Preservation of Anomalously High Porosity in Deeply Buried Sandstones by Grain-Coating Chlorite: Examples from the Norwegian Continental Shelf

S. N. Ehrenberg

ABSTRACT

Five Lower to Middle Jurassic sandstone reservoirs from the Norwegian sector provide examples of deep porosity preservation caused by grain-coating, authigenic chlorite. Wide porosity variations in clean sandstones correlate with an abundance of grain-coating chlorite and consequent inhibition of quartz cementation. Maximum porosities tend to decrease with increasing depth but generally are 10–15% higher than would be predicted from regional trends of mean porosity vs. depth. It is proposed in this paper that the high chlorite content of the porous zones reflects syndepositional concentration of Fe-rich marine clays analogous to minerals of the modern peridine facies. Fe-clay mineralization would have been localized where Fe-rich river water was discharged into the sea. The syndepositional clays were transformed during burial diagenesis into grain coatings of radially oriented chlorite crystals. Petrographic relationships indicate that these coatings grew mainly before the beginning of quartz cementation and feldspar grain dissolution (probably within the first 2 km of burial) but after grain contacts had become adjusted by mechanical compaction. The Norwegian examples demonstrate that a wide range of nearshore marine sand-body types is susceptible to chlorite mineralization. The distribution of anomalous porosity and the proportion of the net sand affected depend upon sedimentary facies architecture and the pattern of discharge of Fe-rich river water during sand deposition.

INTRODUCTION

Numerous published studies have shown that inhibition of quartz cementation by grain-coating authigenic chlorite can result in the preservation of unusually high primary intergranular porosity in deeply buried sandstone reservoirs (Heald and Anderegg, 1960; Heald, 1965; Horn 1965; Pittman and Lumsden, 1968; Heald and Larese, 1974; Dutton, 1977; Hancock, 1978; Taylor, 1978; Thomson, 1979, 1982; Tillman and Almon, 1979; Wescott, 1983; Winn et al., 1983; Larese et al., 1984; D'Agostino, 1985; Imam, 1986; Houseknecht and Hathon, 1987; McBride et al., 1987; Thomson et al., 1987; Swales, 1988; Dixon et al., 1989). The mechanism by which chlorite blocks quartz growth is unclear, but it has commonly been assumed that the chlorite isolates detrital quartz surfaces from contact with pore water, thus preventing nucleation of authigenic quartz. This phenomenon can be critically important for hydrocarbon exploration because it can provide good reservoir quality at depths far below the “economic basement” originally defined on the basis of sandstones lacking chlorite coatings. Discovery of chlorite-related anomalous porosity in one deep prospect thus can open a new play concept in a basin previously regarded as mature. Examples include the deep Tuscaloosa trend in Louisiana (Thomson, 1979), the deep Wilcox in south Texas (D'Agostino, 1985), and the deep Norphlet in Mississippi and Alabama (Thomson et al., 1987; Dixon et al., 1989). Understanding the geometry and petrophysical characteristics of chlorite-coated high-porosity zones also can be important in designing production strategies for these reservoirs.
This paper summarizes the results of a series of internal Statoil technical service studies in which chlorite-related anomalous porosity has been documented in five formations from the Norwegian continental shelf (Figure 1) (Table 1). The five reservoir examples are all Early to Middle Jurassic, consist mainly of subfeldsparitic arenite, and were deposited in marine environments. However, five distinctly different depositional settings are represented, and sand-body shape, the geometry of porous, chlorite-rich zones, grain size and grain sorting all vary widely. The goals of this study are to summarize in a uniform format the porosity-depth relationships, reservoir geometry, sedimentology, and petrology of each example and to use these data to arrive at some general interpretations about the origin of porosity-preserving chlorite, its characteristics, and the potential for its prediction.

**ANALYTICAL TECHNIQUES**

The database for the present study comprises 188 sandstone samples, analyzed by point counting of thin sections (300 counts per sample); visual estimation of median grain size and Trask sorting coefficient (Beard and Weyl, 1973); x-ray diffraction (XRD) analysis of bulk rock and clay (<2 μm) fraction; and bulk chemical analysis (performed by X-ray Assay Laboratories, Ltd., Ontario, Canada). All samples are portions of 1-in. diameter plugs for which porosity and klinkenberg-corrected horizontal permeability also have been measured. Complete tables of analytical data for these samples are available from the author upon request. In addition, porosity and permeability have been measured in the cored intervals studied at a frequency of three plugs per meter (approximately 2600 samples).

XRD analyses of different sample sets were performed in three different labs over the course of several years. Well 6507/3-1 samples were analyzed by Reidar Bøe, IKU, Trondheim. Other Haltenbanken samples were analyzed at Statoil. Veslefrikk field samples were analyzed by M. J. Wilson, Macaulay Land Use Research Institute, Aberdeen, Scotland.

Unfortunately, none of the analytical techniques used in this study give a reliable quantitative measurement of bulk chlorite abundance. However, three approaches do appear to provide quantitative indices that vary in approximate proportion to bulk chlorite content.

(1) Point counting of chlorite rims and chlorite-rich grains in thin section gives a direct measure of grain-coating clay abundance. However, uncertainty is introduced by the presence of substantial and possibly variable amounts of microporosity (Nadeau and Hurst, 1991). Also, the chlorite in many samples appears to be intimately intermixed with substantial proportions of illite or kaolin. The point-counted estimates therefore are regarded as only a general indication of chlorite content.

(2) Recalculation of the bulk-rock Fe content to exclude Fe contained in pyrite and siderite gives a value which should be proportional to chlorite abundance, at least to the extent that chlorite is the only other Fe-rich mineral present. Microprobe data indicate that the chlorite in different samples generally is similar in composition and contains around 32 wt% total Fe expressed as FeO. The bulk-rock sulfur content can be used to subtract Fe contained in pyrite, and, by using the bulk XRD analysis to determine the ratio of siderite:dolomite:calcite, the bulk-
Table 1. Sedimentologic Characteristics and Interpretations of Norwegian Sandstones with Chlorite-Rich Zones

