AUTHIGENIC CHLORITE IN LATE TRIASSIC SANDSTONES FROM THE CENTRAL GRABEN, NORTH SEA

B. HUMPHREYS, S. A. SMITH AND G. E. STRONG

Stratigraphy and Sedimentology Research Group, British Geological Survey, Keyworth, Nottingham NG12 5GG

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ABSTRACT: Late Triassic sandstones from Quadrant 22 in the North Sea contain two generations of chlorite cement. Grain-coating chlorites consisting of curved, irregular crystal plates formed very early in diagenesis and are largely confined to marginal marine beds. Later diagenetic pore-filling chlorites, consisting of euhedral platy crystals, occur throughout the sequence in fluvial as well as marginal marine beds. Both generations of cement show similar XRD patterns; the 001 basal reflection of 14.0-14.06 Å is broad and of low intensity, whereas the 002 reflection at 7.05 Å is sharp and intense. Slight contraction of the 14 Å basal spacing to 13.6 Å occurs after heating to 600°C. Electron microprobe analyses show the cements to be Fe-rich clinochlores with Fe/(Fe + Mg) ratios varying between 0.41 and 0.50. They are more Mg- and Si-enriched than most other reported North Sea authigenic chlorites. The grain-coating chlorites have an average composition of $(Fe_{3.06}Al_{3.93}Mg_{3.32})[(Si_{6.76}Al_{1.24})O_{20}]$ (OH)$_6$. The pore-filling chlorites tend to show more variable compositions. The high Si values probably reflect both minor interstratification with smectite or vermiculite and contamination of the analyses by a closely associated illite/smectite clay. An origin related to alteration of a precursor swelling chlorite or corrensite is attractive on chemical and morphological grounds for the early grain-coating chlorites. However, direct precipitation from porewaters is the favoured origin for the later pore-filling chlorites, with the required ions being supplied by mineral decomposition reactions involving detrital silicate minerals and dolomite cements.

Late Triassic sandstones of Skagerrak Formation affinity have been studied from three cored borehole sequences from Quadrant 22 in the Central Graben (Fig. 1). The sediments were deposited largely under a fluvial regime, but marginal marine facies occur toward the top of the succession. Typical examples of logged sections through these beds, together with diagnostic structures are shown in Fig. 2. While the sediments are dominantly fine-grained laminated sandstones, conglomeratic intraclast lags and mudstone beds occur at many horizons. The sediments contain abundant chlorite of both authigenic and detrital origin. Detrital flakes of chlorite generally occur in discrete laminae, often aligned along bedding planes, as matrix, or as reworked mudstone clasts. The authigenic chlorite occurs as thin isopachous coatings around detrital grains, as a pore-filling cement, and occasionally as a replacement of detrital feldspar and biotite grains. Facies analysis indicates that grain-coating chlorite is largely confined to the marginal marine parts of the sequence, whereas the pore-filling chlorite occurs throughout the sequence.

Diagenetic studies show the presence of a number of cements in addition to chlorite, including non-ferroan and ferroan dolomite, quartz overgrowths, a filamentous, ribbon-shaped neoformed illite, feldspar overgrowths and local developments of anatase, and a variety of apatite and sulphide cements. A clay with low birefringence resembling kaolinite is

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present at the expanded terminations of some detrital biotite flakes, but otherwise neoformed kaolinite is absent. Some of the dolomite may have originated as primary dolocrete. Generally there is an inverse relationship between the amount of dolomite and amount of chlorite cement. Textural evidence suggests that the grain-coating chlorite formed very early in the diagenetic sequence. The more widely occurring pore-filling chlorite relates to a later event during burial, and crystallized after phases of feldspar dissolution (Fig. 3) and probably after phases of corrosion of non-ferroan dolomite. Nevertheless, there is clear textural evidence that even the later phases of chlorite formation pre-dated the main phase of quartz overgrowth cementation in the reservoir.

This paper describes the mineralogy of the authigenic chlorite phases in these sandstones and attempts to interpret their mode of origin. Knowledge of the chemistry and distribution of chlorite cement in the reservoir is of importance for reservoir management studies on two accounts:

(1) The porosity and permeability of the sandstones are generally higher where grain-coating chlorite is present, although this is also due in part to lower amounts of detrital clay matrix and dolomite cement. It is possible that the chlorite cement has hindered the later development of carbonate cements which have reduced porosity and permeability in other facies.
(2) Authigenic chlorite can react unfavourably to drilling fluids and treatment of the reservoir by acid flushing. Chlorite cement can be removed from a reservoir interval, thereby often greatly increasing permeability, by flushing the sandstone with a mixture of hydrochloric acid and hydrofluoric acid, but unless chelating agents are used this may cause iron precipitation (Almon & Davies, 1979; Curtis et al., 1984). Recent experiments on core plugs of North Sea sandstones have shown that there is also the risk of generating formation fines by acid treatments (Lievaart & Davies, 1987). These fines could cause greater formation damage (blockage of pore throats) than the clay cements.

