Diagenesis and Sequence Stratigraphy

An Integrated Approach to Constrain Evolution of Reservoir Quality in Sandstones

BY

JOÃO MARCELO MEDINA KETZER
Abstract


Diagenesis and sequence stratigraphy have been formally treated as two separate disciplines in sedimentary petrology. This thesis demonstrates that synergy between these two subjects can be used to constrain evolution of reservoir quality in sandstones. Such integrated approach is possible because sequence stratigraphy provides useful information on parameters such as pore water chemistry, residence time of sediments under certain geochemistry conditions, and detrital composition, which ultimately control diagenesis of sandstones.

Evidence from five case studies and from literature, enabled the development of a conceptual model for the spatial and temporal distribution of diagenetic alterations and related evolution of reservoir quality in sandstones deposited in paralic environments. Diagenetic alterations that have been constrained within the context of sequence stratigraphy include: (i) formation of kaolinite and intragranular porosity, and mechanical infiltration of clay minerals in sandstones lying at variable depths below sequence boundaries, (ii) formation of pseudomatrix and cementation by calcite, dolomite, and siderite in lag deposits at parasequence boundaries, (iii) cementation by kaolinite, pyrite, and calcite in sandstones lying in the vicinity of parasequence boundaries with coal deposits, (iv) formation of glaucony in condensed interval at parasequence boundaries, transgressive and maximum flooding surfaces, (v) formation of berthierine in fluvial-dominated deltaic deposits of the highstand systems tract, (vi) cementation by calcite in bioclastic sandstones of the transgressive systems tract, and (vii) formation of kaolinite in fluvial deposits of the lowstand systems tract. The distribution of such alterations put important constrains for the pattern of burial diagenesis (e.g., formation of chlorite, illite, quartz), related evolution of reservoir quality in sandstones, and distribution of baffles and barriers for fluid flow in the context of sequence stratigraphy.

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Lisis, S.V.B.E.E.V.
(Si vales, bene est. Ego valeo!)

Lisianae familiaeque dico cum amore hanc thesim.

Ad Sadoonem, magistrum carissimum,
multas gratias ago. Ex imo corde.
PREFACE

This thesis is based on the following papers, which will be hereafter referred to in the text by their Roman numerals:


V. Ketzer, J.M., Morad, S., and Ryer, T., Distribution of diagenetic clay minerals at sequence and parasequence boundaries in Upper Cretaceous, paralic sandstones of the Ferron Sandstone Member and the Tibbet Canyon Member, U.S.A., *submitted*.


The papers are reprinted with kind permission of the publishers: Blackwell Sciences Ltd. (papers I, IV, and VII), and SEPM - Society for Sedimentary Geology (paper II).
Other contemporary publications not included in this thesis:


INTRODUCTION

“Science is built up of facts, as a house is built of stones: but an accumulation of facts is no more a science than a heap of stones is a house.”

Henri Poincaré, Science and Hypothesis, 1905.

Diagenesis and sequence stratigraphy have been formally treated as two independent disciplines in sedimentary geology. It was just recently documented that diagenetic alterations such as calcite and dolomite cementation might be distributed at sites coincident with sequence stratigraphic surfaces (Tucker, 1993; Taylor et al., 1995). Sequence stratigraphy, if applied independently, allows facies prediction, and thus provides information on depositional-related reservoir quality (Van Wagoner et al., 1990; Posamentier and Allen 1999), which is controlled by sorting and grain size. Using the same approach, the distribution of fluid flow barriers and potential reservoir seals, which are fine-grained, mud and silt deposits, can also be constrained (Van Wagoner et al., 1990). The classical sequence stratigraphic model cannot provide direct information about the post-depositional evolution of reservoir quality in sandstones. Synergy between sequence stratigraphy and diagenesis, however, enables the prediction of spatial and temporal distribution of diagenetic alterations, and thus of post-depositional evolution of reservoir quality in sandstones. It may also provide information on the formation of diagenetic baffles and barriers for fluid flow, thus potential diagenetic reservoir compartments and seals.

Knowledge about sequence stratigraphy can provide useful information on parameters controlling the near-surface diagenesis, such as changes in (i) pore water chemistry (Hart et al., 1992; McKay et al., 1995), (ii) residence time of sediments under certain geochemical conditions (Taylor et al., 1995), (iii) detrital composition and proportion of extra- and intra-basinal grains (Garzanti, 1991; Amorosi, 1995; Zuffa et al., 1995), and (iv) presence and abundance of organic matter (Cross, 1988) (Fig. 1). Other parameters that influence diagenesis of sandstones, but cannot be obtained by sequence stratigraphic analysis include paleoclimate, tectonic setting of the basin, and composition of seawater.

