow-marine shelf deposit containing two prominent, laminated to massive, sandstone units interbedded with laminated shaly siltstones and bioturbated muddy sandstones. The sandstone units differ markedly in detrital mineralogical composition: the shallower unit is a lithic arkose containing abundant feldspar, but very little glauconite, whereas the deeper unit is a sublitharenite containing very little feldspar but abundant glauconite. Mechanical analyses of the sandstones indicate a higher percentage of clay minerals in the lithic arkose than in the sublitharenite. X-ray analysis shows that, in the shallower sandstone, glauconite, kaolinite and chlorite are the main clay minerals, along with quartz, whereas the deeper sandstone contains, in addition to the above mentioned minerals. 2:1 mixed-layer silicate. A SEM analysis reveals that kaolinite booklets and some quartz overgrowth dominate the authigenic minerals in the shallower sandstone while the deeper one contains mainly quartz overgrowth and 2:1 layer silicates with some kaolinite. In the latter sandstone, wherever authigenic calcite is present, authigenic layer-silicates are absent.

Keywords: diagenesis, shallow-burial depths, authigenic layer-silicates, sandstones, Viking Formation, Alberta.

SOMMAIRE

La formation Viking du centre-Est de l'Alberta, dépôt de plateforme marine de faible profondeur, contient deux unités imposantes de grès laminé à massif, avec intercalations de siltstones argileux laminés et de grès boueux bioturbés. Les grès se distinguent par la composition minéralogique de leurs détritus: l'unité la moins profonde est une arkose lithique contenant du feldspath en abondance, mais très peu de glauconie; l'unité la plus profonde est une sublitharénite qui contient très peu de feldspath et beaucoup de glauconie. Par analyse mécanique, on montre que l'arkose lithique contient une proportion plus forte de minéraux argileux que la sublitharénite. Une analyse diffractométrique X indique que, dans l'unité la moins profonde, glauconie, kaolinite et chlorite sont les minéraux argileux principaux, accompagnés de quartz; par contre, l'unité de grès profonde contient en plus un phyllosilicate mixte 2:1. Une analyse au microscope électronique à balayage montre de la kaolinite en livrets et du quartz en surcroissance comme minéraux authigènes prédominants dans le grès peu profond, tandis que le grès profond montre surtout du quartz en surcroissance et des phyllosilicates 2:1 avec kaolinite. En présence de calcite authigène dans cette unité, les phyllosilicates sont absents.

(Traduit par la Rédaction)

Mots-clés: diagenèse, faible profondeur d'enfouissement, phyllosilicates authigènes, grès, formation Viking, Alberta.

INTRODUCTION

The presence of secondary minerals in sandstones, specifically authigenic layer-silicates, has been discussed by Carrigy & Mellon (1964), Carrigy (1971) and Almon *et al.* (1976). The influence of authigenic clays on oil and gas exploitation and production from sandstone reservoirs has been discussed by Taylor (1977), Almon (1978) and Galloway (1979).

Recently, the formation of authigenic clays in sandstone has been under investigation in relation to diagenesis of the adjacent shales. Upon burial, shales undergo compaction and dehydration, with a concomitant expulsion of water charged with cations derived from the destruction of layer silicates (Foscolos & Powell 1980). This cation-charged water, when filtering through the sandstones, can precipitate clay minerals (Blatt 1979). In this way shales can provide cementing agents to adjacent sandstones during burial (Curtis 1978, Boles & Franks 1979). Authigenic clays in sandstones can also be derived from the alteration of detrital mineral grains contained within the sandstones (Hayes 1979). Foscolos & Powell (1979) observed a relationship with increasing depth of burial, between the appearance of certain authigenic minerals in sandstones and the level of clay catagenesis in adjacent shales. The observed trend with burial was found to be quartz, quartz + kaolinite, quartz + mixed-layer silicates and some kaolinite, quartz + chlorite and some mixed-layer silicates. In order to evaluate the relative effects of detrital mineralogy of the sandstones and of the adjacent shales during catagenesis in the formation of certain types of authigenic clays in sandstone reservoirs, a