<table>
<thead>
<tr>
<th>Formation</th>
<th>Lower Jurassic (Pliensbachian)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depositional Setting</td>
<td>tidally dominated shoreline and delta lobe progradation.</td>
</tr>
<tr>
<td>Description</td>
<td>Individual reservoir zones tend to be readily correlative locally, but not over distances &gt;10-20 km. Stacked coarse-upward sequences reflect deposition in a series of progradational events (local progradation of sand-dominated delta lobes and interdeltaic shorelines) interrupted by transgressions. Near absence of floodplain sediments (sparse occurrences of coal, coaly shale, and rooted horizons) results from shoreface erosion during transgressions. Three facies can be distinguished: Facies 1—bioturbated mudstones and sandy mudstones with wave ripple lamination and hummocky cross-bedding. Facies 2—very fine- to medium-grained sandstones with weak to moderate bioturbation, hummocky cross-bedding, herringbone and wave ripple lamination, and mud drapes. Facies 3—medium- to coarse-grained sandstones with little or no bioturbation.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Formation</th>
<th>Lower Jurassic (Toarcian)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depositional Setting</td>
<td>local, tectonically sourced outpouring of very coarse sand into a deep marine basin.</td>
</tr>
<tr>
<td>Description</td>
<td>Trace fossils support a marine setting, and evidence of subareal exposure has not been observed. Two facies can be distinguished: Facies A—intensely bioturbated, fine-grained muddy sandstone (interpreted as lower delta front to prodelta). Facies B—coarse-grained, very poorly sorted sandstone with prominent unidirectional, high-angle cross-bedding. Both normally and inversely graded bedding are common. Bioturbation varies from absent to intense. (Interpreted as upper delta front deposits.)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Formation</th>
<th>Middle Jurassic (Bajocian-Bathonian)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depositional Setting</td>
<td>regionally extensive braid delta (40–120 m of nearly 100% clean sand deposited during a major sea level fall).</td>
</tr>
<tr>
<td>Description</td>
<td>Deposition took place along a shoreline dominated by massive sand influx from braided streams. In well 606/3-1, possible evidence of marine deposition is provided by large vertical burrows within the upper 9 m of the formation, but the rest of the core consists of unbioturbated sandstone with common cross-bedding and thin clay laminations (Figure 15).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Formation</th>
<th>Upper Triassic to Lower Jurassic (Rhaetian-Sinemurian)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depositional Setting</td>
<td>3–7 m of transgressive marine sandstone capping a thick alluvial plain sequence.</td>
</tr>
<tr>
<td>Description</td>
<td>The lower 120-140 m of the unit is alternating sandstone and shale (alluvial channel and flood plain deposits), while the upper 80-100 m is almost continuous sandstone (braided river deposits). The capping marine sandstone is present only in the southern part of Vestfjord field, forming a wedge that thins to the northeast. The high-resolution signature of this sandstone on the spectral gamma-ray log is correlated with a zone of sandy marine shale that overlies the sandstone and thickens to the northeast as the sandstone pinches out. Bioturbation is weak to absent, and the only sedimentary structures present are planar to low-angle parallel laminations. The depositional environment is tentatively interpreted as middle to upper shoreface, passing upward and laterally into the offshore zone represented by the sandy shale.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Formation</th>
<th>Lower Jurassic (Pliensbachian)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depositional Setting</td>
<td>45–60-m thick upward-coarsening unit reflecting progradation of nearshore shallow marine sandstone over offshore silt and mud.</td>
</tr>
<tr>
<td>Description (summarized from an unpublished sedimentologic study by E. Prestholm and O. Walderhaug of Rogaland Research, Stavanger, Norway):</td>
<td>The lower coarsening-upward cycle consists of laminated shale grading upwards into very fine-grained, muddy sandstone with variable bioturbation, wave and current ripples, and hummocky cross-lamination. The upper cycle begins with a thin laminated shale zone at its base, grading upwards into interlayered sandstone and shale, with gradual upward increase in the proportion and thickness of sandstone layers. Abundance and diversity of trace fossils is markedly reduced relative to the lower cycle. A marginal marine, freshwater-influenced depositional environment (ebt tidal delta, estuarine shoal, distributary mouth bar) is envisioned for the uppermost clean sandstone zone, based on the common occurrence of coal fragments, presence of currentripple lamination, upward decrease in trace fossil diversity, and the presence of abundant Fe-rich chlorite. Although biostratigraphic data indicate mainly open marine conditions, freshwater algae occur in the basal part of the upper cycle.</td>
</tr>
</tbody>
</table>
rock CO$_2$ content can be used to subtract Fe contained in siderite. Uncertainties arise because of the likely presence of Fe in additional minerals such as ankerite and biotite.

(3) The percent chlorite in the clay-fraction XRD analysis pertains directly to only the clay minerals of less than 2 μm rather than to the bulk sandstone. The measurement is, however, relevant to the bulk chlorite content in that low values of chlorite in the clay fraction imply low bulk chlorite contents as well. Chlorite was measured also in the bulk XRD analyses, but when a clay mineral is a minor component (<5–10%) of a multimineral mixture, one should not expect accurate quantitative determination by this technique.

RESERVOIR DESCRIPTION

In each of the cores studied, sampling was mainly confined to clean sandstones. Low-porosity zones resulting from high contents of clay or carbonate cement generally were avoided because the porosity of these rocks is unrelated to the problem of porosity preservation by chlorite. In Figure 2 the porosities of the individual samples studied are compared with regional trends of porosity vs. depth for sandstones of Haltenbanken and the northern North Sea. The high-porosity (chlorite-rich) samples are clearly anomalous, whereas the lower porosity (generally chlorite-poor) samples from the same cores have porosities consistent with the regional trends.

In this section, sedimentologic, porosity, and wireline log profiles along each of the studied cores are presented in a uniform format and at uniform scale to aid comparison between the five reservoir examples. Sedimentologic information taken from a number of previous unpublished studies is summarized for these five units in Table 1. A standard format also is used for plotting porosity variation vs. abundances of both quartz cement and chlorite, to show the degree to which porosity depends upon inhibition of quartz cementation by chlorite.

Tilje Formation, Haltenbanken

Zones of anomalous, chlorite-coated porosity have been found in the Tilje Formation in two widely separated areas of Haltenbanken (Figure 1): Block 6506/12 (Smørbukk and Smørbukk Sør fields) and approximately 100 km to the northeast in Block 6507/3. In Smørbukk field, the Tilje Formation is the most important of several reservoir units, with more than 50% of the total 90 × 10$^6$ standard m$^3$ (566 million bbl) in-place liquid reserves, and productivity
Figure 3—Tilje Formation: gamma-ray log, porosity variation, and sedimentological descriptions through cored intervals in the five wells studied. Horizontal line in each panel marks formation top. Well locations are shown in Figure 1.
Figure 3—Continued.

Figure 4—Cross section hung on the top of the Tjil Formation in the four wells studied from Block 6506/12, showing the occurrence of chlorite-rich high-porosity zones with respect to facies zones and time-stratigraphic units. The vertical scale is the same as in Figure 3. Well locations are shown in Figure 1.
critically depends upon the presence of a few laterally continuous zones of high permeability (Ehrenberg et al., 1992). In Smorbukskær field, the Tilje Formation is a reservoir of secondary importance, with gas condensate filling the upper two of three main zones. In well 6507/5-1, the upper 33 m of the formation is hydrocarbon filled but tight, and high-porosity zones occur within the underlying water zone.

The distribution of porosity through five wells in the Tilje Formation is plotted alongside the gamma-ray log and sedimentologic descriptions in Figure 3. Note the wide variations in sand:shale ratio, as reflected in the varying gamma-ray activity. Figure 4 is a cross section through the four Smorbukskær area wells showing a two-dimensional view of the occurrence of porous zones with respect to facies and time lines. The high-porosity zones occur at different stratigraphic positions in different wells, displaying at most only short-range correlation, but occur mostly in the relatively proximal facies-3 sandstones (Table 1). No consistent sedimentological differences have been found between the chlorite-rich, high-porosity facies-3 zones and the tightly quartz-cemented facies-3 zones in the same well.