The relationship between sequence stratigraphy and diagenesis for carbonate deposits is well documented in the literature (Read and Horbury, 1993 and references therein; Tucker, 1993; Moss and Tucker, 1995), but less well constrained for siliciclastic deposits (Taylor et al. 1995, 2000; Loomis and Crossey, 1996; Amorosi and Centineo, 2000). This discrepancy is partly because siliciclastic grains are much less reactive to surface waters (e.g., meteoric and marine waters) than carbonate grains. Hence, short-term changes in diagenetic parameters, such as occurring within the time spend during sequence deposition (i.e., third or fourth order relative sea level cycles; cf. Vail et al., 1977) will be easier recognized in carbonate than
Fig. 1 - Diagrams showing relationships between sequence stratigraphy and parameters controlling diagenesis of sandstones. Diagram A illustrates how changes in the relative sea level modify the initial pore water chemistry of near surface deposits. Diagram B shows the role of flooding surfaces at parasequence boundaries in prolonging the residence time of sediments close to the sea floor (depositional hiatus) owing to the low sediment accumulation rate (modified from Jervey, 1988). Diagram C shows changes in the detrital composition of shelf sand deposits (proportion of intra- to extrabasinal grains) owing to transgression of the shoreline. During transgression, clastic influx is reduced as extrabasinal grains are trapped landwards (e.g., in estuaries), and the relative quantity of intrabasinal grains is increased (compositional triangular diagram modified from Zuffa, 1980).
siliciclastic deposits. Diagenetic alterations owing to the percolation of meteoric water below subaerially exposed sequence boundaries, for instance, can cause extensive dissolution of carbonate rocks (karstification; Bardossy and Combes, 1999) but cause only minor dissolution and formation of kaolinite in siliciclastic rocks (McCarthy and Plint, 1998).

The aim of this thesis is to integrate diagenesis and sequence stratigraphy in order to unravel and discuss the spatial and temporal distribution of diagenetic alterations in sandstones. It is also aimed to develop conceptual models for the distribution of these diagenetic alterations. Such an approach will ultimately contribute to enhance our ability to understand and predict the evolution of reservoir quality in sandstones, and of diagenetic baffles for fluid flow and seals. The data set collected to support the hypothesis of this thesis comprised extensive literature survey that resulted in two review papers (papers I and IV) and five case studies (papers II, III, V, VI, and VII). In the first four case studies, Carboniferous of Ireland, Permian of Brazil, Cretaceous of U.S.A., and Miocene of Egypt, we discuss the distribution of diagenetic alterations in a classic sequence stratigraphic framework, i.e., within systems tracts and along sequence stratigraphic surfaces (sequence and parasequence boundaries, transgressive surface and maximum flooding surface). In the last case study (Triassic of Norwegian North Sea), which was included in this thesis for the purpose of comparison with the four former cases, we discuss the distribution of diagenetic alteration in a unconformity surface produced by rifting and regional tectonic uplift instead of relative sea level fall. This unconformity is thus distinct in its origin and has much longer subaerially exposure times than sequence boundaries in the classical sequence stratigraphic sense (cf. Van Wagoner et al., 1990).

This comprehensive summary comprises: (1) an overview of the key sequence stratigraphic concepts used in this thesis, (2) a discussion on sequence stratigraphic controls on sandstone diagenesis and the model elaborated for the distribution of the diagenetic alteration in a sequence stratigraphic framework, (3) a discussion on the related evolution of reservoir quality in sandstone, (4) summaries of the papers included in this thesis, and finally the main conclusions.

1 SEQUENCE STRATIGRAPHY: AN OVERVIEW OF THE KEY CONCEPTS

The sequence stratigraphic terminology presented here is based on the classical concepts introduced by Posamentier et al. (1988), Posamentier and Vail (1988), and particularly by Van Wagoner et al. (1990). Recent reviews and critics of these concepts have been presented in the literature (Emery and Myers, 1996; Miall, 1997; Posamentier and Allen 1999) but the main terminology and basic principles remain essentially the same. The examples presented in this thesis are all within the range of observation of the “high-resolution sequence stratigraphy”, i.e., based on a data set
that integrates observations at a log, core, and/or outcrop scales (Emery and Myers, 1996), in contrast to the so called “low-resolution sequence stratigraphy”, which is based essentially on seismic data. Additionally, the examples presented here are all from facies and depositional environments situated between coastal plain and lower shoreface (i.e., paralic) environments, where the concepts of sequence stratigraphy are best applied (Emery and Myers, 1996).

