Porosity-preserving chlorite cements in shallow-marine volcaniclastic sandstones: Evidence from Cretaceous sandstones of the Sawan gas field, Pakistan

Anna Berger, Susanne Gier, and Peter Krois

ABSTRACT
Sandstones that have high porosity and permeability at great burial depth and high temperatures are of economic importance because a significant amount of hydrocarbons have been discovered in such reservoirs. The Sawan gas field, with an expected ultimate recovery of more than 1 tcf, lies in the middle Indus Basin. The reservoir rocks, Cretaceous volcaniclastic sandstones of the lower Goru Formation, show very high porosities at a reservoir temperature of 175°C and depths of 3000 to 3500 m (9842 to 11,483 ft). The sandstones are mostly feldspathic litharenites. Strongly altered volcanic rock fragments are the most important lithic component. The clay fraction consists of Fe-rich chlorite (chamosite) and illite. Diagenetic features such as compaction, quartz overgrowths, carbonate cements, and feldspar dissolution are observed. The most distinguishing feature is a double layer of authigenic chlorite, lining the pores of the sandstones. Chlorite additionally occurs as a pore-filling cement and as chloritized detrital components, all having similar chemical composition. The pore-lining cement clearly developed in two stages: an earlier, poorly crystallized, and a later, better crystallized growth. Missing rims at grain contacts show that precipitation occurred after an initial stage of compaction but early relative to other diagenetic phases. Both chlorite rims grew by direct precipitation from pore waters, using products derived

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EDITOR’S NOTE
A color version of Figure 7 may be seen in the online version of this article.
from volcanic rock fragments. In areas with no, thin, or discontinuous chlorite rims, quartz cementation is common. Well-developed chlorite rims inhibited quartz cementation, preserved porosities of up to 20%, and good permeabilities. Porosity-preserving chlorite cementation in Sawan is restricted to sediments of a shallow-marine environment.

INTRODUCTION

The reservoirs of the Sawan gas field, which is situated 500 km (311 mi) northeast of Karachi in the middle Indus Basin (Figure 1), are Cretaceous sandstones (Albian–Cenomanian) of the lower Goru Member of the Goru Formation. These sandstones show anomalously high porosities and permeabilities at high temperatures and depths of 3000 to 4000 m (9842 to 13,123 ft) and a conspicuous chlorite cementation in the form of porelining rims. Average absolute porosities are 16%, with individual samples reaching more than 25%. Similar cements have been described from the Woodbine and Tuscaloosa formations in Louisiana (Thomson, 1979), the Norphlet Formation in Alabama and Mississippi (Dixon et al., 1989), Jurassic

![Figure 1. Map of Pakistan with the positions of the Sawan, Kadanwari, and Miano gas fields. KH = Khairpur high.](image)
reservoir sandstones in the North Sea (Ehrenberg, 1993), and sandstones of the Santos Basin in Brazil (Anjos et al., 2003). In sandstones of the Tuscaloosa Formation, porosities as high as 25% have been reported at depths of 4000 to 7000 m (13,123 to 22,966 ft) (Thomson, 1979). Similarly, upper Cretaceous marine turbidites and shelf sandstones of the Santos Basin (Anjos et al., 2003) show porosities greater than 20% below 4000-m (13,123-ft) depth. Porosity-preserving chlorites have also been described from Lower Devonian sandstone reservoirs of the Ghadames Basin in North Africa (Echikh, 1998) and Miocene reservoirs of the Nile Delta Basin in Egypt (Salem et al., 2005).

Anomalous porosity and permeability can be defined as statistically higher than the porosity and permeability values occurring in typical sandstone reservoirs of a given lithology (composition and texture), age, burial, and temperature history. In sandstones containing anomalously high porosities, such porosities exceed the maximum porosity of the typical sandstone subpopulation (Bloch et al., 2002).

One major cause of anomalous porosity is the authigenic growth of chlorite rims around detrital grains. Many studies (Pittman and Lumsden, 1968; Thomson, 1979; Dixon et al., 1989; Pittman et al., 1992) showed that diagenetic chlorites rich in iron or magnesium tend to inhibit the development of quartz overgrowth in primary pore spaces and therefore have a determining function in porosity preservation in deeply buried reservoir sandstones (Ehrenberg, 1993).

This study focused on the following questions:

- Which diagenetic processes in these sandstones allowed the formation of chlorite rims and what is the diagenetic sequence?
- Does the primary depositional environment have an effect on the preservation of reservoir quality and can it be used as a proxy for reservoir quality prediction in the middle Indus Basin?