The sandstones of the Tilje Formation have feldspar:detrital quartz ratios ranging mainly from 0.05 to 0.25 and feldspar:rock fragment ratios mainly greater than one and thus are classified as subarkosic arenites (Dott, 1964). Molds of partly dissolved grains make up 1-7% of the rock volume. These grains typically appear to have been feldspars, and therefore have been counted together with the existing feldspar in calculating the preceding ratios. K-feldspar is several times as abundant as plagioclase, and mica makes up less than a few volume percent in most samples. Median grain size varies widely (mainly 0.15-0.70 mm), but does not correlate with porosity. Sorting varies from moderate to poor.

Thin sections reveal that the most porous (>20%) sandstones are characterized by low to moderate contents of quartz cement and abundant intergranular macropores surrounded by thick chloride coatings (Figure 5). A scanning electron microscope (SEM) study of these samples shows that most pore surfaces are carpeted with radially oriented chloride platelets (Figure 6A-D), as is also the case in the high-porosity sandstones from the other units studied (Figure 7). In contrast, the least porous samples in each well tend to have much higher quartz cement contents and either lack chloride coatings or have relatively thin, discontinuous coatings that allow direct contact between quartz grains and the optically continuous quartz overgrowths [see also Ehrenberg et al. (1992), their Figure 13C-F, for a series of color photomicrographs comparing quartz-cemented vs. porous Tilje sandstones].

If the model of porosity preservation by chloride coatings is correct for the Tilje samples, then one should expect to observe two correlations in the quantitative petrologic data. The high-porosity samples should be both (1) low in quartz cement and (2) rich in chlorite relative to the low-porosity samples. However, the results from point counting thin sections show that the first of these correlations is poorly developed (Figure 8A). Porosity is not a simple function of quartz cement content because many low-porosity samples also have low to moderate contents of quartz cement.

The other major factor besides quartz cementation that controls porosity in these samples is the percent intergranular volume (IGV). This parameter can be measured by summing up the nongrain components counted in a modal analysis (Houseknecht, 1987; Ehrenberg, 1990). IGV is partly an index of
Figure 6—SEM photomicrographs of Tilje and Garn sandstones.
(A and B) Tilje Formation, well 6506/12-5, 4357 m RKB. A quartz sand grain is coated entirely by radially oriented chlorite (type A surface) except for footprints marking surfaces of contact with adjacent grains (type B surface).
(C and D) Tilje Formation, well 6506/12-6, 4606 m RKB. Three types of quartz surfaces are visible: type B (grain-grain contacts), type C (cubedal cement faces), and type D (a grain footprint). Superficially, the type D surfaces appear to show chlorite growing on quartz cement, but closer inspection reveals a distinctive “cuneiform” texture, formed as the quartz cement impinged upon the tops of chlorite crystals coating the opposing surface of an adjacent sand grain. Note that the surfaces labeled B and D both reflect the former presence of a single sand grain, to the upper right of the view shown in C.
(E and F) Garn Formation, well 6406/3-1, 3807 m RKB. A chlorite-coated quartz grain showing a type B surface (left) deeply pitted by pressure dissolution.
Figure 7—SEM photomicrographs of Statfjord and Intra-Dunlin sandstones.
(A and B) Statfjord Formation, well 30/3-A5, 4253 m RKB. The chlorite-coated mold of a dissolved grain has been broken open, showing the delicate internal structure of clay and skeletal relict feldspar.
(C and D) Same sample as in A and B. The chlorite coating has spalled off, revealing the smooth, unpitted texture of a primary (type A) quartz surface.
(E and F) Intra-Dunlin sandstone, well 30/3-A1, 3077 m RKB. Chlorite-coated quartz grains are overgrown partly by quartz cement crystals. The closeup shows how at least nine separate cement crystals have formed at different points, all having a common crystallographic orientation. With continued growth, these crystals would merge eventually, forming a single uniform overgrowth.
the degree of compaction, but also reflects the primary porosity at the time of sand deposition, which is around 40% in well-sorted sand and decreases substantially as sorting becomes poorer (Ehrenberg, 1989). In addition, porosity in a few of the samples has been reduced by carbonate cementation. Figure 8B shows that most of the Tilje porosity variation is accounted for by combining these parameters. Quartz cementation in Mesozoic sandstones of the Norwegian shelf is a rather late diagenetic process, occurring mainly at burial depths greater than 2.5 km below the sea floor (Ehrenberg, 1990; Bjorlykke et al., 1992). The variations in IGV, carbonate cementation, and matrix in the Tilje sandstones probably predate quartz cement growth, such that it is only the porosity not previously removed by the other factors that has been either infilled by quartz cementation or preserved by chlorite coatings.

The other correlation to be sought is the occurrence of higher chlorite contents in the more porous sandstones. This relationship is shown by Figure 9A and C, and is particularly apparent when the data are examined one well at a time. However, no relationship is apparent between the siderite-corrected bulk Fe contents and porosity (Figure 9B).

**Tofte Formation, Haltenbanken**

Following deposition of the Tilje Formation, major transgression of the Haltenbanken area resulted in deposition of the Ror Formation, an overall upward-coarsening sequence of marine shale with storm-deposited sandstone beds in its upper portion. Around Smørbukk field, however, Ror deposition was interrupted by the localized outpouring of a fan delta of coarse-grained, very poorly sorted, cross-bedded sand, forming an areally restricted unit named the Tofte Formation. Cores have been taken through the Tofte Formation in only three wells. In wells 6506/12-1 and 6506/12-6 in Smørbukk field, porosity is low due to extensive quartz cementation, but in the nearby well 6506/11-1, anomalously high porosity has been preserved by chlorite coatings despite greater burial depth.

Porosities of samples selected for petrologic anal
Figure 9—Helium porosity of Tilje sandstones vs. indices of chlorite content. (A) point counted % chlorite rims; (B) bulk-rock Fe content minus Fe contained in siderite and pyrite (as estimated from bulk XRD analyses of relative proportions of carbonate minerals present, together with bulk CO₂ and S contents); (C) Percent chlorite in clay-fraction XRD analysis. Plotting symbols identify wells.

ysis are plotted in Figure 2, showing that the samples from well 6506/11-1 are anomalously porous, whereas the other two wells have normal porosity. In well 6506/11-1, lower porosity toward the top of the core reflects high contents of detrital clay matrix and intense bioturbation. In the lower 8 m of the core, the sandstones generally are coarser grained and cleaner and have porosities of 20–25%. The wireline logs indicate that this lithology continues below the bottom of the cored interval for at least another 20 m (Figure 10).

The Tofte sandstone is believed to have been rapidly deposited into deep water in response to a tectonic uplift immediately to the west. The cross section through the Tofte Formation in the three wells studied (Figure 11) shows the pattern of westward thickening that is the basis for the preceding interpretation. In well 6506/11-1, the Tofte Formation rests erosionally on the Tilje Formation and is greatly thickened due to growth faulting. To the east in well 6506/12-1, coarse, proximal sand (facies B) still makes up most of the formation, but the gamma-ray log shows a distinct increase in shaliness (Figure 10). The proportion of fine-grained, highly bioturbated sandstone (facies A) increases eastward into well 6506/12-6. Farther east, as well as to the south, the Tofte Formation has shaled out. The distribution of chlorite-coated, high-porosity sandstone shows striking contrast to the situation in the Tilje Formation (Figure 4), because it is localized near the presumed fluvial source of the sandstone wedge.