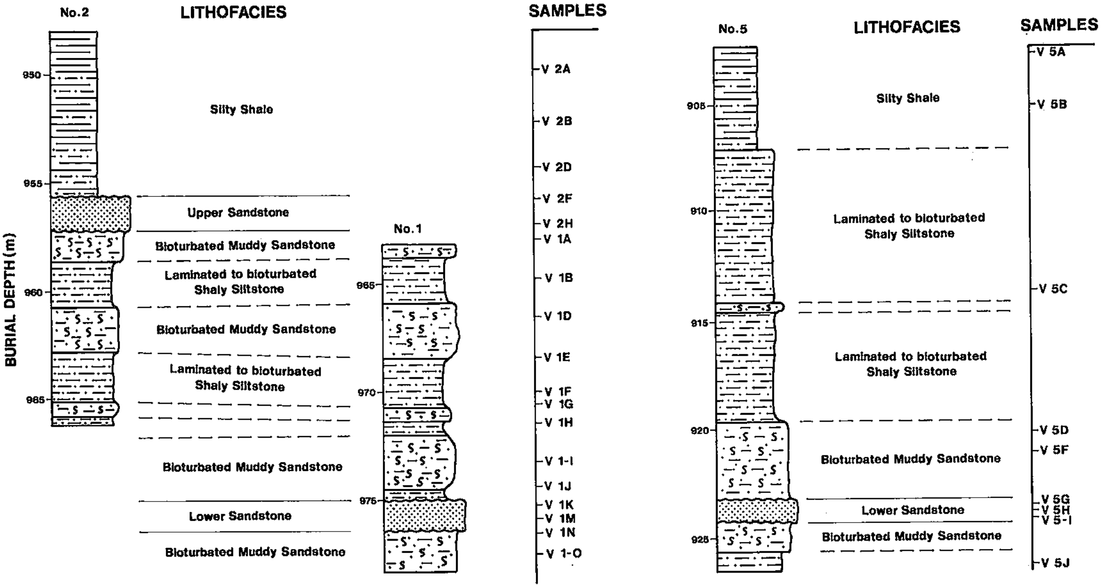

FIG. 1. Lithostratigraphy and samples of the Viking Formation from three wells, Provost Region, east-central Alberta (well #2: Lsd. 11, Sec. 20, Tp 35, Rg 13 west of 4th meridian; well #1: Lsd. 11, Sec. 22, Tp 35, Rg 13 west of 4th meridian; well #5: Lsd. 10, Sec. 21, Tp 36, Rg 11 west of 4th meridian).

major study of the Lower Cretaceous Viking Formation of central Alberta is being undertaken. This paper reports on results obtained from two mineralogically different sandstone units from the shallow (1000 m) Viking Formation of east-central Alberta. Research on deeper units of this sandstone is under way to further document depth-related diagenetic trends in mineralogy in order to substantiate or modify observed relationships between authigenesis of minerals and levels of catagenesis as reported by Foscolos & Powell (1979).

The Viking Formation of east-central Alberta consists of 19 to 22 m of interbedded clean laminated sandstones, bioturbated sandstones, sandy siltstones and shales. Two, and sometimes three, discrete sandstone units characterize the Viking Formation in the Provost region, where oil is produced from the lowermost sandstone, officially termed the "Provost Viking C oil pool". The stratigraphy and petroleum geology of the Provost Viking field are described by Lerand & Thompson (1976) and Alho *et al.* (1977). A detailed examination of the lithofacies and depositional environments of the Viking Formation adjacent to and overlapping the western part of the Provost field was undertaken in order to study the type of clay minerals in two prominent sandstone units, which differ markedly with respect to their detrital composition.

MATERIAL AND METHODS

Samples of the Viking Formation were obtained from three wells (locations: well #5, Lsd. 10, Sec. 21, Tp. 36, Rg. 11 west of 4th meridian; well #2, Lsd. 11, Sec. 20, Tp. 35, Rg. 13 west of 4th meridian; well #1, Lsd. 11, Sec. 22, Tp. 35, Rg. 13 west of 4th meridian). The lithofacies, depths, interval studied and sample designation are shown in Figure 1.

Mineralogical identification in all lithofacies was carried out by X-ray-diffraction analysis; thin-section petrography was restricted to the sandstones. The sample preparation for concentrating the clay-size fraction followed the techniques of Müller (1967), and the actual determination was carried out following mechanical analysis (Day 1965). Clay minerals were identified, and K_2O content of the clays was determined by the methods of Foscolos *et al.* (1976). Quantitative determination of quartz and amorphous silica, aluminum and iron was carried out following Jackson's technique (1965). The concentration of layer silicates was carried out using the crystal-lattice H_2O values, as determined by thermogravimetric analysis (Barshad 1965). The quantification of glauconite was based on the K_2O content, assuming a content of 8.3% (Grim 1953). Scanning electron microscopy (SEM) was carried out using a Cambridge stereoscan 150 MK2 with an attached

TABLE 1. DETRITAL COMPOSITION OF UPPER AND LOWER SANDSTONE SAMPLES AS DETERMINED BY POINT COUNTING OF THIN SECTIONS

		Framework Grains						
Depth in Metres	Sample Designation	Quartz	Chert	Feldspars	Argillite	Glauconite	Accessories	Detrital Matrix
	Upper Sandstone							
956	V-2F	35	16	22	2	0	2	23
957	V-2H	42	9	18	7	1	2	21
	Lower Sandstone							
975	V-1K	67	15	3	3	11	1	0
976	V-1M	63	19	5	1	9	3	0
923	V-5G	69	21	1	trace	8	1	0
924	V-5I	71	17	0	0	12	trace	0

KEVEX energy-dispersion X-ray spectometer. The SEM technique is useful for differentiating authigenic from detrital clays and for examining the occurrence and morphological habits in relation to pore spaces and adjacent stable-grain surfaces.

THE VIKING SANDSTONES

Two distinct sandstone units are consistently present and can be correlated throughout the area of study. Both sandstones are interpreted as offshore marine-bar facies, and generally range in thickness from less than 0.5 to 2.5 m. Both sandstones display a similar sequence of sedimentary structures, but the upper sandstone ranges from fine to coarse in grain size, with poor to moderate sorting, whereas the lower sandstone is generally fine grained and well sorted. The upper sandstone has low porosity but locally produces gas, whereas the lower sandstone has an average porosity of 25% in the Provost field (Alho *et al.* 1977).