Sandstones of the lower Goru Member, informally called the C interval, in the Sawan gas field were investigated in detail. This included a mineralogical and chemical characterization of the chlorite cements and of the variable habits of chlorite. For the study, 23 samples from cores, from wells 2, 3B, and 4 (Table 1), separated by no more than 15 km (9.3 mi) and taken from depths of 3258.6–3447.85 m (10,690.9–11,311.8 ft) have been analyzed.

### GEOLOGICAL SETTING

The dominantly north-south–trending Indus Basin is bounded by the Indian shield to the east, the Kohat Potwar Plateau to the north, and the fold and fault belts of the Sulaiman and Kirthar ranges to the west (Figure 1). From the Permian to Middle Jurassic, the present-day Indus Basin was located at the continental margin of the Indian plate and formed part of the southerly continent of Gondwana. Late Jurassic to Early Cretaceous rifting was followed by a northward drift of the Indian plate. This drift eventually resulted in the Tertiary collision of the Indian plate with the Eurasian plate.

The study area is located on the eastern and southeastern flank of the regional north-south–trending Khairpur high. This high is an important factor in forming traps in the Kadanwari (Ahmad and Chaudhry, 2002), Miano (Krois et al., 1998), and Sawan gas fields (Figure 1). The trapping mechanism for the Miano and Sawan fields is a combination of the structural dip and diagenetic loss of reservoir quality. The uplift of the Khairpur high puts nonreservoir-quality distal parts of the lower Goru depositional system into a structurally higher position than the more proximal, reservoir quality sands (Figure 2).

Three post-rifting tectonic events can be distinguished (Ahmad and Chaudhry, 2002): a late Cretaceous uplift and inversion, a late Paleocene right-lateral wrenching, and a late Tertiary to Holocene uplift of the Khairpur high. The Khairpur high is also characterized by a high geothermal gradient of up to 4.8°C/100 m (328 ft).

No sediments older than Late Triassic have been drilled in the middle Indus Basin. A hiatus or an erosional period of variable duration is present between the platform carbonates of the Jurassic
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*Quartz Mono (monocrystalline quartz), Quartz Poly (polycrystalline quartz), K-Fsp (K-feldspar), Plag (plagioclase), VRF Untext (volcanic rock fragments, untextured), VRF Text (volcanic rock fragments, textured), Carb fragm (carbonate fragment), Glauconite, Chl Comp (chloritized component), Qu-Cem (quartz cement), Cal Cem (calcite cement), Fe-Cal Cem (iron-calcite cement), Fe-Dol Cem (iron-dolomite cement), Iron Chl Cem (iron chlorite cement), Clay Gm Undiff (undifferentiated clayey groundmass). Porosity values are plotted in Figure 6.
(Figures 2, 3) and the lowermost clastic sediments of the Cretaceous (Krois et al., 1998). These clastics are the Sembar Formation and lower Goru Member of the Goru Formation, respectively, deposited at the western passive margin of the Indian plate. A time gap of 30 m.y., related to the late Aptian to early Albian sea level lowstand, is present between the Sembar Formation and the lower Goru Member (Krois et al., 1998). Organic-rich shales within the Sembar Formation are the main hydrocarbon source rock for the lower and middle Indus basins.

Sandstones of the Cretaceous lower Goru Member form the most productive reservoir in the middle Indus Basin. The lower part of this member has been informally divided (from bottom to top) into the A, B, and C intervals (Figure 2) (Krois et al., 1998). These are three westerly prograding, depositionally down-stepping clastic packages. They were sourced from the uplifted, thermally domed Indian shield to the east and deposited within a relatively short period of 7 m.y. The age of the section places it within the Albian to Cenomanian cycle of global sea level rise, and they document third-order fluctuations of the sea level.

Medium to coarse-grained sandstones in a shallow-marine setting constitute the main reservoir in the field. The reservoir unit is characterized as deposits of a proximal wave-dominated delta system and barrier-bar complex with a variety of subenvironments. Tidal influence led to back piling of sands and the formation of sublinear sand ridges. The present-day depositional strike of

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**Figure 2.** Schematic cross section of the Sawan gas field showing seismic geometries. The figure is not to scale. Circular symbol denotes a gas well.
Figure 3. Generalized stratigraphic column of the middle Indus Basin. The Sawan sandstones belong to the lower Goru Member. The figure is not to scale. Circular symbol in the lower Goru denotes a gas well.
the sands is roughly north–south, reflecting the orientation of the paleoshoreline with the hinterland located to the east.

Deposition of the reservoir unit occurred during a lowstand phase; when detached, coarse-grained forced-regressive wedges were deposited on top of distal shaly and silty sediments of the previous highstand systems tract. The reservoir interval is directly overlain and sealed by an iron-carbonate-cemented transgressive lag and transgressive shales and siltstones. Petrographically, the reservoir quality parts of the A and B intervals can be classified as quartz arenites, whereas the C interval shows a significant amount of volcanic rock fragments (VRF).