The Tofte sandstones are subarkosic arenites having compositions similar to the Tilje samples described previously. However, median grain size is medium to coarse (0.3–1.0 mm), which generally is coarser than in the Tilje sandstones, and sorting tends to be poorer. In well 6506/11-1, most samples have low contents of quartz cement, abundant intergranular macroporosity, and thick chlorite coatings (Figure 12B, C). The high porosity of these rocks is due to preservation of the primary intergranular pore system. In wells 6506/12-1 and 6506/12-6, chlorite coatings are not present, and porosity has been greatly reduced by quartz cement or, in two of the samples, by abundant siderite cement (Figure 13). The available quantitative indices of bulk chlorite content do not give linear correlations with porosity (Figure 14), but do show the general relationship that the sandstones in well 6506/11-1 are chlorite rich and the sandstones in wells 6506/12-1 and 6506/12-6 are chlorite poor.

Garn Formation, Haltenbanken

This important reservoir unit, 40–120 m thick throughout much of the Haltenbanken area, consists mainly of well sorted, medium-grained subarkosic arenite. Of 16 wells where cores were analyzed in a regional diagenetic study (Ehrenberg, 1990, 1991), only well 6406/3-1 was found to contain grain-coating chlorite in more than minor amounts. The poros-
Porosity Preservation

ity distribution is very uniform throughout the formation in this well (Figure 15), as is generally the case in other Garn Formation cores. The 6406/3-1 core has only marginally higher porosity than the regional trend of porosity decrease with depth in the Garn Formation (Figure 2), so one cannot argue very convincingly that this is a case of anomalous porosity. However, quartz cementation may have been inhibited by the chlorite, such that porosity loss took place mainly by compaction.

As documented by Ehrenberg (1990), quartz cementation is the main factor responsible for the regional trend of porosity decrease with increasing depth in the Garn Formation. Quartz cement abundance in the 6406/3-1 core is low compared with other Garn Formation cores having burial depths greater than 3.3 km below the sea floor (Figure 16). At the same time, the IGV is relatively low compared to the other Garn cores (Figure 16). Lower IGV in the 6406/3-1 sandstones is not the result of poor sorting, but appears to reflect relatively greater compaction than in the other deeply buried cores studied, possibly because the low quartz cement content provided little resistance to late-stage intergranular pressure dissolution and subsequent mechanical readjustment of grain positions.

The low quartz cement content of the 6406/3-1 sandstones may reflect inhibition by the chlorite coatings. In thin section, these coatings appear much thinner than in the Tilje and Toft Formation samples described previously. However, SEM examination reveals that the coatings are remarkably extensive, covering most grain surfaces with a continuous blanket of radially oriented platelets (Figure 6E, F). It is not understood why chlorite coatings formed in the 6406/3-1 location but not in the rest of the Garn Formation. Comparison of total Fe contents among the 16 cores analyzed shows that the 6406/3-1 sandstones are not distinctly richer in Fe than the other localities (Figure 17), so it must be only the mineralogical distribution of the Fe that is different.

Statfjord Formation, Veslefrikk Field

This unit is a minor reservoir in Veslefrikk field, containing only about 1.5% of the field's estimated recoverable oil. A 14-m oil column is overlain by a 15-m thick gas cap at the top of the formation. Of interest to the present study is a 3-7-m thick zone of anomalously porous, transgressive marine sandstone occurring at the top of this approximately 220-m thick sequence of alluvial plain deposits. This thin marine zone has been cored in two wells (Figure 18). The porosities in the marine bed and in the underlying fluvial sandstones are compared with regional porosity-depth data in Figure 2.

The sandstones analyzed from the two cores are mainly medium-grained (0.3–0.5 mm), poorly sorted, subarkosic arenites. Comparison of the overlying marine sandstones with the underlying fluvial sandstones shows that both groups are similar in grain size, sorting, and feldspar content. However, the marine sandstones are distinctly richer in chlorite pellets and authigenic chlorite coatings, whereas the fluvial sandstones tend to be richer in mica, K-feldspar, and quartz cement and have lower porosity. Figure 19 shows how the marine and fluvial sandstones fall into two separate fields with respect to the latter two variables. The quantitative indices of bulk chlorite content all indicate chlorite enrichment in the sandstones of the marine bed (Figure 20).

Intra-Dunlin Sandstone, Veslefrikk Field

This unit does not have a formal stratigraphic name; it is regarded as being equivalent to the Cook Formation of Oseberg field (Livbjerg and Mjos, 1989), but in both Veslefrikk and Oseberg fields, the Intra-Dunlin sandstone unit is believed to be somewhat older than the Cook Formation proper (Vollset and Dore, 1984). It contains an estimated 6.7 × 10⁶ standard m³ of recoverable oil, or 18% of Veslefrikk’s total liquid reserves. The unit is 45–60 m thick and
consists of two upward-coarsening cycles. (Table 1). The upper cycle shows a gradual upward decrease in frequency of mudstone layers, passing into an upper zone of clean, fine- to medium-grained sandstone which has anomalously high porosity in most wells. Cores from two such wells were selected for petrologic study (Figure 21).

Grain size in well 30/3-2 is very uniform and fine (0.15 mm), with excellent sorting, and well 30/3-A1 grain size is variable (0.2–0.3 mm); sorting is moderate to poor. In each well, porous, chlorite-rich sandstones occur at the top of the unit, and downward the sandstones become heavily cemented with quartz. With the exception of a few dolomite-cemented samples, the Intra-Dunlin sandstones show the same simple correlation between porosity and quartz cement as the Statfjord sandstones (Figure 19). In general, the lower porosity values can be explained simply by infilling by quartz cement, without substantial variations in compaction.

The quantitative indices of bulk chlorite content show that the high-porosity samples tend to be much richer in chlorite in well 30/3-2 than in well 30/3-A1 (Figure 22). This probably reflects the finer grain size and consequently greater grain surface area available for chlorite growth in the sandstones of well 30/3-2. Correlation of increasing chlorite content with higher porosity is indicated in well 30/3-2, but not in well 30/3-A1.

**CHLORITE CHEMISTRY AND STRUCTURE**

Chemical analyses of chlorite in several of the subject cores were performed by Jens Jahren, University of Oslo, using both electron microprobe (EM) and analytical transmission electron microscope (ATEM) techniques. The ATEM results are summarized else-
Figure 12—Photomicrographs of Tofta, Statfjord, and Intra-Dunlin sandstones. Scale bars are 0.1 mm in all views. (A) Statfjord Formation, well 30/3-A5, 4235 m RKB. Two chlorite-rich pellets can be seen, the larger of which contains a number of quartz silt grains. Both consist mainly of randomly oriented clay particles, the larger pellet containing mostly chlorite; the smaller, both chlorite and illite (birefringent) clay. (B) Tofta Formation, well 6506/11-1, 4498 m RKB. A chlorite-rich pellet with an outer ooidal coating of concentrically laminated clay. (C) Tofta Formation, well 6506/11-1, 4491 m RKB. A partly chloritized expanded mica grain. The zoned appearance results from partial impregnation of blue epoxy, possibly forcing residual oil ahead of it to form the dark zone. Commonly, impregnation appears to have been blocked locally at contacts with adjacent grains. (D) Statfjord Formation, well 30/3-A5, 4235 m RKB. Three partly chloritized expanded mica grains are visible. The two at center and right have outer ooidal coatings of concentrically laminated clay and appear zoned due to partial impregnation. (E) Intra-Dunlin sandstone, well 30/3-2, 3075 m RKB. Molds of two dissolved grains (probably angular feldspars) are visible. Note the uniform thickness of the chlorite coatings (as contrasted with the coatings in Figure 5A). The arrow points to a quartz cement crystal that has grown into one of the molds from the adjacent quartz grain. (F) Statfjord Formation, well 30/3-A5, 4235 m RKB. A partially dissolved chlorite-rich ooid. Arrows point to quartz cement crystals that have grown into the dissolved ooid from adjacent quartz grains.