**MORPHOLOGY OF AUTHIGENIC CHLORITE**

There are two main occurrences of authigenic chlorite in the reservoir: grain-coating cements and pore-filling cements replacing detrital grains. Chlorite tends to have the same morphology as the pore-filling cement. In thin-section all forms of chlorite are pale green in colour under transmitted light and show grey-yellow birefringence colours in polarized light.

**Grain-coating chlorite**

This form of chlorite is very distinctive. The chlorite crystals have grown perpendicularly onto the host grains and form an isopachous rim of cement ~ 10 μm thick. The rim cement is
FIG. 3(A) Backscattered electron micrograph showing a detrital feldspar grain surrounded by an isopachous grain-coating chlorite cement (indicated by white arrows). Minor peripheral dissolution of the host grain after formation of the chlorite has helped to create small voids between the host grain and the cement. A later generation of chlorite cement occurs within the voids (indicated by the dashed white rectangle and black arrow). Note that chlorite cement is absent at the grain contact X. (B) Scanning electron micrographs showing the grain-coating habit of the first generation of chlorite cement, with enlarged view of poorly developed, often curved crystal plates, reminiscent of a swelling chlorite. Scale bar applies to enlarged view. Note large amounts of porosity (black) in both (A) and (B).

absent at grain contacts (Fig. 3A). There appears to be a tendency for the grain-coating cement to be better and preferentially developed around detrital feldspar grains. The cement is particularly conspicuous where feldspar dissolution has created a void between the cement and the host grain. Under the electron microscope, the enveloping chlorite typically shows slightly curved or crenulated plates (Fig. 3B), arranged in a cellular or honeycomb pattern. Individual crystal plates may not always be resolved. In this form, chlorite resembles the crinkly morphology of mixed-layer chlorite/smectite or corrensite (Tompkins, 1981; Helmold & van de Kamp, 1984), but a non-swelling chlorite structure can be confirmed by X-ray diffraction.

**Pore-filling authigenic chlorite**

This form of chlorite usually consists of euhedral to subhedral crystal plates, typically 3–8 µm in maximum dimension, arranged in a haphazard face-to-edge cardhouse arrangement. Some pores are totally occluded, whereas adjacent pores may remain largely empty (Fig. 4A). Sometimes the cement forms fan-shaped clusters of crystals (rosettes) up to 10 µm in diameter (Fig. 4B).
FIG. 4(A) Scanning electron micrograph showing pore-filling chlorite surrounding detrital quartz grains with well-developed overgrowth surfaces. The quartz overgrowths can be seen enveloping plates of chlorite (centre) and appear to be the later of the two cements. Note how all pores except one (labelled P) are clogged by authigenic chlorite. (B) Scanning electron micrograph of the pore-filling chlorite showing the occurrence of rosette-like clusters of crystal plates.

X-RAY DIFFRACTION

XRD analyses were undertaken on the $<2 \, \mu m$ fractions of both sandstones and mudstones from the three cored sequences. Throughout the succession the mudstones record a detrital
clay assemblage of chlorite + illite with trace amounts of ordered mixed-layer illite/smectite which is intimately associated with the illite. The mixed-layer clay forms a shoulder on the low-angle side of the 10 Å illite reflection. The essential characteristics of the clay assemblage are illustrated in Fig. 5. The detrital chlorite is mainly Mg-chlorite (clinochlore species), although the relative intensity of the odd- to even-order basal reflections varies in different samples indicating that Fe-enriched varieties of chlorite are also present. The absence of detrital kaolinite was confirmed on two accounts: it was not possible to separate a 3.57 Å reflection for kaolinite from the 004 chlorite reflection at 3.54 Å, and a 7 Å kaolinite reflection was not revealed after treatment with 20% sulphuric acid, a procedure that selectively destroys most chlorites but would have left kaolinite unaffected. Slight variations in the proportion of illite to chlorite occur in different mudstone beds, but otherwise this detrital assemblage remains essentially constant between samples.