Petrography

The upper and lower sandstone units differ markedly with respect to detrital constituents. Using the sandstone classification of Folk (1968), the upper sandstone is classified as a lithic arkose and the lower sandstone as a sublitharenite (Table 1). The upper sandstone is rich in feldspars and detrital matrix with little glauconite. The lower sandstone is poor in feldspars and detrital matrix but contains more quartz and glauconite. The detrital material in the matrix is dominated by illite and unidentifiable clay minerals. Accessory minerals in both sandstone units include pyrite, heavy minerals, mica flakes and phosphatic bone fragments. The results of semiquantitative X-ray analysis of bulk sandstone samples are presented in Table 2. The analyses indicate the presence of quartz, clay minerals, feldspar and traces of pyrite. Calcite cement is also present in the lower sandstone unit.

Diagenetic features

In the shallower sandstone, the most noticeable cement is kaolinite, present as pseudohexagonal booklets in rectilinear voids. The volume occupied by authigenic kaolinite varies; the kaolinite appears to be largely a replace-

TABLE 2. SEMIQUANTITATIVE MINERALOGICAL COMPOSITION OF THE VARIOUS LITHOLOGIES IN THE VIKING FORMATION

			Mineralogy						
Depth in Metres	Sample Designation	Lithofacies	Mixed-Layer Silicates	Illite	Kaolinite and Chlorite	Quartz	Feldspar	Pyrite	Calcite
950	V-2A	Shale		†	†	†††	trace	trace	
954	V-2D	Silty Shale		†	†	†††	trace	trace	
956	V-2F	Upper Sands		trace	trace	††††	†	trace	
957	V-2H	Upper Sands		trace	trace	††††	trace	trace	
963	V-1A	Bio Muddy Sand		trace	trace	††††	trace	trace	
965	V-1B	Shaly Silts		†	trace	††††	trace	trace	
967	V-1D	Bio Muddy Sand		trace	trace	††††	trace	trace	
970	V-1F	Shaly Silt		†	†	†††	trace	trace	
971	V-1G	Bio Muddy Sand	trace	trace	trace	††††	trace	trace	
972	V-1H	Silty Shale	trace	†	trace	††††	trace	trace	
973	V-1I	Bio Muddy Sand	trace	trace	trace	††††	trace	trace	
975	V-1J	Silty Shale	trace	†	†	††††	trace	trace	
976	V-1M	Lower Sands		trace*		††††	trace	trace	
977	V-1N	Bio Muddy Sand	trace	trace	trace	††††	trace	trace	
903	V-5A	Silty Shale	trace	†	†	†††	trace	trace	
913	V-5C	Shaly Silts	trace	†	†	†††	trace		
920	V-5D	Bio Muddy Sand	trace	trace	trace	††††	trace	trace	
923	V-5G	Lower Sands		trace*		††††	trace		†
924	V-5I	Lower Sands		trace*		††††	trace	trace	
926	V-5J	Silty Shale	†	†	†	†††	trace	trace	

* glauconite; trace: less than 5%; †: 5-25%; †††: 50-75%; ††††: 75-100%.

ment product of alkali feldspar. Quartz overgrowths are sparse in this sandstone unit. Scanning electron micrographs also indicate that the main authigenic mineral is kaolinite with minor authigenic quartz (Fig. 2). Authigenic smectite and chlorite were not detected either in thin section or by SEM analysis. However, traces of these two clay minerals occur as detrital constituents.

In the lower sandstone, calcite cement plus porosity form up to 25% of the rock. That is, porosity occurs where calcite cement is absent, and *vice versa.* Silica, in the form of quartz overgrowths, is the second most abundant cement in the lower sandstone (Figs. 3, 4). A common diagenetic feature of the lower sandstone is shrinkage porosity (Schmidt & McDonald 1979), created by the alteration of glauconite (Fig. 3c). This type of porosity is most prevalent in the lower sandstone owing to its higher glauconite content. In calcite-cemented zones, porosity exists almost exclusively as circular voids, and ring-shaped ovoids surrounding altered glauconite pellets. Wherever calcite is absent, however, authigenic quartz, kaolinite and traces of mixed-layer silicates are present (Figs. 3, 4).

MINERALOGY OF CLAY-SIZE FRACTION

The clay-size fraction ($<2\mu$m) of all Viking lithofacies consists of quartz, discrete smectite or mixed-layer silicates, glauconite, kaolinite and chlorite (Fig. 5). Expandable clays can consist either of smectite or mixed layers. Chlorite, however, is absent from the upper sandstone. File procedures for identification of discrete and mixed-layered silicates are presented by Brown (1962), Harward *et al.* (1968) and Kodama & Brydon (1968).