The Sawan gas field was discovered in 1998, and commercial production started in 2003. With an expected ultimate recovery of more than 1 tcf, it is one of Pakistan’s largest gas fields. On production tests, individual wells flowed more than 100 million standard ft³ (2.8 million standard m³) of gas per day. The gas consists of around 90% CH₄, with a CO₂ content of less than 10%.

The high geothermal gradient in this part of the basin results in reservoir temperatures of more than 175°C.

**SAMPLES AND METHODS**

Most samples from well 2, all samples from well 3B, and sample 3247.8 m (10,655.5 ft) from well 4 were taken from the main reservoir interval. Compositional variations reflect the decimeter-scale heterogeneity of the reservoir section. These sediments were mainly deposited in distributary channels and mouth bars at the proximal delta front of a lowstand shelf-edge delta system. The three lowermost samples of well 2 (3353.02, 3357.9, and 3362.3 m [11,000.7, 11,061.7, and 11,031.1 ft]) and sample 3304.3 m (10,840.8 ft) of well 4 were taken from lower shoreface to offshore sediments of the highstand systems tract of the sequence underlying the reservoir interval. Samples 3258.6 and 3264.6 m (10,690.9 and 10,710.6 ft) in well 2 and 3234.5 m (10,611.8 ft) in well 4 overlie the main reservoir interval and indicate a decrease in sediment supply in the transgressive systems tract.

Samples were impregnated with blue resin before thin sectioning to highlight porosity. Thin sections were stained with Alizarin Red S and K-ferricyanide for carbonate mineral determination. Sandstone modal composition was determined from all thin sections by counting 300 points per thin section. Additionally, the grain-size distribution of samples with well-developed chlorite rims was determined by measuring 300 grains per thin section.

To separate the clay fraction (<2 μm) from the sandstone, the inner part of the core was first gently crushed into small pieces and the organic material removed with H₂O₂ and then treated with a 400-W ultrasonic probe for 3 min. Atterberg cylinders were used to separate the less than 2-μm fraction. The less than 0.2-μm fraction was obtained by centrifugation from the suspension of the less than 2-μm fraction (Tanner and Jackson, 1947). The outer part of the core was discarded to avoid contamination from drilling mud.

Mineralogical compositions of the samples were established by x-ray diffraction (XRD) analysis using a Philips PW 3710 diffractometer (CuKα-radiation, 45 kV, 35 mA, step scan, step size 0.02, 1 s per step). The clay fractions were saturated with 1-N KCl solutions and 1-N MgCl₂ solutions by shaking overnight and washing in distilled water afterward. Oriented XRD mounts were prepared by pipetting the clay suspensions (7 mg/ml) onto glass slides. They were analyzed after air drying; after saturation with Mg and K ions, ethylene glycol, and glycerol; and after heating to 550°C. Random powder specimens of monomineralic chlorite samples were prepared for polytype determination.

Quantitative analyses of chlorite elemental compositions on five representative thin sections were obtained with a CAMECA SX-100 electron microprobe, operating at 15-kV acceleration voltage, 20-nA beam current, and a beam diameter of 1–10 μm. Counting times for all elements were 20 s in peak position and 10-s background right and left. Synthetic and natural minerals were used as standards.

Textural characterizations of chloride (size and morphology) were made using a JEOL scanning electron microscope (SEM), equipped with an energy
dispersive detector (EDS) and in a Philips-XL 30 ESEM. The samples were coated with gold.

A CITL Cold Cathode Luminescence 8200 mk3 was used to characterize different cement generations and to characterize the origin of detrital quartz grains. The acceleration voltage was 20 kV, 200–400 µA.

Permeability to air measurements were performed in a Hassler type core holder with 400 psi confining stress. Grain volume and pore volumes were determined by helium injection using a porosimeter. Porosity and grain densities were then calculated.

RESULTS

Mineralogy and Petrography

The sandstones are generally medium to coarse grained and moderately to well sorted with differing degrees of compaction. The grain-size distribution of selected samples with chlorite rims is shown in Figure 4. Sample 3427.8 m (11,246 ft) of well 4 (Figure 4) is a fine-grained sandstone and demonstrates the dramatic loss in permeability and to a lesser extent in porosity as a function of grain size (see also Tables 1 and 2). In some cases, a marked bimodal size distribution of the detrital grains caused by bioturbation has been observed. The main detrital mineralogical components (Table 1) are quartz (mono- and polycrystalline grains), strongly altered mafic VRF, and feldspar (mostly K-feldspar). The VRF appear in two types, one type is hemicrystalline, typically containing fine lath-shaped K-feldspar crystals and inclusions of titanium oxides and apatite, the other type is holohyaline; both types are intensely altered to chlorite. Of secondary importance are carbonate fragments, muscovite, strongly altered biotite, and chert. Tourmaline and zircon occur as accessories.