The sandstones record an authigenic clay assemblage of chlorite with subordinate amounts of neoformed illite (showing some interstratification with smectite), but this assemblage is
TREATED WITH 20% SULPHURIC ACID

HEATED TO 600°C

AIR-DRIED

Fig. 6. XRD traces of the authigenic clay assemblage showing the marked difference in intensity of the 001 and 002 basal reflections of chlorite and the slight shift in spacing of the 001 reflection after heating. Illite/smectite (I/S) is also recorded. Samples prepared as thin smears on glass slides and run at 1°2θ/minute using Ni-filtered Co-Kα radiation.

often contaminated by variable amounts of detrital illite and chlorite. Taking samples from intervals with low detrital clay contamination, the authogenic chlorite was found to have very weak and broad 001 (14 Å) and 003 (4.7 Å) reflections, but the 002 (7 Å) reflection, and to a lesser extent the 004 (3.55 Å) reflection, were very sharp and intense. Characteristic XRD traces are shown in Fig. 6. Treatment with 20% sulphuric acid destroyed the chlorite structure leaving illite as the only identifiable phase, thus confirming the absence of kaolinite in these samples. As far as can be ascertained, the small broad 001 reflection was largely unaffected by glycerolation, although a slight reduction in intensity was noted. When heated to 450°C, the 002 reflection decreased slightly in intensity. Only a small but ever present 001 reflection, which shifted to a constant 13.6 Å, was seen when the samples were heated to 600°C.

On the basis of XRD alone, the chlorite has a typical chamosite structure (Iijima & Matsumoto, 1982; Wilson, 1987). A weak, low-intensity 001 reflection and intense 002 reflection would seem to be a characteristic of authigenic chlorites (Wilson, 1987).
FIG. 7. Summary diagram of electron microprobe data presented on a total Fe–Mg–Al plot. Analyses were made on carbon-coated polished thin-sections using a Cambridge Instruments Microscan 5 electron microprobe with a Link Systems model 290 energy dispersive X-ray analyser. The electron beam was focused to \(~2\,\mu\text{m}\). Data processing was carried out using a ZAF 4 programme.

ELECTRON MICROPROBE ANALYSES

Use of an electron microprobe allows the chemistry of the chlorites, in particular the relative amounts of Fe, Mg and Al, to be determined. There are limitations to these analyses. The principal drawback is that the probe cannot separate ferrous from ferric iron. This is a problem with, for example, recent green clay pellets or berthierine, when it has to be assumed that all the iron present is ferrous, but in reality appreciable amounts of ferric iron could be present (Odin, 1988). Another serious problem results from the fine grain size of the authigenic chlorite and its common occurrence coating detrital grains; it is often difficult to direct the beam onto the clay plates without probing the host detrital grain or other contaminants because the volume analysed (the surface area, \(~2\,\mu\text{m}\) diameter, and also the depth of penetration into the sample of \(~5\,\mu\text{m}\)) is often greater than the dimensions of individual clay particles. Subtotals of wt\% oxides are commonly low owing to the void spaces between individual crystals. The latter problems have been encountered by other workers (e.g. Boles & Franks, 1979) and thus any inaccuracies incurred are not specific to this study. In respect of optical resolution, probe analyses are thus inferior to those obtained from analytical transmission electron microscopy (ATEM). Minor discrepancies in chemical analyses might occur between the two techniques because of normalization of data with ATEM. Finally, there is the possibility of minerals such as hematite becoming attached to the clay plates and adversely affecting the measured Fe : Mg : Al ratios (Curtis et al., 1984). Given these difficulties, it nevertheless has proved possible to analyse satisfactorily a sufficient number of detrital and authigenic chlorites for a general pattern to emerge.
Chlorite in Triassic sandstones