where as part of a larger compilation of chlorite analyses (Jahren and Aagaard, 1993; Aagaard and Jahren, 1993). The EM analyses were done at the Mineralogical Geological Museum, Oslo, using a wavelength-dispersive spectrometer with 15-keV accelerating potential, 10-nA current, 2-μm beam diameter, and three 10-s counting intervals, with K and Na analyzed in the first interval to minimize loss by beam damage.

The EM data have the advantage that the points analyzed can be examined petrographically in a standard thin section. However, the relatively large EM beam diameter (2 μm) often results in inclusion of other minerals besides chlorite in the analyses. Such mixed analyses most commonly reflect the occurrence of illitic clay, which is finely intergrown with the chlorite in widely varying proportions in many of the samples (as illustrated, for example, in Figure 5C, D). Figure 23 shows how the analyses from two of the subject cores vary in potassium and Fe content for each of three petrographic categories of points analyzed. The linear variation between Fe-rich and K-rich compositions reflects varying proportions of chlorite and illite in the spots analyzed. Examination of numerous mixed chlorite-illite areas in thin section and by SEM provides the impression that these clays occur as discrete phases in widely varying proportions, rather than being any kind of mixed-layer mineral. Structural formulas calculated for 77 relatively pure chlorite analyses are plotted in Figure 24. Chlorites from different formations have distinct ranges of Fe/Mg, but the proposed temperature-dependent indices of tetrahedral Al and total octahedral occupancy (Jahren and Aagaard, 1989; Hillier and Velde, 1991) both show complete overlap between the various sample groups.

Moore and Reynolds (1989) described how interlayering between 14A chlorite and 7A serpentine can be recognized by the occurrence of broad odd-order (001 and 003) and sharp even-order (002 and 004) basal XRD reflections. Hillier (1991) reported an example of mixed-layer chlorite-serpentine from a chlorite-coated Haltenbanken sandstone reservoir. The clay-fraction XRD patterns of the present samples were examined for evidence of such interlayering by M. J. Wilson of the Macaulay Land Use

Figure 13—Helium porosity of Tofta sandstones vs. point counted % quartz cement. The diagonal line shows the ideal correlation that would result if porosity variation resulted entirely from addition of quartz cement. Plotting symbols identify wells.
Figure 14—Helium porosity of Tofte sandstones vs. indices of chlorite content. (A) point counted % chlorite rims; (B) bulk-rock Fe content minus Fe contained in siderite and pyrite (as estimated from bulk XRD analyses of relative proportions of carbonate minerals present, together with bulk CO₂ and S contents); (C) Percent chlorite in clay-fraction XRD analysis. Plotting symbols identify wells.

Figure 16—Point counted IGV vs. quartz cement in Garn sandstones from 13 wells, where the formation is buried to >3.3 km below the sea floor (described in Ehrenberg, 1990).

Figure 15—Garn Formation: gamma-ray log, porosity variation, and sedimentological description through the cored interval in well 6406/3-1. Horizontal lines mark formation top and bottom. Symbols are explained in the legend to Figure 3.
Research Institute, Aberdeen, Scotland. In the samples from the shallowest burial depths (2.8–3.0 km; Figure 1), including all Intra-Dunlin samples and all but two of the samples from the chlorite-rich marine bed of the Statfjord Formation, there is marked broadening of the 001 and 003 reflections, indicating that these chlorites are in fact mixed-layered chlorite/serpentines. In contrast, the chlorite-rich samples from greater depths (>3.4 km) (Tilje, Tofte, and Garn formations) were found to be highly variable. Some samples contain mixed-layered chlorite/serpentine, but other samples from the same cores contain only 14Å chlorite.

Figure 17—Percent chlorite in clay-fraction XRD analyses vs. bulk-rock Fe content in Garn sandstones from 16 wells (Ehrenberg, 1990).

Figure 18—Statfjord Formation: gamma-ray log, porosity variation, and sedimentological descriptions through the cored intervals in the two wells studied. Horizontal line marks formation top. Symbols are explained in the legend to Figure 3.

Figure 19—Helium porosity of Statfjord and Intra-Dunlin sandstones vs. point counted % quartz cement. The diagonal line shows the ideal correlation that would result if porosity variation resulted entirely from addition of quartz cement. Plotting symbols identify wells.
Figure 20—Helium porosity of Statfjord sandstones vs. indices of chlorite content. (A) point counted % chlorite rims; (B) bulk-rock Fe content minus Fe contained in siderite and pyrite (as estimated from bulk XRD analyses of relative proportions of carbonate minerals present, together with bulk CO₂ and S contents); (C) Percent chlorite in clay-fraction XRD analysis. Plotting symbols identify wells.

Figure 21—Intra-Dunlin sandstone: gamma-ray log, porosity variation, and sedimentological descriptions through the cored intervals in the two wells studied. Horizontal lines mark top and bottom of unit. Symbols are explained in the legend to Figure 3.

The 7Å component of the mixed-layered cases is likely to be berthierine, in view of the Fe-rich compositions determined by EM and ATEM. The apparent increase in occurrence of pure 14Å chlorite with depth implies inheritance of the 7Å component from surface or shallow diagenetic conditions and progressive recrystallization from interstratified chlorite/berthierine to pure 14Å chlorite with increasing temperature.

**CHLORITE-RICH GRAINS**

A ubiquitous minor component present in all of the chlorite-coated sandstones described above is grains composed mainly of chlorite. These chlorite-rich grains fall into three categories: ooids, pellets, and expanded mica grains. As discussed in the following section, these grains are believed to be highly significant for interpreting the relationship
Figure 22—Helium porosity of Intra-Dunlin sandstones vs. indices of chlorite content. (A) point counted % chlorite rims; (B) bulk-rock Fe content minus Fe contained in siderite and pyrite (as estimated from bulk XRD analyses of relative proportions of carbonate minerals present, together with bulk CO₂ and S contents); (C) Percent chlorite in clay-fraction XRD analysis. Plotting symbols identify wells.

Figure 23—Electron microprobe analyses of clays in polished thin sections of Tilje and Tofte sandstones. The analyses are grouped according to the petrographic appearance of the spots analyzed. Plotting symbols identify formation.
between chlorite enrichment and depositional environment.