![Figure 4. Grain-size distribution of sandstones with well-developed chlorite rims (grain-size values in millimeters). Numbers in the x-axis indicate well no./depth (m).](image-url)
Diagenetic components are quartz cements, chlorite cements (pore-lining cement, pore-filling cement, and chloritized components), carbonates (mainly calcite and Fe-dolomite cements), and glauconite.

The sandstones are classified as subarkoses, lithic arkoses, sublitharenites, feldspathic litharenites, and litharenites according to Folk (1968) (Figure 5).

**Porosity**

A strong interdependence of porosity and cement type is observed (Figure 6). Porosity, as determined by point counting, ranges from 4 to 22% for chlorite-cemented samples. Samples with quartz cement only have a porosity range from 2 to 6%. Carbonate-cemented samples have typically less than 2% porosity. For comparison, absolute petrophysical helium porosity and permeability measurements are shown (Table 2). These were taken at plugs close to the point-counted samples.

### Diagenetic Alterations

The Sawan sandstones show advanced diagenetic alteration. During initial compaction, mica plates (Figure 7a) and glauconitic pellets were deformed; subsequent pressure-dissolution formed planar, concave-convex, and sutured intergranular contacts between quartz grains (Figure 7a). The prevalent cements are quartz, carbonate, and chlorite, commonly with a patchy distribution (Figure 7b). Carbonate cements in particular have replaced other components, such as quartz grains and VRF. The purple bands in the red-stained calcite cement in contact to the grains (Figure 7b) result from a higher Fe content in these areas. Parts of the remaining pore space are filled by calcite cement (Figure 7b).

Secondary porosity formed because of dissolution of feldspar grains (Figure 7c) and VRF. In some instances, these components have been fully dissolved and only the chlorite rims that covered the grains remain. Quartz cements occur both as pore filling and as idiomorphic quartz outgrowths (Figure 7d). The latter are not covered by chlorite rims. Quartz overgrowths and outgrowths occur preferentially where chlorite rims covering detrital quartz grains are thin or discontinuous (Figures 7d, 8f). Chlorite rims are not visible between detrital grain contacts (Figure 7b, d).

Microcrystalline TiO₂ crystallized in close proximity to the chlorite pore linings in the Sawan sandstones. This is apparently related to the incompatibility between the highly charged Ti⁴⁺ and the chlorite structure (Ryan and Reynolds, 1996).
The source for Ti is the breakdown of titanium-bearing minerals in the VRF during diagenesis (Anjos et al., 2003).

**Chlorite Cements**

Chlorite cements are the most important characteristic of the Sawan sandstones. In general, chlorites are the most common authigenic clay minerals in sediments (Spötl et al., 1994), and they supply information about the diagenetic history and the chemical composition of pore waters. During diagenesis, chlorites form preferentially in fluids with high pH values and high Mg and Fe ion contents.

**Chlorite Morphology**

Authigenic chlorite is present in three forms.

1. Pore-lining cement, commonly consisting of a 5–10-μm-thick rim covering all detrital grains (Figure 8a, b). Two rim types have been identified in the SEM; an older, poorly crystallized one and a younger, better crystallized one. The latter comprises subhedral to euhedral, pseudo-hexagonal crystals, oriented with their faces...
perpendicular to the host detrital grain surface. The underlying older chlorite rim generation is only seen in areas where the younger one has broken away (Figure 8c, d).

2. Pore-filling cements comprising small chlorite plates that are oriented parallel and arranged with a denser packing. Chlorite rims can be covered by pore-filling chlorite cements (Figure 8e).

3. Chloritized components, most probably derived from the alteration of volcanic glass or rock fragments, consisting of a chlorite plate meshwork of high microporosity and commonly covered by pore-lining chlorite cements.

**Mineralogy of Authigenic Chlorites**

The mineralogy of the clay (<2 μm) and the fine-clay fraction (<0.2 μm) was determined by XRD; in these fractions, the authigenic minerals are enriched. Overall, a well-crystallized 14-Å chlorite and a poorly crystallized 10-Å illite were identified (Figure 9a, b) but no evidence of mixed layer clay minerals was found. The XRD patterns of the chlorites show low intensities of the d(001), d(003), and d(005) peaks relative to the d(002) and d(004) reflections (Figure 9a), indicating a high Fe content (Moore and Reynolds, 1997).