Smectite is identified by X-ray diffraction from the d_{001} value of 1.82 nm (18.2 Å) in glycerolated samples and the d_{001} value of 1.53 nm (15.3 Å) in the Ca-saturated specimen at 50% relative humidity (R.H.) (Fig. 5). Glauconite was recognized from thin-section microscopy and the presence of the d_{001} peak at 1.0 nm (10 Å) at 50% R.H.; chlorite was identified by the presence of the 1.42 nm (14.2 Å) peak in the specimen heated to 550°C; kaolinite was recognized from the 0.71 nm (7.1 Å) peak on the HCl-treated samples (Fig. 6). The presence

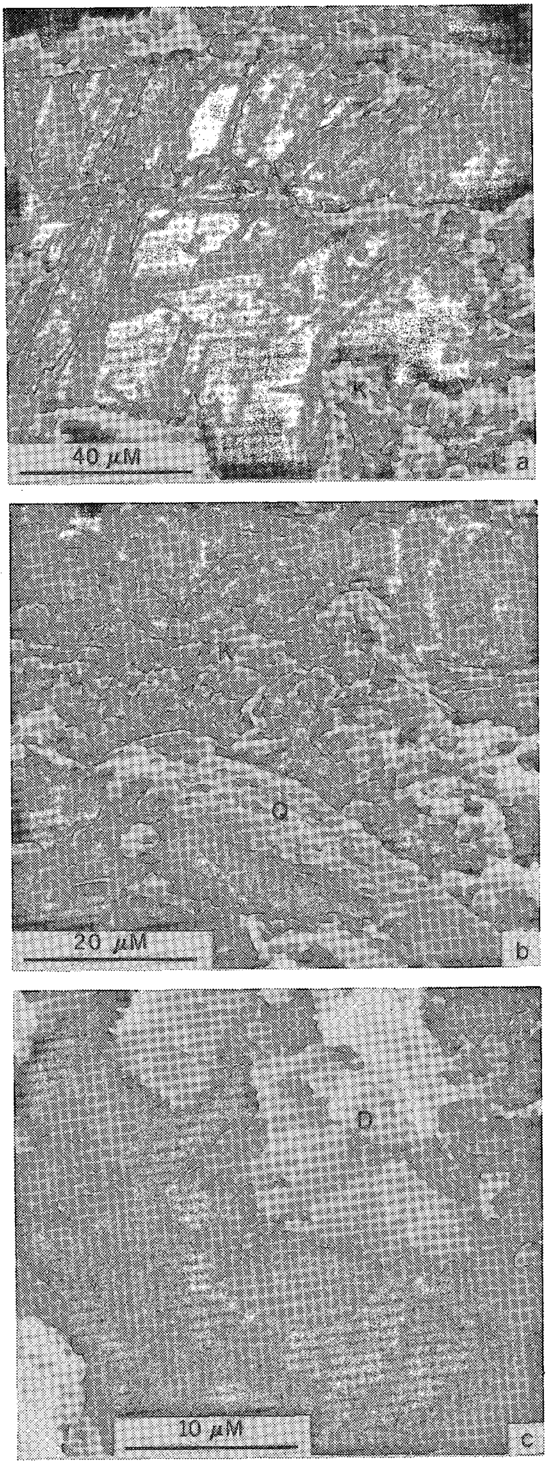

FIG. 2. Scanning electron micrographs of the upper sandstone unit showing weathered feldspar, kaolinite, quartz, detrital clay and pyrite; (a) altered feldspar and kaolinite, (b) authigenic quartz and kaolinite, and (c) detrital clay and framboidal pyrite. Q quartz, K kaolinite, A anorthite, D detrital clays, P pyrite.

of kaolinite along with chlorite was also corroborated from the d_{002} and d_{004} peak doubled at 0.354 nm (3.54 Å) and 0.357 nm (3.57 Å), respectively (Figs. 5, 6). Mixed-layered silicates were identified from the plateau located between 1.0 nm (10 Å) and 1.53 nm (15.3 Å) on the Ca-saturated specimen at 50% R.H. (Fig. 5). An SEM analysis indicates that these 2:1 mixed-layered silicates occur in the sandstones as authigenic forms (Fig. 4).

The morphological appearance of these authigenic 2:1 mixed-layer silicates is similar to that of the honeycomb chlorite reported by Wilson & Pittman (1977) and Tillman & Almon (1979), which occurs on the surface of glauconite grains. However, qualitative elemental analysis confirms that this material is a 2:1 mixed-layer phase because it contains potassium as well as aluminum, silicon and iron (Fig. 4). Thus, the authigenic appearance of the mineral, along with the elemental analysis and the X-ray-diffraction pattern, indicates that the silicate mineral is a 2:1 clay mineral forming on the surface of altered glauconite in the sandstones. In the finer grained lithofacies, however, the major process for the formation of a mixed-layer phase probably is the transformation of smectite. Whether the expandable clay present is smectite or a mixed-layer phase is independent of stratigraphic level or depth within the narrow interval examined (see Discussion). The concentration of quartz within the <2μm fraction is correlated with presence of mixed-layer clays. Where the expandable clay is smectite, the quartz concentration is low, ranging from 15 to 32%; where the expandable clay is a mixed-layer phase, the quartz concentration is high, ranging from 31 to 46% (Table 3). This is also evident in the X-ray-diffraction data, where the 0.332 nm (3.32 Å) peak of quartz becomes enhanced in the samples containing mixed-layer clays (Fig. 5).