**This Study:**
- Grain-coating chlorites
- Pore-filling chlorites

**Metamorphic chlorites**

**Tetrahedral $\text{Fe} / (\text{Fe} + \text{Mg})$**

**OCTAHEDRAL $\text{Fe} / (\text{Fe} + \text{Mg})$**

**Probe data for the Triassic sandstones are summarized on a Fe–Mg–Al triangular plot in Fig. 7. The diagram also shows fields of the known compositional range of detrital metamorphic chlorite, diagenetic chlorite and berthierine, taken from Velde (1985). It can be seen that most of the detrital flakes ($\text{Ilb}$ chlorite polytypes) fall within the field of metamorphic chlorite, and that all the authigenic chlorites fall within Velde's diagenetic field (Fig. 7). The few analyses of replaced detrital grains that fall within both fields probably record a mixed composition of relic grain and authigenic clay. The plot clearly indicates that these Triassic chlorites are depleted in Fe compared with typical sedimentary berthierine pellets. This is verified by structural formulae (Table 1) which show a slightly higher presence of Mg than Fe. A different type of plot is shown in Fig. 8, first used by Hayes (1970), where values of tetrahedral Al (calculated as 8 minus Si — see Table 1) are plotted against the ratio of octahedral $\text{Fe} / (\text{Fe} + \text{Mg})$. In this case a slight chemical difference between the grain-coating and pore-filling chlorites is apparent, with the former showing a tendency towards lower $\text{Fe} / (\text{Fe} + \text{Mg})$ ratios. Anomalously high Si contents are indicated by some low values of tetrahedral Al. Average values of the octahedral totals for the Triassic chlorites approximate to 10.30, considerably less than the theoretical total of 12.0. Octahedral Al exceeds tetrahedral Al in many sedimentary chlorites and will account for this departure from an ideal formula (Whittle, 1986).
FIG. 9. Backscattered electron micrograph showing early non-ferroan dolomites (D1 and D2) and later ferroan manganiferous dolomites (D3 and D4). A phase of corrosion of the non-ferroan dolomites (arrow) occurred before crystallization of the later ferroan dolomite.

FIG. 10. Decomposition of an expanded Fe-chlorite grain is shown by electron microprobe analysis to proceed by a gradual loss of Fe and Mg relative to Al.
Following the recommendations of the AIPEA Nomenclature Committee (Bailey, 1980), the Triassic chlorites studied here, with Fe/(Fe + Mg) ratios of <0.5, are Fe-rich clinochlores.

CHEMICAL VARIABILITY OF AUTHIGENIC CHLORITES

Although authigenic chlorites of similar optical characteristics have commonly been described in the recent literature (e.g. Hayes, 1970; Wescott, 1983; Curtis et al., 1984, 1985; Moncure et al., 1984), there is considerable variation in their reported chemical compositions (Table 1). In our study, variations in composition of authigenic chlorite were detected within the same polished thin-section (Figs 9, 10). Other authors have reported similar findings (e.g. Boles & Franks, 1979).

Compared to average structural formulae for authigenic chlorites recorded in the literature (Table 1), the Triassic chlorites are notably Si-rich and include higher than average amounts of Mg. However, other North Sea grain-coating chlorites studied by Curtis et al. (1985) are equally Mg-enriched (Table 1). The Triassic Fe-rich clinochlore cements show XRD patterns with suppressed 00l reflections that, in the absence of chemical data, would usually be ascribed to chamosite. Whittle (1986) reported that pore-lining chlorite formulae calculated from XRD traces showed a marked discrepancy with analyses by ATEM, and suggested that the intensity ratio of the 001 : 002 reflections for chlorite may, to some extent, be independent of composition. Doubts must therefore be placed on the attribution of a Mg-rich or Fe-rich composition to a chlorite on the basis of its XRD pattern.

The higher than normal Si content of these Triassic chlorite cements is both intriguing and problematical. In the case of the pore-filling cements this may be artificial and result from contamination of the analyses by the presence of quartz or feldspar formation fines, or fibrous illite cement, accentuated by insufficient resolution of the probe beam. Detection of small, but persistent amounts of K and occasionally Ca supports the possibility of contamination by an illite-like layer-silicate, such as the mixed-layer illite/smectite shown in Fig. 6. Scanning and backscattered electron microscopy often show fibrous illite in close association with chlorite. Moreover, chlorite plates have grown between detrital illite–chlorite laminae. If chlorite structural formulae were calculated from analyses on a physical mixture of illitic clay and chlorite, raised Si contents and deficiencies in tetrahedral Al would inevitably result (Curtis et al., 1984, 1985). Alternatively, the same result could occur if the analysed clay particles showed fine-scale interlayering of chlorite with illite or mixed-layer illite/smectite, diagenetic examples of which are being reported with ever increasing frequency from sedimentary rocks (e.g. White et al., 1984; Ahn & Peacor, 1985). It is therefore useful that the grain-coating chlorites frequently occur in the absence of other clay contaminants. If the high Si values of these chlorites are not elevated by the probe beam penetrating the host silicate grains, then interstratification with small (10–20%) amounts of another clay type must be a real possibility. Slight contraction of the 14 Å reflection of the Triassic chlorite cements to 13.6 Å after heating (Fig. 6), a behaviour recorded by many but not all chlorites, might be attributable to minor interlayering of a collapsible phase such as smectite or vermiculite (MacNeill, 1978). In this respect, it is of interest that Curtis et al. (1985) documented the occurrence of Si-rich chamosites with Si values between 6.77 and 7.94 (assuming 28 oxygen equivalents). Such spuriously high Si contents were obtained from grain-coating cements with unequivocal interstratification of vermiculite or smectite. These swelling chlorites showed slightly curved crystal plates under the scanning electron
TABLE 1. Authigenic chlorite structural formulae. Formula stoichiometry assumes 28 oxygens (or 36 anions, i.e. 20 O + 16 OH) in unit cell: (Mg,Al,Fe)₂[(Si,Al)₂O₆](OH)₁₆.