The ooids are concentrically laminated grains (Figures 5B, C and 12F) petrographically similar to the extensively described clay ooids characteristic of iron formations (Odin et al., 1988a). Textural variations between different layers in the ooids, e.g., variations in silt content and chlorite:illite ratio (Figure 5C, D), are best explained by mechanical accretion as the grains rolled over clayey substrates of varying composition. At the center of each ooid, there is typically a detrital grain, around which the chlorite-rich clay has accreted. This nucleus commonly consists of a heavy mineral, a chloritized mica, or a portion of an earlier ooid, but quartz and feldspar grains also are common as nuclei. In some samples, many normal quartz grains are surrounded partly by thin ooidal coatings (Figure 5B). These coatings are too thin for the grains to be referred to as ooids, but all gradations can be observed from very thin concentric coatings up to bona fide ooids where the coatings comprise 50% or more of the grain cross section.

The pellets (Figure 12A, B) consist mainly of structureless or randomly oriented clay that is confined to a rounded mass with distinct grain boundaries. The general morphology and composition of these grains is consistent with their being fecal pellets, as described by Pryor (1975), but other origins also are possible, e.g., inorganically produced mud clasts. Both pellets and expanded micas commonly are surrounded by an outer sheath of concentrically laminated clay similar to the ooids. Indeed, all gradations are observed between pellets and expanded micas with ooidal rims (Figure 12B, D) and ooids with nuclei consisting of pellets or expanded mica.

The expanded mica grains differ morphologically from the kaolinitized detrital micas commonly present in Norwegian sandstone reservoirs (e.g., Bjorlykke and Bredtsdal, 1986) in that the mica crystal is expanded uniformly throughout, rather than being more expanded near the edges of the cleavage traces (Figure 12C, D). Also, the degree of expansion is relatively great, such that the grain commonly is longer in the c-axis than in the direction of the cleavage traces. Another distinctive characteristic is that the edges of the grain typically are rounded, indicating a degree of abrasion by transport after expansion. Microprobe analyses show that the expanded micas have chemical compositions varying from Fe-rich (similar to the chlorite coatings in the same samples) to K-rich, apparently reflecting varying degrees of alteration of the original K-rich mica compositions.

All three types of chlorite-rich grains appear to have high contents of microporosity because they are impregnated readily by the blue-dyed epoxy that fills the pore spaces in the thin sections. However, the epoxy commonly fails to impregnate all the way to the center of individual grains, resulting in a zoned appearance (Figure 12C, D). Microprobe analyses of cores and rims of numerous such grains reveal no systematic chemical differences, indicating that the zoned appearance is simply an artifact of impregnation. A dark contact isoplasma is present, separating the impregnated rim from the unimpregnated core (Figure 12A, C). This dark material may consist of residual oil that was driven into the grain along the impregnation front.

The point-counting results show that the ooids, pellets, and expanded mica grains together generally comprise a few volume percent of the sandstone, and as much as 4–6% in several cases. However, several Statford Formation samples are extremely rich, containing 9–20% chlorite-rich grains (Figure 12D). In general, the relative proportions of ooids, pellets, and expanded micas vary widely in the different cores studied and even from one sample to the next in the same core. In the Garn Formation core from...
well 6406/3-1, chlorite-rich grains are rare, with generally only one, two, or zero ooids per thin section, and no expanded micas or pellets.

**ORIGIN OF CHLORITE-RELATED ANOMALOUS POROSITY**

**Synsedimentary Concentration of Fe-Rich Clay**

Evidence that the chlorite content of the high-porosity zones is a primary depositional feature is provided by the chlorite ooids, which are a characteristic feature of the chlorite-rich sandstones in all of the cores studied. These concentrically layered structures appear to have formed by mechanical accretion as the grains were rolled by water currents. They therefore indicate that chlorite or, more probably, an Fe-rich precursor clay was concentrated in the sand at the time of deposition.

The chloritized pellets and expanded, chloritized micas also are significant because they indicate that Fe mineralization was taking place on the sea floor. Similar grains are characteristic of modern shallow marine environments where authigenic crystallization of green, Fe-rich clay takes place at or near the sediment/water interface. Clay-rich pellets and vermiculized mica grains are especially susceptible to such alteration because of their high microporosity; the presence of disordered, reactive phyllosilicate crystal lattices; and, in the case of pellets, their content of organic matter (Pryor, 1975; Odin and Gupta, 1988). Odin (1988) has defined three facies of Fe-clay mineralization that may provide analogs for the geochemical conditions responsible for the chlorite-rich sandstones described in the present study: the glaucony, veridine, and oolithic ironstone facies.

The most widely familiar Fe-clay facies is glaucony, characterized by formation of glauconite, a series of Fe-rich clays whose end members (glauconitic smectite and glauconitic mica) are structurally analogous to smectite and illite, respectively. Glaucony forms at or near the sediment/water interface where sediment accumulation is slow enough to allow diffusive interaction between seawater and the semiconfined environment within the pore spaces of granular (sandy) sediment. Glauconite pellets form by replacement of various existing grains that provide favorable substrates for mineralization (weathered biotite grains, fecal pellets, foraminiferal cavities, shell fragments).

Like glaucony, the veridine facies also forms by Fe-enrichment of certain compositionally susceptible grains within the upper meter or so of the sediment/water interface in sandy sediment. Here, the clays involved are the 7Å odinite (formerly called phyllicite V, a sort of ferric kaolinite), an as yet poorly defined 14Å variety of phyllicite V (characteristic of older, more evolved veridine occurrences), and a 14Å phyllicite C (apparently a mixed-layer chlorite-smectite). Whereas glaucony forms in open marine water, veridine appears to be restricted to areas near river mouths and is found exclusively in tropical latitudes. A classic example from the Niger Delta is described by Porrenza (1966). (Figure 25). Verdine forms at water depths shallower than 40 m (temperatures of 25-27°C), whereas glaucony forms at water depths of 50-200m (temperatures of 7-15°C). This depth- or temperature-dependent transition from veridine to glaucony is sufficiently common elsewhere to be
suggested as a paleobathymeter indicating a water depth of 50-80 m (Odin and Gupta, 1988).

The oolitic ironstone facies is of particular interest because it is the only Fe-clay facies containing ooids similar to those in chlorite-coated sandstones. This facies has been described from rocks of the Cambrian to Pliocene, but is absent from modern sediments, with one possible exception reported from Scotland (Rohrlch et al., 1969 and Rohrlch, 1974). It typically is found in condensed, muddy sequences coincident with the end of a regressive sedimentary cycle. Although many varied genetic hypotheses have been proposed in the enormous literature on ooidal structures, Odin et al. (1988a) conclude that mechanical accretion during repeated, intermittent agitation of a muddy substrate is the most plausible model for how the ooids formed. Like verdine, the oolitic ironstone facies is associated with points of local fluvial discharge into the marine environment and is found in a similar landward position relative to the glaucony facies (Odin et al., 1988a, their Figure 6).

Three varieties of Fe-rich clay are characteristic of oolitic ironstones: berthierine (a 7Å serpentine group clay), chamosite (Fe-rich 14Å chlorite), and a variety of swelling chlorite (the least abundant of the three). In contrast to the minerals of the verdine facies, these minerals are all trioctahedral and contain Fe mainly in the ferrous state. Odin et al. (1988a) argued that the oolitic ironstone minerals formed by diagenetic recrystallization of precursor minerals containing dominantly ferric Fe similar to the minerals of the verdine facies. Thus, berthierine may have recrystallized from a precursor similar to odinite, chamosite from 14Å phyllice V, and the swelling chlorite from phyllice C. Nevertheless, certain chemical differences, including lower Mg and Si of berthierine and chamosite, suggest that the precursor minerals were not entirely equivalent to the modern verdine minerals.