The fine-clay fraction (<0.2 μm) was analyzed by XRD to establish the mineralogy of the older, finer, and less well-crystallized chlorite rim generation (Figure 9b). Although this was thought to contain mixed layer clay minerals, only chlorite and illite were found. Compared to the less than 2-μm fraction, the less than 0.2-μm fraction contains more illite than chlorite. The illite is less crystallized compared to chlorite.

**Determination of Chlorite Polytype**

The chlorite polytype, which gives information about the diagenetic state and the crystalline maturity of the chlorites (Spötl et al., 1994), was determined using the hkl XRD reflections (Moore and Reynolds, 1997) of a monomineralic sample (well 4, 3234.6 m [10,612.2 ft], <2-μm fraction) to avoid interferences with other peaks. This indicates that the chlorites have a polytype Ib structure, a low-temperature form characteristic of authigenic growth, morphologically characterized by thin pseudohexagonal plates.
Chemistry of Sawan Chlorites

Chlorite formulae were calculated from electron microprobe data using the program Min-sort (Version 010204, GNU-677 DOS-Win, written by K. Petrakakis). Representative microprobe analyses and calculated formulae are listed in Table 3.

Measured total oxide values are no greater than 85% because of the high microporosity, the high water content (12%), and the fine-grain size. The formulae show that the measured values only vary in their intensity because calculated ratios show no variation. The FeO values are very high (28–30%), while MgO values are very low (4–5%), typical for chamosite.

The different forms of chlorite show only slight variations in their chemical compositions. In some samples, the chlorite cements are slightly more iron rich than the chlorite rims and chloritized particles. The ratio of octahedral Fe and Mg cations in the analyzed chlorites hardly varies, and tetrahedral Al ranges between 0.6 and 1.4 (Figure 10).

DISCUSSION

Interpretation of Diagenetic Developments

All the observed diagenetic features can be linked into a relative sequence (Figure 11). The chlorite...
Figure 8. (a) Well 3B, 3407.2 m (11,178.4 ft): Pore-lining chlorite cement, consisting of a 5–10-μm-thick rim covering all detrital grains. (b) Well 3, 3407.2 m (11,178.4 ft): Close-up view of a chlorite rim. (c) Well 2, 3313.6 m (10,871.3 ft): Two morphologies of authigenic chlorite rims; the underlying, fine-crystalline chlorite rim is visible in areas where the coarse-crystalline rim has broken away by sample preparation. (d) Enlargement of marked area in Figure 8c. The first rim is poorly crystallized; the second consists of subhedral, pseudo-hexagonal crystals, oriented with their faces perpendicular to the detrital grain surfaces. (e) Well 4, 3234.5 m (10,611.8 ft): Pore-filling cements comprising small chlorite plates that are oriented parallel and arranged with a denser packing. Chlorite cements fill pores after chlorite rims. (f) Well 2, 3313.6 m (10,871.3 ft): Quartz outgrowths (Qo) develop preferentially where chlorite rims covering detrital quartz grains are thin or discontinuous.
Figure 9. (a) X-ray diffraction patterns of less than 2-μm fraction of sample well 2/3283.6 m (10,772.9 ft); Chl = chlorite, I = illite, K = potassium-saturated sample, EG = ethylenglycol-saturated sample, N = air-dried sample, 550°C = sample heated to 550°C. (b) XRD pattern of less than 0.2-μm fraction of sample well 2/3313.6 m (10,871.3 ft); Chl = chlorite, I = illite, EG = ethylenglycol saturated sample, N = air-dried sample, 550°C = sample heated to 550°C, °2-Theta = angle of diffraction, inserted values are d spacings in angstrom.
Table 3. Representative Microprobe Analyses and Calculated Formulae (Based on O₁₀ [OH]₈) of Authigenic Chlorites*