<table>
<thead>
<tr>
<th>Author</th>
<th>Formulae</th>
<th>Fe/(Fe + Mg)</th>
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<tr>
<td>This study:</td>
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<tr>
<td>Grain-coating</td>
<td>*(Fe₃.₄₂Al₃.₀₃Mg₄.₃₃) [(Si₆.₅₆Al₁.₅₀)O₂₀] (OH)₁₆</td>
<td>0.₄₄</td>
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<tr>
<td>Fe-clinochores</td>
<td>*(Fe₃.₅₅Al₃.₅₆Mg₃.₃₉) [(Si₆.₃₃Al₁.₈₁)O₂₀] (OH)₁₆</td>
<td>0.₅₀</td>
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<tr>
<td>Pore-filling</td>
<td>*(Fe₂.₃₃Al₃.₇₉Mg₃.₃₂) [(Si₆.₆₆Al₁.₁₂)O₂₀] (OH)₁₆</td>
<td>0.₄₁</td>
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<tr>
<td>Fe-clinochores</td>
<td>*(Fe₃.₆₉Al₄.₃₃Mg₃.₉₉) [(Si₆.₃₃Al₁.₆₀)O₂₀] (OH)₁₆</td>
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<td>Other North Sea chlorite analyses:</td>
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<td>Curtis <em>et al.</em> (1985)</td>
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<tr>
<td>Fe-clinochores</td>
<td>B₀⁹ (Fe₂.₆₁Al₃.₃₇Mg₄.₀₁) [(Si₅.₉₅Al₂.₀₃)O₂₀] (OH)₁₆</td>
<td>0.₄₇</td>
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<tr>
<td>Mg-chamosites</td>
<td>B₁₀ (Fe₄.₃₆Al₂.₈₆Mg₄.₃₈) [(Si₅.₅₂Al₂.₄₂)O₂₀] (OH)₁₆</td>
<td>0.₅₀</td>
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<td>Whittle (1986)</td>
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<td>Al-rich,</td>
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<tr>
<td>Mg-chamosites</td>
<td>B₀₂ (Fe₄.₀₂Al₃.₃₂Mg₂.₇₈) [(Si₅.₄₂Al₁.₁₈)O₂₀] (OH)₁₆</td>
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<td>Other miscellaneous analyses:</td>
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<tr>
<td>Curtis <em>et al.</em> (1984)</td>
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<tr>
<td>Chamosite</td>
<td>(Fe₅.₂₀Al₃.₃₃Mg₂.₇₁) [(Si₅.₈₈Al₁.₂₃)O₂₀] (OH)₁₆</td>
<td>0.₆₆</td>
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<tr>
<td>Swelling chlorite</td>
<td>(Fe₄.₃₅Al₂.₅₃Mg₃.₆₉) [(Si₆.₉₃Al₁.₀₉)O₂₀] (OH)₁₆</td>
<td>0.₅₇</td>
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<td>Whittle (1986)</td>
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<td>Curtis <em>et al.</em> (1985)</td>
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<tr>
<td>Swelling chlorite</td>
<td>A₁₀ (Fe₄.₃₈Al₃.₃₆Mg₂.₉₂) [(Si₆.₇₇Al₁.₂₃)O₂₀] (OH)₁₆</td>
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<td>Berthierine</td>
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<tr>
<td>Al-Chlorite</td>
<td>av. (Fe₃.₆₆Al₃.₉₀Mg₃.₄₇) [(Si₅.₈₂Al₁.₂₈)O₂₀] (OH)₁₆</td>
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<td>Moncure <em>et al.</em> (1984)</td>
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<tr>
<td>Fe-chlorite</td>
<td>av. (Fe₅.₃₀Al₃.₃₀Mg₂.₆₃) [(Si₅.₉₂Al₁.₀₉)O₂₀] (OH)₁₆</td>
<td>0.₆₇</td>
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<tr>
<td>Iijima &amp; Matsumoto (1982)</td>
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<tr>
<td>Chamosite</td>
<td>(Fe₇.₇₆Al₂.₈₁Mg₁.₃₅) [(Si₅.₁₆Al₁.₀₉)O₂₀] (OH)₁₆</td>
<td>0.₈₃</td>
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* single analyses showing limits of variation of the ratio Fe/(Fe + Mg).

av. – average compositions calculated from all analyses. Average compositions for the Triassic chlorites may be affected by contamination with illite-smectite (see discussion in text).