Aside from its mineralogy, the oolitic ironstone facies differs from the verdine facies in that its Fe-rich clays are contained mainly in concentrically laminated ooids and diffuse Fe-rich matrix clay, whereas ooids are not observed in either the verdine or glaucony facies, and the diffuse habit is rare in the verdine facies. Also, the oolitic ironstone facies occurs mainly in muddy sediments, whereas verdine typically is found in sandy sediments.

The oolitic ironstone minerals, rather than glauconite, seem to provide a plausible precursor for the chlorite coatings found in deeply buried sandstones. Berthierine is similar in composition to Fe-rich chlorite (chamosite) and, with increasing temperature, is transformed readily into chlorite (Nelson and Roy, 1954). Berthierine has negligible potassium content (Brindley, 1982), or at most low potassium content (1.0-1.4 wt % K₂O) (Odin and Matter, 1981), and chlorite essentially is potassium free. Glaucnite, on the other hand, tends to be potassium-rich (6-9 wt % K₂O) (Odin and Matter, 1981), and, with deep burial, would be expected to retain its illicite 2:1 crystal structure and potassium content.

The source of Fe for verdine and oolitic ironstone mineralization is widely agreed to be river water, which, especially in tropical latitudes, carries a rich load of colloidal suspended Fe derived from weathering. Near the river mouth, increase in salinity causes the Fe to be flocculated and deposited, mainly in an amorphous and therefore highly reactive state. This relationship explains the characteristic localization of both verdine and oolitic ironstone deposits near points of fluvial discharge into shallow marine water.

The same geographic localization probably also holds true for the chlorite-rich sandstones of the present study. The Toft Formation provides the most convincing illustration of this, with chlorite occurring nearer the presumed western fluvial source of sand influx and being absent further basinward to the east (Figure 11). The other four examples are consistent with such a relationship, as the chlorite-coated zones are found in near-shore marine facies likely to have been deposited in proximity to fluvial sources of sand influx. The hypothesis that chlorite-coated sandstones were enriched in a Fe-clay precursor in a shallow marine setting influenced by freshwater discharge has been suggested previously by Longstaffe (1986) and Ayalon and Longstaffe (1988) based on isotopic data from a sandstone in Canada, where chlorite occurs mainly in the distributary channel facies of a paralic sequence.

Fe-Clay Mineralization in High-Energy Sandstones

A major problem with making analogies between chlorite-coated sandstones and any of Odin's (1988) Fe-clay facies is that the sandstones are all high-energy deposits with rapid rates of sediment accumulation, whereas very low sedimentation rates are characteristic of and possibly essential for development of the various Fe-clay facies (Hallam, 1966; Talbot, 1974; Odin, 1988). Two possible explanations may be considered: (1) the Fe-clay component was not formed in place in the sandstones but was introduced by reworking of nearby condensed-sequence deposits or (2) rapid Fe-clay mineralization occurred in an environment of high-energy sand deposition due to especially favorable local geochemical conditions.

Suggestion 1 is to some degree supported by the presence of the chlorite ooids. If these formed by rolling on a muddy substrate, then some transport is required from the mud bottom to the site of high-
energy sand deposition, where accumulation ultimately took place. However, this distance possibly was minor, because muddy and sandy bottom conditions commonly are closely juxtaposed in modern estuary and beach environments.

Suggestion 2 is preferred because it is simpler and thus can more plausibly account for the repeated occurrence of chlorite-rich sandstones in widely varying settings. As little is known about the actual chemistry or kinetics of the process of Fe-clay formation, it is possible that duration of exposure on the sea floor is not the main constraint involved. It may be postulated, therefore, that a more important factor controlling the occurrence of the chlorite-rich sand zones of the present study was the abundant supply of reactive, amorphous Fe-hydroxides delivered by local river discharge. This Fe would have been flocculated and deposited at the river mouth, forming a layer of clay-rich, gel-like material from which ooids could be formed at points of maximum current energy, such as mouth bars and tidal channels.

As noted, the oolitic ironstone minerals are thought to have formed as ferric clays similar to the veridine minerals, but the presence of the ooids indicates a sedimentologic environment that is apparently not found on the Earth today. The oolitic ironstones testify that during certain intervals of the geological record, local conditions were especially favorable for the formation of large volumes of Fe-clay minerals in current-agitated shallow marine settings. The Jurassic Period was one such favorable time, when oolitic ironstones were deposited repeatedly over wide expanses of central and northern Europe. The Jurassic chlorite-coated sandstones of the Norwegian shelf may represent fundamentally the same geochemical conditions as the oolitic ironstones, but in a setting of rapid, high-energy sand influx, as opposed to the current-agitated, sand-starved, muddy environment of the ironstones.

Timing and Mechanism of Chlorite Growth

Chlorite is present in the sandstones both as outer rims of radially oriented crystals and as a component of grains and matrix material. Dutton and Land (1985) also noted that chlorite-coated sandstones contain these two petrographic categories of chlorite. The outer rims are clearly authigenic, as indicated by their crystal morphology and orientation (Figures 6 and 7), whereas the grains, including the concentrically laminated, ooidal chlorite coatings, and the clay matrix are detrital materials. Nevertheless, the chlorite component in the grains and matrix may be largely authigenic because their high microporosity would facilitate continuous chemical communication and reequilibration involving the chlorite throughout the sandstone.

Several petrographic relationships are relevant to interpreting the timing of the outer, radially oriented chlorite rims: (1) Chlorite rims typically are absent along contacts between grains, where limited pressure dissolution is often apparent (Figures 5E and 6B, E). (2) In all samples, quartz cement postdates chlorite rim formation. Quartz cement overlaps earlier chlorite, but chlorite is never found growing on quartz cement. (Figure 5E). (3) Chlorite rims typically form delicate hollow structures outlining the original grain boundaries of dissolved grains (Figures 12E-F and 7A, B).

Point 1 strongly suggests that the chlorite rims formed after the sand grains had come into contact and had become adjusted to their present relative positions by mechanical compaction. It is possible, however, that many detrital quartz surfaces in the chlorite-rich zones originally had thin coatings of Fe-rich clay that subsequently recrystallized to radially oriented chlorite. Such original detrital clay coatings would have been thick in some places and absent in others, as reflected in the present variability of chlorite rim thickness in many samples (Figure 5A).

Point 2 indicates that the chlorite rims formed before the sandstones reached a burial depth of around 2.5 km, the depth where quartz cementation is observed to become significant in various Jurassic/Triassic sandstone reservoirs from the Norwegian shelf (Ehrenberg, 1990; Bjørlykke et al., 1992). Point 3 additionally indicates that at least the beginning stage of chlorite rim growth predates feldspar grain dissolution. Dissolution is suggested to have occurred early in the diagenetic sequence (Bjørlykke et al., 1989), but it obviously must have occurred after the sandstone framework had become stabilized with respect to mechanical compaction; otherwise, the delicate grain molds would have collapsed.