The concentration of amorphous material in the <2μm fraction of all analyzed samples varies from 5.56 to 1.53% (Table 4). The two extremes are detected in the two different types of sandstones. The lithic arkose sandstone has the highest concentration of amorphous

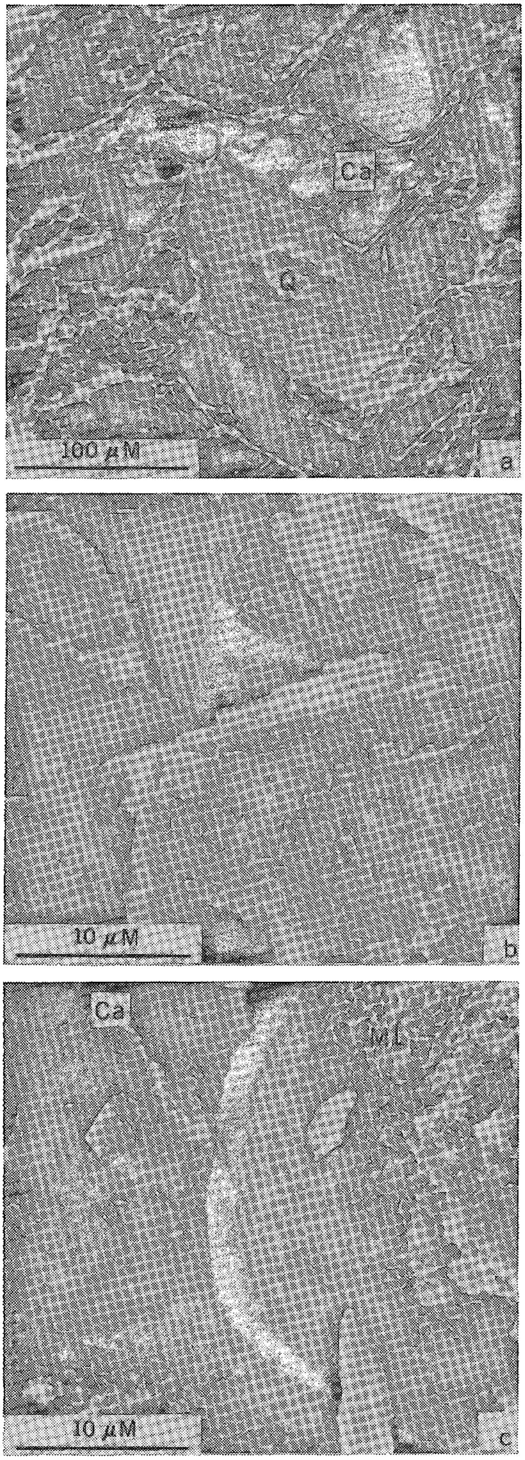

FIG. 3. Scanning electron micrographs of the lower sandstone unit showing calcite, authigenic quartz and kaolinite, glauconite and incipient formation of mixed-layer silicates on glauconite grains; (a) calcite quartz grains, (b) authigenic quartz and kaolinite, and (c) authigenic mixed-layer silicates on the surface of a glauconite grain. Note the curvilinear pore caused by the "shrinkage" of the glauconite grain. Q quartz, K kaolinite, Ca calcite, M.L. mixed-layer silicates.