A₁₀, A₁₁, B₀₁, B₀₂, B₀₃, B₀₅, B₀₆, B₀₇, B₀₈, B₀₉, B₁₀, & B₁₆ – reference sample numbers used by previous authors; formulae are averages for numerous single-crystal analyses from one sample.
Chlorite in Triassic sandstones

...microscope (cf. Fig. 3B), but differed from the Triassic rim chlorites in respect of their general XRD characteristics (Curtis et al., 1984), reflecting a much higher expandable component. In summary, the elevated Si values of the Triassic chlorites would seem to result from the dual effect of minor interstratifications and variable degrees of contamination of the analyses.

Despite the variability of composition of authigenic chlorites, they can usually be distinguished chemically from detrital metamorphic chlorites. The latter generally contain less Si and Al, but are richer in (Fe + Mg) and therefore occupy different compositional fields (Figs 7 and 8).

**ORIGIN OF THE CHLORITE CEMENTS**

**Constraints**

The previous account places a number of constraints on possible models for the origin of the chlorite. The model must allow for an early diagenetic (shallow burial) origin for the cements, with a generation of grain-coating chlorite largely pre-dating crystallization of euhedral pore-filling chlorite. It should also explain the distribution of chlorite, with the earliest grain-coating cements restricted largely to the marginal marine facies, but with the later pore-filling cements occurring in fluvial as well as marginal marine facies. Finally, the model should suggest reasons for the Mg- and Si-enriched composition of the cements. An inverse relationship between the amount of dolomite and chlorite cement present in the reservoir might be indirectly explained by the model.

A number of possible explanations for the origin of authigenic chlorite in sandstones have been proposed in the literature. These are briefly considered in order of increasing likelihood.

**Alteration of precursor kaolinite**

The idea that authigenic chlorite could result from the interaction of detrital clay and Fe(II) in a shallow marine environment was often favoured in the earlier literature (e.g. Carroll, 1958). Recent pelletal green clay minerals found in shallow marine sediments in tropical latitudes are often associated with detrital kaolinite substrates (Odin, 1988), but the form and composition of these pellets is quite different from the chlorite described here. More recently, the concept that chlorite cement can also form by replacement of a kaolinite precursor was proposed by Boles & Franks (1979) from study of the diagenesis of Eocene Wilcox Group sandstones in Texas. The authors recorded the disappearance of kaolinite and formation of chlorite over depths representing a temperature range of 150° to 200°C. They suggested that the high Al content of the chlorite was inherited from a precursor kaolinite, and that Fe and Mg were released from the alteration of smectite to illite, a process which occurs in interbedded mudstones with increasing depth of burial along the Gulf Coast.

This mechanism seems inappropriate to our study on several accounts. In the Triassic sandstones the chlorite formed early in diagenesis whereas in the Wilcox Group sandstones the chlorite formed largely when the depth of burial exceeded 3500 m (the approximate present depth of the Triassic sandstones). There are also no vestiges of a precursor kaolinite cement in the Triassic sandstones, although neoformed kaolinite has commonly been recorded in Permo-Triassic sandstones in the North Sea area (e.g. Rossel, 1982). It can be generally said that, within the limits of present knowledge, detrital kaolinite is rare in late Triassic and Rhaetic sediments in the European area (Jeans, 1978). Detrital kaolinite first appears in any quantity in the late Rhaetic and early Jurassic.
Reaction of clay minerals with carbonates during deep burial

Several chemical reactions were suggested by Hutcheon et al. (1980) as possible explanations for the formation of Mg-chlorite cement at temperatures of between 180° and 250°C during deep burial. The only reaction remotely applicable to the Triassic sandstones involved dolomite, illite and quartz, generating Mg-chlorite and calcite cements (Hutcheon et al., 1980). Some of the earliest diagenetic dolomite does show evidence of dissolution (Fig. 9) and is clearly a potential source of Mg for chlorite formation during early burial in the Triassic sandstones. However, cathodoluminescence studies reveal that there is no evidence of corrosion of later diagenetic zoned ferroan dolomites, suggesting that little Mg would have been released to pore-fluids by this means during deeper burial. Furthermore, there is no calcite cement in the sandstones so this mode of origin seems improbable.