| Sample  | Point | 2/3313.6 | 2/3313.6 | 2/3313.6 | 2/3313.6 | 2/3313.6 | 2/3313.6 | 2/3313.6 | 2/3313.6 | 2/3313.6 | 2/3313.6 | 2/3313.6 | 2/3313.6 | 2/3313.6 | 2/3313.6 | 2/3313.6 | 2/3313.6 | 2/3313.6 |
|---------|-------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Point   |       | Rim       | Rim       | Rim       | Rim       | Rim       | Rim       | Rim       | Rim       | Rim       | Chl comp  | Chl comp  | Rim       | Cement    | Cement    | Cement    | Cement    | Rim       | Rim       |
|         |       |           |           |           |           |           |           |           |           |           |           |           |           |           |           |           |           |           |           |
| SiO₂    | 26.8  | 21.7      | 23.4      | 20.4      | 23.4      | 23.3      | 22.0      | 23.0      | 21.8      | 23.2      | 18.0      | 14.7      | 28.4      | 22.7      | 24.3      | 21.5      | 22.4      | 24.4      | 23.3      | 19.9      |
| TiO₂    | 0.1   | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       | 0.1       | 0.0       | 0.0       | 0.1       | 0.0       | 1.1       | 0.0       | 1.0       | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       |
| Al₂O₃   | 19.6  | 20.3      | 21.2      | 18.1      | 20.0      | 19.1      | 19.3      | 20.2      | 20.6      | 20.8      | 13.9      | 13.4      | 17.5      | 19.0      | 19.0      | 17.7      | 18.5      | 17.5      | 16.9      | 15.1      |
| FeO     | 30.9  | 29.6      | 32.8      | 30.0      | 32.3      | 32.2      | 31.1      | 32.5      | 32.0      | 33.7      | 18.9      | 19.4      | 27.9      | 36.2      | 37.3      | 32.2      | 34.0      | 37.5      | 36.8      | 31.4      |
| MnO     | 0.0   | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       | 0.0       |
| MgO     | 5.0   | 4.7       | 5.2       | 4.7       | 5.4       | 5.2       | 5.1       | 5.3       | 4.9       | 5.2       | 3.5       | 3.3       | 4.4       | 5.0       | 5.2       | 4.8       | 5.0       | 5.4       | 5.0       | 4.5       |
| CaO     | 0.1   | 0.0       | 0.0       | 0.0       | 0.1       | 0.1       | 0.0       | 0.0       | 0.0       | 0.1       | 1.8       | 0.0       | 0.1       | 0.0       | 0.1       | 0.0       | 0.1       | 0.0       | 0.0       | 0.8       |
| Total   | 82.5  | 76.3      | 82.6      | 73.2      | 81.2      | 80.0      | 77.6      | 81.1      | 79.4      | 83.0      | 54.5      | 52.6      | 78.2      | 84.0      | 85.8      | 77.2      | 80.0      | 84.9      | 82.1      | 78.9      |

Formulae**

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<th>0.91</th>
<th>0.91</th>
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<th>0.92</th>
<th>0.94</th>
<th>0.90</th>
<th>0.84</th>
</tr>
</thead>
</table>

*Chl comp = chloritized component; Al IV indicates aluminum in tetrahedral coordination; Al VI indicates aluminum in octahedral coordination.

**The elements and amounts in the list (calculated from chemical analyses) give the formulae of the chlorites when written next to each other. For example (Al 1.74 Ti 0.01 Fe 2.97 Mg 0.86 Ca 0.01) (Si 3.08 Al 0.92) O₁₀ [OH]₈.
rims were precipitated after an initial phase of mechanical compaction but before the quartz overgrowths, pore-filling chlorite, and main carbonate cementation. Chlorite rims (coatings) are not visible between detrital grain contacts (Figure 7b, d). Furthermore, the chlorite rims developed in two phases (see below). The alteration of VRF and feldspars is interpreted to have occurred at the

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**Figure 10.** Composition of Sawan chlorites; tetrahedral Al is plotted against the ratio of octahedral Fe/(Fe + Mg); chl prt = chloritized particle, chl cem = chlorite cement, chl rim = chlorite rim (from Curtis et al., 1985).

**Figure 11.** Paragenetic sequence for the main diagenetic processes based on petrographic relationships. VRF = volcanic rock fragments.
same time as chlorite growth to provide the ions for rim and cement growth.

Quartz cements occur both as pore-filling and as idiomorphic quartz outgrowths (Figure 7d). As the latter are not covered by chlorite rims, precipitation of diagenetic, authigenic quartz occurred after the development of the chlorite rims.

Well-developed chlorite rims acted as effective barriers inhibiting secondary quartz cementation on detrital quartz grains, although they could not inhibit carbonate cement precipitation.

The main phase of carbonate cementation postdates all other diagenetic processes; however, evidence for carbonate cementation at an earlier stage exists, contemporary with the recrystallization of carbonate bioclasts or carbonate grains. These early carbonate cements are partly precompactional, very localized, and of a patchy character.

The backscattered image (Figure 12), which illustrates the diagenetic sequence, shows quartz grains and VRF covered by chlorite rims. Quartz overgrowths are present, but these are not lined by chlorite rims. At grain contacts between detrital grains (black arrow in Figure 12), no chlorite was detected by electron microprobe, demonstrating that no chlorite rims were present before compaction.

**Development and Origin of Chlorites in Sawan Sandstones**

To explain the growth of the two types of chlorite in the Sawan sandstones, both the source of Fe and Mg and the chlorite forming processes must be established.