Points 2 and 3 do not necessarily imply that chlorite growth entirely ceased at an early stage of the diagenesis. Once the chlorite rims were formed, continued chlorite growth would have been localized on existing chlorite surfaces. After a certain amount of growth, the rims now outlining dissolved grain molds would have attained sufficient structural strength to be self-supporting, so that their growth could continue as the underlying grain melted away.

Recent studies of diageneric chlorites in sandstones have demonstrated a correlation between chlorite mineral chemistry and temperature, implying that the chlorite continuously reequilibrates with its diageneric environment throughout its burial history (Jahren & Aagaard, 1989; Hillier & Velde, 1991). Thus, growth of the authigenic chlorite coatings is viewed as a gradual, continuous process reflecting the progressive instability of lower temperature compositions with increasing burial depth. Jahren (1991) has shown that the individual chlorite crystals preserve chemical zoning profiles match
ing the pattern predicted for the process of dissolution and growth by Ostwald ripening.

As noted, the sandstones contain within themselves a convenient local source for the ions needed to grow the authigenic chlorite rims—syndepositional Fe-clays contained in chlorite-rich grains, detrital matrix, and concentrically laminated grain coatings.

Points 1 and 2 above have the result that four distinct types of quartz surfaces may be observed in SEM and thin section (excluding artificially produced concoidal fracture surfaces) and are defined as follows.

Type A consists of detrital grain surfaces coated by either radially oriented authigenic chlorite rims (which appear to be easily dislodged mechanically; Figure 7C, D) or concentrically laminated coatings of detrital clay (Figure 5B).

Type B consists of areas of grain-to-grain contact, typically showing pitting due to pressure dissolution (Figure 6B, E).

Type C consists of cubed quartz cement crystal surfaces, reflecting unobstructed growth into open pore spaces. (A subcategory of type C is surfaces where two cement crystals have grown up against one another.)

Type D consists of cubic quartz cement crystal surfaces, reflecting impingement of a type C surface upon the top of a radially oriented chlorite rim growing on an adjacent type A surface (Figure 6D).

Because of the absence of chlorite rims along grain contacts, incipient quartz overgrowth crystals in heavily chlorite-coated sandstones commonly are found growing into the molds of dissolved grains, having nucleated on adjacent type B surfaces where the now-dissolved grain had prevented growth of the chlorite rim (Figure 11E, F).

**Mechanism of Quartz Cement Inhibition**

Apparently chlorite coatings inhibit quartz cement growth by isolating detrital quartz surfaces from contact with the pore water and thus preventing authigenic quartz from nucleating on these surfaces. However, at least minor amounts of quartz cement always seem to be present in even the most chlorite-rich sandstones, indicating that quartz nucleation is never blocked completely. One must conclude therefore that effective quartz cementation cannot proceed from a few isolated nucleation sites, but requires growth from multiple sites distributed over a large percentage of the detrital quartz surface. For any given monocristalline quartz grain, the multiple growth sites would all have the same crystallographic orientation (e.g., Figure 7F), so that as growth proceeded, the individual cement crystals eventually would coalesce to form a single overgrowth crystal. It may be postulated, therefore, that the chlorite works mainly by reducing the number of individual growth sites present per sand grain.

Given the preceding model for cement inhibition, it appears certain that not all of the chlorite present in a sandstone is equally effective for inhibition. The authigenic grain coatings of radially oriented chlorite are expected to be responsible for cement inhibition not the chlorite present in ooids, pellets, and clay matrix. Also, the continuity of the coatings must be an important consideration; numerous examples are observed where quartz cement is well developed despite the presence of thick, but discontinuous chlorite coatings. Because chlorite coatings should be regarded as inhibiting rather than preventing quartz cementation, it is to be expected that increasing mobilization of dissolved silica with increasing thermal exposure (temperature and time) will tend to counteract the chlorite effect. Support for this is seen in the overall decrease in the maximum porosity of the chlorite-rich samples with increasing depth in Figure 2.

**CONCLUSION: PREDICTION OF CHLORITE-RELATED ANOMALOUS POROSITY**

The model of Fe-clay mineralization near points of river discharge into marine water provides a framework for understanding the occurrence of chlorite-rich sandstones in the five Norwegian examples described in this paper. All five share the possibility of having been deposited in freshwater-influenced marine settings, although only in the case of the Totte Formation is there independent evidence showing that chlorite concentration increases with proximity to palaeo-river discharge. It should be noted here that other models besides freshwater influx exist whereby Fe-rich chlorite can be concentrated in sandstone reservoirs, including Thomson's (1979) model of quartzose sand having a provenance rich in ultramafic igneous material (Tuscaloosa Formation) and Dixon et al.'s (1989) model of precipitation of clay/Fe oxide rims during evaporative pumping in aeolian sand (Norphlet Formation).

The freshwater influx model has certain general implications for prediction of anomalous porosity in deep sandstone reservoirs. Upon first consideration, the model may appear useful mainly in allowing non-marine facies and marine facies deposited distant from freshwater influx to be excluded from consideration. However, such exclusion may be dangerously uncertain. Within units dominated by such unfavorable facies, chlorite-rich zones can be developed either where marine conditions impinge upon the fluvial setting (as in the Stafford Formation example) or where fresh water discharge reaches out into the presumed distal shelf setting (as in the Intra-Dunlin sandstone example). The general use-
fulness of the model therefore appears to be not in excluding units from consideration, but in focusing attention on relatively favorable possibilities, wherever intermingling of Fe-rich river water and seawater possibly can have taken place.

A further implication of the model is that the geometry of chloride-rich high porosity zones mainly is dependent upon (1) sedimentary facies architecture and (2) the pattern of paleo-river discharge into this architecture. The Norwegian examples demonstrate that a wide range of sand-body types and depositional settings carry the potential for occurrence of chloride-preserved porosity. However, the facies involved appears to be rather constant, corresponding to the highest current-energy zone of various nearshore marine environments (Table 1).

Evaluation of the potential for prediction of anomalous porosity mainly is dependent upon empirical observation. After it has been established from well data that chloride-rich anomalously porous zones do in fact exist within a given lithostatigraphic unit, work can be started on delineating the specific sedimentological, geometrical, and petrophysical characteristics of those zones so that prediction capabilities for that particular unit can be sharpened. Key parameters to be quantified are the position of the chloride-rich zones within the sedimentary architecture, the three-dimensional geometry of the zones, the proportion of the net sand affected, and the effects of the chloride coatings on porosity-permeability relationships and wireline log responses.

REFERENCES CITED


Swales, D. L. 1988, Petrology and diagenesis of Ponocone-Price Big Injun sandstone, Granny's Creek field, West Virginia (abs.): AAPG Bulletin. v. 72, p. 972.


ABOUT THE AUTHOR

Stephen Neville Ehrenberg

Stephen Neville Ehrenberg received his Ph.D. in geology from the University of California, Los Angeles in 1978. Following a few desultory years in hard-rock geology, he began working with clastic diagenesis in 1981 at Shell's Bellaire Research Center. In 1985, he moved to Statoil's Geological Laboratory, where his work emphasizes practical applications of clastic and carbonate petrology to problems of concern to exploration and production operations. Free time is devoted to a wonderful wife and four children, ages 1 through 10.