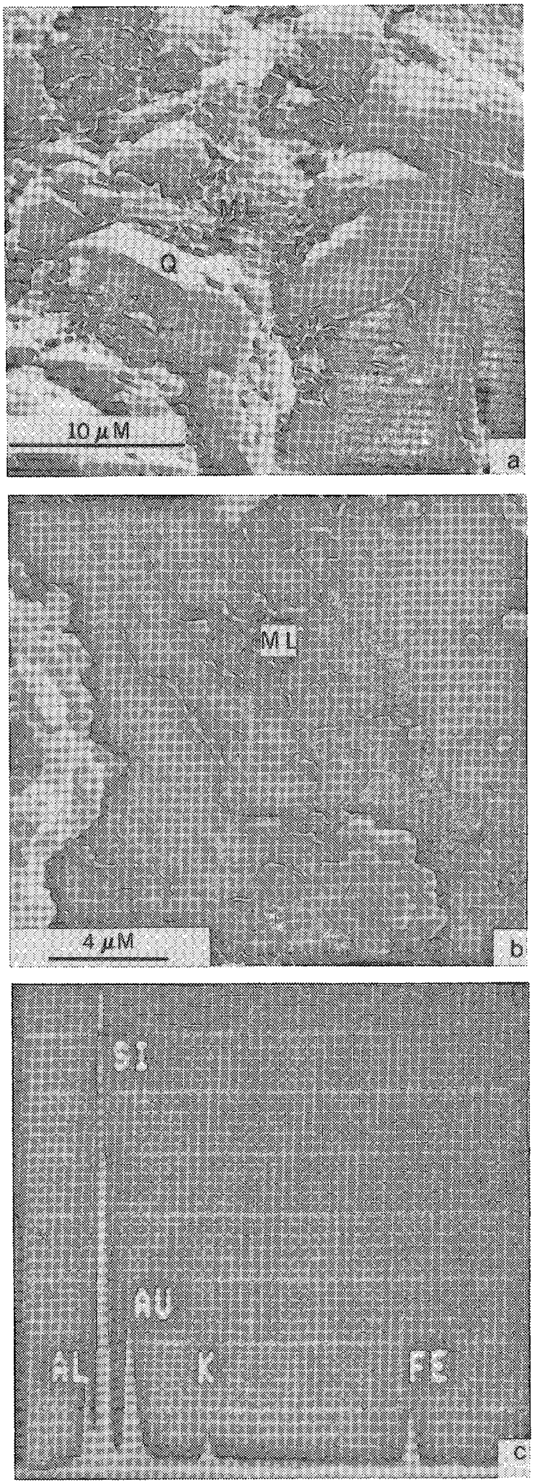

FIG. 4. Scanning electron micrographs of the lower sandstone unit showing authigenic quartz and the incipient formation of mixed-layer silicates; (a) authigenic mixed-layer silicates and quartz, (b) a magnified picture showing the location at which energy-dispersion spectrum was taken, and (c) X-ray energy-dispersion spectrum illustrating the occurrence of potassium, aluminum, silicon and iron of the mixed-layer silicates. Q quartz, M.L. mixed-layer silicate, P pyrite.

material owing to the presence of altered feldspar, whereas the sublitharenite has the lowest concentration.

DISCUSSION

By comparing the X-ray patterns of various lithologies (Fig. 5) with the lithostratigraphy and samples of the Viking Formation from the three wells studied (Fig. 1), it is observed that smectite and mixed-layer silicates are randomly distributed with respect to depth in this narrow stratigraphic interval. Whether an individual sample contains smectite or mixed-layer silicates is a function of the local physicochemical conditions. The presence, however, of either mineral indicates that the interval represents an early stage of catagenesis equivalent to the first clay-dehydration step, which accompanies the transformation of smectite to mixed-layer clays as defined by Powell *et al.* (1978). The fact that the mixed-layer phases are the products of a catagenetic transformation of smectite is supported by the higher concentrations of quartz present in the $<2\mu m$ fractions that contain the mixed-layer silicates. Both Hower *et al.* (1976) and Boles & Franks (1979) have proposed smectite-dehydration models in which silica is the major by-product of the process. Thus, it is concluded that this interval represents the first stage of clay catagenesis equivalent to the first dehydration step of the transformation of smectite to mixed-layer clays as defined by Powell *et al.* (1978).

Authigenic silicate minerals occurring in the Viking sandstones are kaolinite, quartz overgrowths, and traces of 2:1 mixed-layer clay minerals, previously observed by Foscolos & Powell (1980) at this level of catagenesis. Both sandstones, even though they have quite different mineralogical compositions, contain authigenic kaolinite and silica cements. However, authigenic kaolinite is more prevalent in the lithic arkose than in the sublitharenite, owing to the higher content of feldspar in the former. Silica, in the form of quartz overgrowths, is less abundant in the lithic arkose than in the sublitharenite, perhaps because any dissolved silica is used up in the formation of kaolinite.