Important processes of chlorite neoformation in sandstones have been reviewed by Anjos et al. (2003):

1. Replacement of nonclay material: Many minerals react with Fe- and Mg-rich pore waters and transform to chlorite. Although such reactions occur preferably with ferromagnesian minerals, like biotite and amphibole (De Ros et al., 1994), and basic VRF (Svardam and Boles, 1979; Remy, 1994), alteration of feldspar also occurs (Morad and Aldahan, 1987).
2. Replacement of a clay precursor: Infiltrated smectites, authigenic smectites, and Fe-rich 7-Å
clays and kaolinites are all likely to be transformed to chlorite.

The transformation of mechanically infiltrated smectites and also eogenetic authigenic smectites into chlorites commonly occurs through chlorite-smectite mixed layer stages. Trioctahedral smectites preferentially transform to chlorites through chlorite-smectite mixed layers, whereas dioctahedral smectites tend to evolve into illite-smectite mixed layers and illite (Chang et al., 1986). Trioctahedral smectites are the most common alteration products of basic to intermediate volcanic material, under both continental and marine conditions (De Ros et al., 1997).

Replacement of Fe-rich, green 7-Å clays, like berthierine, verdine, odinite, and phyllite V (Odin, 1988), by ferroan chlorite (chamosite) occurs upon deep burial (Hillier, 1994). The 7-Å clays are formed as syngenetic and eogenetic ooids; as precompactional coatings; and as matrix in estuarine, deltaic, or inner-shelf settings. All of these depositional settings are characterized by an influx of meteoric waters and mixing between meteoric and marine waters.

Mesogenetic destruction of kaolinite in environments rich in Fe and Mg supplies adequate conditions for the authigenesis of chlorite. Increasing burial depths and temperatures are decisive factors (Moraes and De Ros, 1992).

3. Neoformation caused by direct precipitation from the pore water: Direct precipitation of chlorite cements from pore water is favored in mesodiagenetic conditions in volcaniclastic sandstones and in siliciclastic sandstones at great depths. The neoformation processes commonly occur together with the chloritization of different mineral substrates (Anjos et al., 2003). The source of Mg and Fe ions for chlorite authigenesis in such siliciclastic reservoirs can be dissolved, ferromagnesian, detrital grains (De Ros et al., 1994); eogenetic hematite (Dixon et al., 1989); and mudstone (Moncure et al., 1984).

Chlorite rims in volcaniclastic sandstones can form through transformation of precursor clay substrates and through direct precipitation from Fe- and Mg-rich pore waters. Grains that are already covered by transformed coatings can additionally be coated by rims formed by precipitation from pore waters, indicating a two-stage growth process (Remy, 1994).

In the Sawan sandstones, no prediagenetic clay coatings, smectite coatings, mixed-layer minerals, kaolinite, or relics of 7-Å clays have been identified. Earlier pre- or eodiagenetic clay rims at grain contacts are not preserved in the samples. The older, poorly crystallized chlorite rims could be an indication of transformed pre- or eodiagenetic clay rims. Inherited (prediagenetic) clay rims are characterized by their presence at points of contact between framework grains (Wilson, 1992). Figures 7c, d, and 12 show planar contacts of detrital quartz grains, enclosed by neoformed chlorite rims. This indicates a period of compaction and pressure solution prior to chlorite growth. No chlorite has been found at detrital grain contacts in the Sawan sandstones. Thus, we conclude that both present-day generations of chlorite rims emerged from direct precipitation from pore water. A change in physiochemical conditions possibly caused the temporal interruption of growth, and two morphologically different chlorite rim generations formed.

The most important source for the Fe, Mg, Si, and Al ions for diageneric chlorite authigenesis in the Sawan sandstones was the alteration and dissolution of VRF, feldspar, and biotite. Volumetrically, the contribution of biotite and feldspar is of minor importance (Table 1). For chlorite coats to form and be effective at preserving porosity, the original VRF content must be sufficient to provide an adequate source of ions to precipitate chlorite but not high enough to cause porosity destruction by ductile deformation (Bloch et al., 2002). The optimum mafic VRF content is approximately 10% in sandstones containing more than 65% detrital quartz (Pittman et al., 1992). The average original VRF content in the Sawan reservoir sandstones is 12%.