Post-depositional alteration of 7 Å green clay minerals

Recent pelletal green marine clays, formerly identified as berthierine (e.g. Odin & Matter, 1981), have formulae that fall outside the compositional field usually attributed to a true berthierine (Velde, 1985). Odin et al. (1988) have shown that these green clays are not monomineralic, but actually comprise several new mineral species. Accordingly, the temporary term of phyllite V should now be applied to these Recent green 7 Å clays (Odin, 1988) and the term odinite has been approved as a new species name for the 7 Å phyllite V (Bailey, 1988). Evolution of phyllite V to berthierine, resulting in a better organized 7 Å structure, occurs during early diagenesis (Odin, 1988). Transformation to a 14 Å chlorite structure probably occurs during later burial (Odin et al., 1988; Velde, 1985).

The occurrence of grain-coating chlorite mainly in the marginal marine facies of the Triassic sequence accords with the observations of Odin & Matter (1981) and Odin & Sen Gupta (1988) that most Recent phyllite V occurrences are located near river mouths. It is tempting to suggest that transformation from an inherited 7 Å structure, such as poorly crystalline phyllite V, to a 14 Å chlorite structure, might explain the broad and weak 001 basal reflection of the authigenic chlorites. If the chlorite had originated as a 7 Å berthierine, then the cements have lost considerable amounts of Fe from their structure during alteration (see Fig. 7). This Fe could have been incorporated into the structure of later ferroan dolomite cements.

However, there remain significant problems with a model involving such precursor green clay minerals. First, there is a problem of morphology. Phyllite V in Recent sediments, and Tertiary berthierine, usually occur as faecal pellets, infillings of microfossil tests or as replacements of carbonate bioclasts. Judging by the geological literature, grain coatings of these minerals would appear to be rarer than the green films of glauconitic smectite that may often coat detrital silicate grains or bioclasts on modern continental shelves (Odin & Matter, 1981). There is considerable evidence to show that, during burial, the pelletal form of green grains is preserved, even though major chemical changes may have occurred. For example, Velde et al. (1974) described pelletal chlorite from low-grade metamorphic rocks in Algeria. Yet there is no evidence of pelletal clay, as distinct from detrital clasts, preserved in the Triassic sandstones. Hurst & Buller (1984) invoked redistribution of dispersed Fe-rich clays during diagenesis to form grain-coating cements in some Paleocene turbidite sandstones, but their model involved dewatering processes, evidence for which is lacking in these Triassic
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sandstones. In general, the diagenetic redistribution of poorly crystalline pigmentary phyllite V rather than pelletal berthierine seems a more likely possibility (Odin, 1988).

The other main problem is the common occurrence of pore-filling chlorite in the fluvial sandstones, which were an unlikely host for green marine clays. Even allowing for very slow burial of the fluvialite beds, with gradual replacement of the meteorically-derived porewater by seawater, conditions were unlikely ever to have been conducive to formation of the phyllite V family of minerals which, at the present time, form under conditions similar to glauconitic smectite, i.e. at or just below the sediment/seawater interface in semi-confined geochemical environments, but in shallower water (Odin & Matter, 1981; Odin & Sen Gupta, 1988).

Transformation of a swelling chlorite (corrensite)

Dunoyer de Segonzac (1970) and Curtis et al. (1985) drew attention to a potential transformation from a precursor smectite through an intermediate swelling chlorite to chlorite. The phyllite C family of green clay minerals, also found in Recent shallow marine sediments, can be considered as possible starting material here. Phyllite C is intermediate in composition between a smectite and a swelling chlorite and is typically enriched in Si (Odin et al. 1988; Odin & Sen Gupta, 1988). Little is known about the effects of burial diagenesis on this recently discovered family of green clay minerals. However, it is not inconceivable that a link may exist between these incipient green clay pigments and grain-coating swelling chlorite cements that have been reported from a number of sandstone reservoirs. Helmold & van de Kamp (1984) documented a decrease in expandability of a grain-coating mixed-layer chlorite/smectite with depth in Paleogene sandstones and suggested that chlorite rim cements in the same sequence were the product of transformation of a precursor swelling phase. The similarity of the grain-coating Triassic chlorite in terms of their high Si-contents, and sometimes their chemistry as a whole (Table I), and morphology to the swelling chlorites described by Curtis et al. (1985) has already been remarked on (see also Fig. 8). Neoformed swelling chlorites (irregularly interstratified chlorite/smectite or, alternatively, well-ordered corrensite) have been reported from Triassic sediments in the UK area (Jeans, 1978; Fisher & Jeans, 1982; Purvis, 1988) and thus could have been originally present in the Triassic sediments.