In the lower sandstone, authigenic kaolinite

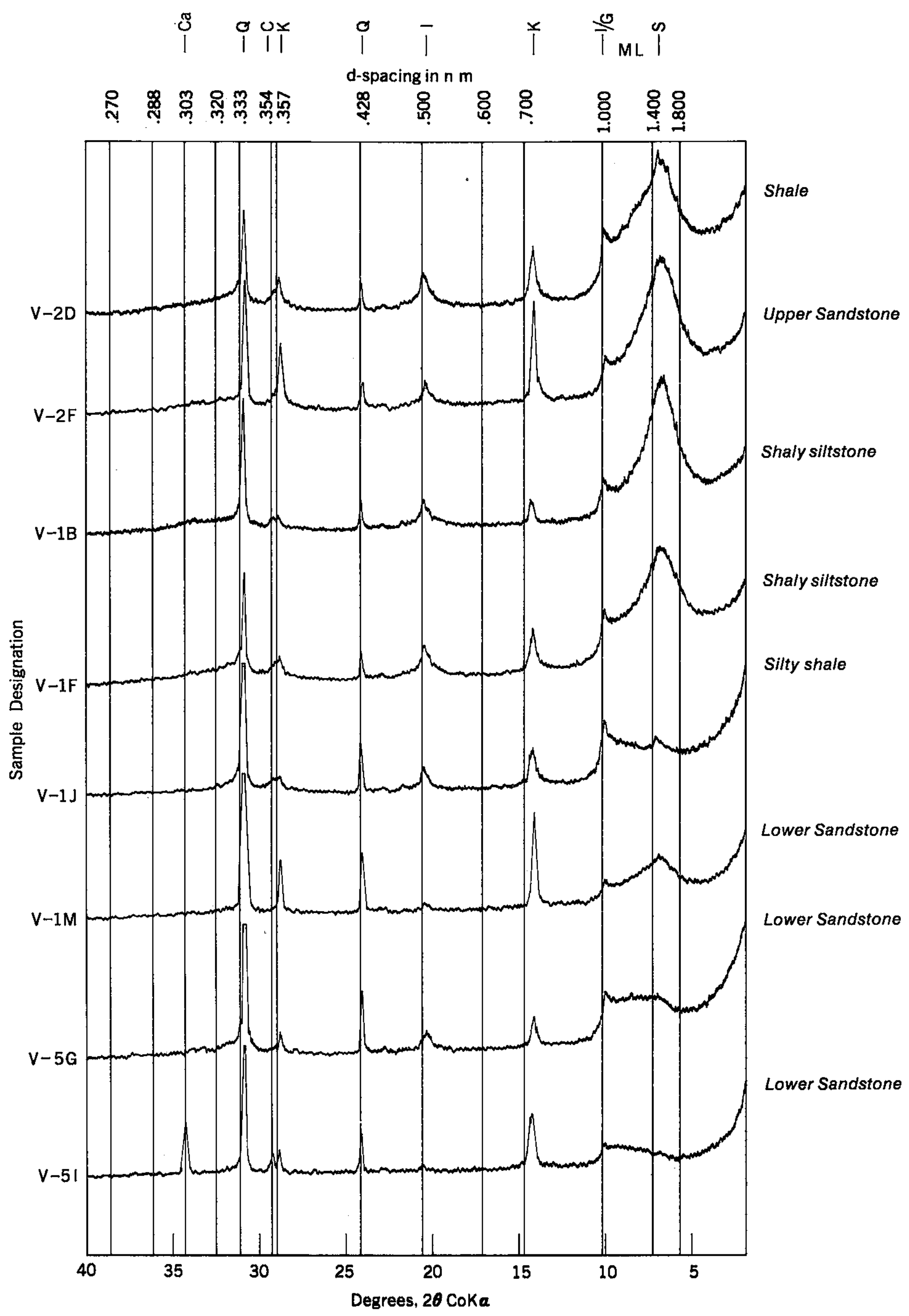

FIG. 5. X-ray-diffraction patterns of Ca-saturated clay fractions at 50% R.H. from various lithologies of the Viking Formation. S smectite, M.L. mixed-layer silicates, I/G illite or glauconite, K kaolinite, Q quartz, C chlorite and Ca calcite.