The porosity-preserving effect of chlorite rims in deeply buried sandstones depends on the continuity of the rims, which cover detrital grains (Morad et al., 2000). Quartz overgrowths and outgrowths in the Sawan sandstones occur preferentially where chlorite rims covering detrital quartz grains are thin or discontinuous (Figures 7d, 8f). The mechanism
of quartz cement inhibition is not fully resolved. Some authors say that chemical aspects, like undersaturated Si solutions, are the reason for the inhibited quartz cementation in chloritized sandstones (Billault et al., 2003); others argue that physical mechanisms are responsible for the prevention of quartz overgrowth (Billault et al., 2003). How chlorite is able to inhibit the growth of quartz is yet unclear, but it is generally agreed that chlorite rims are only efficient where precipitated earlier than quartz overgrowths (Hillier, 1994), and hence, the surface of detrital quartz grains is isolated from pore waters, which prevents the precipitation of quartz. Theories accounting for the minor development of secondary quartz in chloritized sandstones are:

1. Quartz overgrowths are absent because pressure solution has not occurred (Pittman and Lumsden, 1968). This is not the case in the Sawan sandstones because some pressure solution occurred without abundant development of quartz overgrowths.

2. Conditions are favorable for quartz precipitation, but chlorite rims covering the surfaces of clastic grains have inhibited secondary quartz cements (cf. Heald and Larese, 1974). Chlorite rims inhibit the growth of quartz because they isolate the surfaces of clastic grains from pore waters and hence block the quartz nucleation (Ehrenberg, 1993).

However, transmission electron microscope observations by Billault et al. (2003) clearly indicated that detrital quartz surfaces were not physically isolated from the pore fluids by the crystals of the chlorite and that inhibition of quartz cementation is caused by the drastic limitation of the epitaxial growth of quartz into the interparticle space at the base of the chlorite coating.

**Depositional Control on Reservoir Quality?**

Sandstones directly overlying the reservoir (well 2, 3258.6 and 3264.6 m [10,690.9 and 10,710.6 ft]) were deposited during a transgressive phase. They are heavily cemented by calcite, Fe chlorite, and Fe dolomite, which destroyed permeability (Table 2).

In well 2, samples above 3353.02 m (11,000.7) have pore-lining chlorite cements and good preservation of porosity and permeability. Samples below this depth show no chlorite cements and a pervasive quartz cementation resulting in low porosities and poor permeabilities (Figure 7a). These units are separated from each other by a sequence boundary. Core-based interpretation of the depositional facies and ichnofacies shows the lower samples to represent lower shoreface to offshore sediments. The sediments above 3353.02 m (11,000.7), which form the reservoir, are of a very shallow-marine origin from a proximal delta-front setting. Their ichnofauna shows the occasional presence of a brackish water environment.

In summary, porosity- and permeability-preserving chloride grain coating and thus reservoir quality within the lower Goru Member in the Sawan gas field are restricted to the proximal, shallowest marine, medium- to coarse-grained sandstones.

Eodiagenetic formation of chlorites or their precursors has been reported from shallow-marine sandstones (e.g., Ehrenberg, 1993). Based on Bloch et al. (2002), a fluvial source of iron for chloride-rich sandstones in shallow-marine environments is common because the concentration of iron in seawater is very low.

The Sawan sandstones do not contain any evidence for eodiagenetic, precursor Fe-rich clay rims. In Sawan, the abundance of VRF provides ample source for iron. In addition, an empirical relationship between depositional environment and the presence of porosity- and permeability-preserving chloride grain coatings is observed. The Sawan sandstones are thus an example where a combination of provenance and depositional environment allows the preservation of reservoir quality.

**CONCLUSIONS**

Three types of authigenic chloride are present in the Sawan sandstones: pore-lining cements, pore-filling cements, and chloritized detrital components. Electron microprobe analyses show all of
these having similar Fe-rich chamosite chemical composition.

Two generations of authigenic chlorite rims have been identified in the SEM: an earlier, poorly crystallized growth and a later, better crystallized growth, which covers the former. Both rim generations grew by direct precipitation from pore waters. A temporal interruption during growth, with an associated change in physicochemical conditions, led to the two morphologically different chlorite-rim generations. Chlorite-rim precipitation occurred after an initial phase of compaction because rims are not observed between grain contacts but prior to the growth of other diagenetic phases such as quartz overgrowths and outgrowths, pore-filling chlorite, and carbonate cements.

The high porosities (up to 20%) at depths below 3000 m (9842 ft) and temperatures around 175°C are caused by the inhibiting effects of the chlorite rims on quartz cementation. The rims, which range between 5 and 10 μm in thickness, acted as an effective barrier when continuous and well developed, blocking the growth of secondary quartz cements on detrital quartz grains. In areas with thin or discontinuous chlorite rims, quartz cementation is common. The chlorite rims did not inhibit carbonate cementation.

The alteration and dissolution of not only VRF, but also feldspar and biotite were most likely the source for the Fe, Mg, Si, and Al ions for chlorite authigenesis. An empirical relationship between the presence of porosity- and permeability-preserving chlorite grain coatings and their depositional environment is observed in the reservoir sandstones of the Sawan gas field.

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