A model involving a precursor swelling chlorite has its attractions for the origin of the early grain-coating chlorites, but cannot explain the distribution of pore-filling chlorite in the fluvial sandstones. The delicate and euhedral morphology of many of the later diagenetic chlorites is suggestive of direct precipitation from solutes in porewaters.

Direct precipitation during shallow burial

The common occurrence of ferroan dolomite cements in the reservoir indicates that sources of Mg and Fe were readily available in the porewaters at times during burial. Some of the required ions such as Si and Fe could also have been supplied by freshwater recharge from the fluvial environments during early burial. Gradual chemical dissolution of feldspar in the reservoir which would have released plentiful supplies of Al and Si into solution. Textural relationships suggest the main phase of feldspar dissolution post-dates formation of the grain-coating chlorites, but was well underway before precipitation of the pore-filling
chlorite. There is also evidence for corrosion of non-ferroan dolomites in the reservoir during early diagenesis (Fig. 9) which would have released some Mg into solution. Iron and Mg would also have been supplied to porewaters from the breakdown of detrital chlorite and biotite grains, some of which show fan-like terminations composed of a low birefringent clay; electron microprobe analyses confirm a loss of Fe and Mg relative to Al in altered parts of the grain (Fig. 10). The low Fe content of some of the pore-filling chlorites (Table 1) may have been caused by crystallization in close proximity to decomposing Fe-poor detrital clinochlores. Finally, the possibility of complete or partial chemical breakdown of a pre-existing, invariably poorly crystalline non-granular green mineral, such as phylrite C, cannot be totally dismissed. Given that the activity of the required ions in porewaters was sufficiently high, it is difficult to see why chlorite should not form as a direct precipitate during burial in the same way as neoformed kaolinite and illite. A number of other authors have concluded that well-crystallized diagenetic chlorite must result from direct precipitation (Hayes, 1970; Curtis et al., 1984).

This model of direct precipitation is especially applicable to the pore-filling chlorites because it is not constrained by the original depositional environments. During burial diagenesis, porewaters could have migrated through marginal marine and fluvial sediments, allowing direct precipitation of euhedral chlorite in all permeable sandstone beds. The apparent inverse relationship between the amount of dolomite and chlorite cement in the sequence could reflect competition between the two cements for available Mg. Where conditions favoured dolomite precipitation, the availability of Mg for chlorite formation would have been restricted and vice-versa. This has previously been suggested by Fisher & Jeans (1982) who also documented neoformation of Mg-rich chlorite in competition with the precipitation of dolomite. The chemistry of the pore-filling chlorite cements is therefore a reflection of porewater chemistry during burial, controlled in turn by the dissolution reactions involving dolomite and detrital silicates and the overall chemistry of the host rocks.

**SUMMARY**

This study has attempted to determine the origin of chlorite cements in some North Sea Triassic sandstones by documenting their occurrence, morphology and chemistry, and comparing these results to other published works. The sandstones studied contain two main generations of chlorite cement, the earliest of which is restricted to marginal marine facies, but the later generation also occurs in fluvial facies. Clear differences in morphology, and slight differences in Fe/(Fe + Mg) ratios, were found between the earliest cements which occur as isopachous grain-coatings and have a crystal form reminiscent of a swelling chlorite, and later euhedral pore-filling cements which show rosette-like clusters of crystals which are characteristic of an authigenic chlorite. The XRD patterns are suggestive of chamosite, but compositions determined by electron microprobe analyses are of Fe-rich clinohlores with Fe/(Fe + Mg) ratios varying from 0.41 to 0.50. The Fe contents of the cements are much lower than would be predicted from their XRD characteristics.

The preferred origin of the pore-filling cements is by direct precipitation from porewaters during burial, with the corrosion of dolomite cements and the decomposition of detrital feldspar, biotite and chlorite grains supplying most of the necessary chemical components. This origin is the most satisfactory explanation for the occurrence of chlorite cements in fluvial sandstones. The earlier diagenetic grain-coating chlorites in the marginal marine sediments could also be direct precipitates, but alternatively may have originated by
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alteration of a precursor swelling chlorite or corrensite cement. Evidence for this includes the irregular curved crystal form of the early chlorites, their high Si contents, similar to the composition of swelling chlorites analysed by Curtis et al. (1985), and, indirectly, the commonly documented cases of early diagenetic swelling chlorite in marginal marine or marine Triassic sediments. Other explanations such as alteration from precursor kaolinite or granular phyllite V or berthierine are considered unlikely.

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