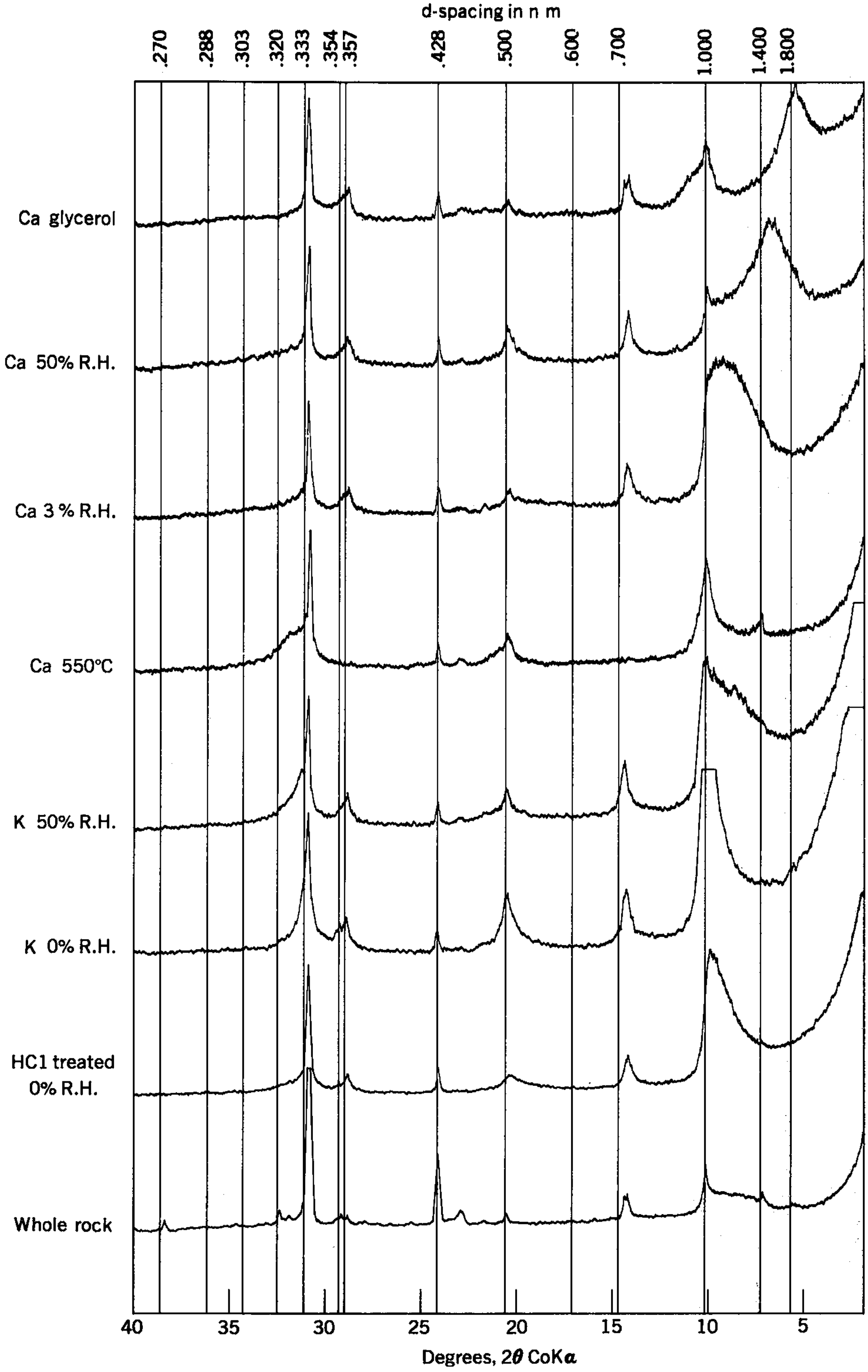

FIG. 6. Mineral identification in the whole rock and clay fraction from a shaly siltstone V–1F, at 970 m depth.

TABLE 3. PER CENT <2 μm FRACTION IN THE ROCK AND PER CENT MINERAL COMPOSITION OF THE CLAYSIZE FRACTION

				Per Cent Mineral Composition of Claysize Fraction				
Depth in Metres	Sample Designation	Lithofacies	Per Cent <2 μm Fraction	Quartz	Kaolinite & Chlorite	Illite	Expandable	Calcite
950	V-2A	Shale	62	16	20	35	31	
954	V-2D	Silty Shale	57	15	17	38	29	
956	V-2F	Upper Sands	31	20	18	25	37	
957	V-2H	Upper Sands	31	23	9	34	34	
963	V-1A	Bio. Muddy Sands	31	32	18	36	14	
965	V-1B	Shaly Silts	42	13	7	34	44	
967	V-1D	Bio. Muddy Sands	42	23	2	34	41	
970	V-1F	Shaly Silts	56	16	14	47	23	
971	V-1G	Bio. Muddy Sands	31	21	16	36	17	
975	V-1J	Silty Shale	43	31	7	38	21	
976	V-1M	Lower Sands	11	49	13	23	15	
977	V-1N	Bio. Muddy Sands	29	45	3	30	22	
920	V-5D	Bio. Muddy Sands	25	46	10	29	13	
923	V-5G	Lower Sands	31	33	14	22	12	19
924	V-5I	Lower Sands	16	35	29	33	3	

has probably been formed as a precipitate from formation water. In this unit, traces of 2:1 mixed-layer silicates are detected where glauconite is common, and are attributed to the alteration of glauconite. Scanning electron photomicrographs (Fig. 4) show that this process occurs on the surface of glauconite grains. In the lower sandstone unit, however, wherever calcite is present, kaolinite and mixed-layer clays are absent. This suggests that the formation of calcite was an earlier diagenetic event and, where present, has prevented clay authigenesis. Similar diagenetic trends in mineralogy have been observed in the Wilcox sandstones, which are sandwiched between thick siltstone–shale sequences (Boles & Franks 1979).

The fact that the nature of the authigenic minerals is identical in both types of sandstones suggests that the types of authigenic minerals present depend upon the physicochemical conditions existing at this level of catagenesis. The difference in abundance of authigenic kaolinite merely reflects the availability of starting materials in the lithic arkose. The presence of authigenic kaolinite and authigenic quartz in the sublitharenite supports the concept of migration of cation-charged water from adjacent shales. The authigenic minerals present certainly are identical to those found at a similar level of catagenesis in a previous study (Foscolos & Powell 1979). These results, along with the data of Boles & Franks (1979), seem to suggest that regardless of the abundance of certain minerals in either the adjacent shales or the sandstones, the net effect of diagenesis in sandstone reservoirs of similar depth will be a similar suite of authigenic minerals. This implies that, for a given level of catagenesis, temperature is the major controlling factor in determining the type of authigenic clays in sandstone reservoirs.

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TABLE 4. PER CENT NON-CRYSTALLINE MATERIAL IN THE CLAY FRACTION

			Per Cent Non-Crystalline Material			
Depth in Metres	Sample Designation	Lithofacies	SiO_2	Al_2O_3	Fe_2O_3	Total
950	V-2A	Shale	2.05	1.08	.78	3.71
954	V-2D	Silty Shale	2.46	1.08	.64	4.18
956	V-2F	Upper Sands	2.51	1.23	1.56	5.30
957	V-2H	Upper Sands	2.05	1.16	2.35	5.56
963	V-1A	Bio Muddy Sands	1.34	.71	2.33	4.38
965	V-1B	Shaly Silts	1.57	.71	1.94	4.22
967	V-1D	Bio Muddy Sands	1.57	.63	1.12	3.32
970	V-1F	Shaly Silts	1.42	.66	1.22	3.30
971	V-1G	Bio Muddy Sands	1.20	.60	2.63	4.43
975	V-1J	Silty Shale	1.81	.72	.95	3.49
976	V-1M	Lower Sands	1.93	.72	1.25	3.90
977	V-1N	Bio Muddy Sands	1.73	.58	.71	3.02
920	V-5D	Bio Muddy Sands	1.22	.39	2.95	4.56
923	V-5G	Lower Sands	2.17	.42	.68	3.27
924	V-5I	Lower Sands	.67	.26	.60	1.53

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