The basic principle of sequence stratigraphy is that deposition of sediments and their spatial and temporal distribution in a basin are controlled by the interplay between sediment supply, basin-floor physiography and changes in the relative sea level. The latter refers to changes in the elevation of sea level by a combination of eustatic fluctuations and basin-floor subsidence or uplift. Sequence stratigraphic analysis aims to divide the stratigraphic record into depositional sequences, in which the sequence boundaries are subaerial erosion surfaces (unconformities) or their correlative conformities. Sequence boundaries are formed by an abrupt fall in relative sea level, i.e., type one sequence boundary (Van Wagoner et al., 1990), and sequences are thus deposited between two episodes of relative sea level fall, which coincide, for instance, with falling inflection points on a hypothetical relative sea level curve (Fig. 2). If relative sea level eventually falls below the shelf edge, valley incision, pronounced erosion of the shelf, and extensive deep water turbidite deposition will occur (Posamentier and Allen, 1999).

Sequences are comprised of parasequences, which are genetically related deposits bounded by marine flooding surfaces (Van Wagoner et al., 1990). Each parasequence shows a shallowing upward trend, i.e., a progressive deposition of shallower water strata on top of deeper water strata, which is usually expressed by a coarsening upward trend (Fig. 3). Parasequences are grouped into parasequence sets according to their stacking pattern, which is, in turn, controlled by the ratio of depositional rate and accommodation rate (Van Wagoner et al., 1990). If the overall depositional rate is higher than the accommodation rate, the shoreline will have a regressive tendency, and a parasequence set is progradational, with the succeeding parasequence being deposited in a average shallower water environments that the previous one within the same set (Fig. 3). If the overall deposional rate is equal to or lower than the accommodation rate, than the parasequence set is aggradational (stillstand shoreline) or retrogradational (overall transgressive shoreline), respectively (Fig. 3).

As accommodation space creation is controlled by relative sea level changes, parasequence sets can be associated to specific periods of a relative sea level curve. The contemporary depositional systems to each period of the relative sea level curve will thus have a characteristic parasequence set stacking pattern and define a systems tract. Three main systems tracts are defined, the lowstand systems tract (LST), the transgressive systems tract (TST), and the highstand systems tract (HST). The LST is deposited between the lower sequence boundary (abrupt relative sea level fall) and the beginning of relative sea level rise, which is represented by the first transgression of the shelf, and formation of a wave ravinement surface named transgressive
Fig. 2 - Cartoon showing stratal patterns, types of deposits, and their relationship with the relative sea level change curve of a sequence deposited in a basin with a shelf break (modified from Van Wagoner et al., 1990).
Fig. 3 - Cartoon illustrating typical distribution pattern of facies in a parasequence developed in a wave-dominated environment, which displays a coarsening upwards pattern. The parasequence is bounded by marine flooding surfaces and the upper parasequence boundary is marked by a transgressive lag. Parasequences form parasequence sets according to their stacking pattern: progradational, aggradational or retrogradational.
surface (Fig. 2). The LST is comprised of: (i) deep water turbidite systems, which are the basin-floor fan and the slope fan (not considered in this thesis), and (ii) lowstand wedge, which are fluvial deposits within incised valleys and shelf edge deltas with aggradational and/or progradational parasequence sets (Fig. 2). The TST is situated between the transgressive surface and the maximum flooding surface. The latter represents the point of maximum landward advance of the coast and maximum rate of relative sea level rise (Fig. 2). The TST is comprised of a retrogradational parasequence set (Fig. 2). The HST occurs between the maximum flooding surface and the upper sequence boundary, and contains aggradational to progradational parasequence sets (Fig. 2). A fourth systems tract, named forced regressive wedge systems tract (FRWST; Hunt and Tucker, 1992), was proposed to include deposits formed during relative sea level fall, between the highstand and the point of maximum rate of sea level fall (i.e., formation of the succeeding sequence boundary). This systems tract is comprised of progradational stranded parasequences that commonly reach the shelf edge. The FRWST was not recognized in the studied sequences and will thus not be treated in this thesis.

2 DIAGENESIS AND SEQUENCE STRATIGRAPHY: AN INTEGRATED APPROACH

This section deals with the distribution of diagenetic alterations in a sequence stratigraphic framework, i.e., at sequence and parasequence boundaries, transgressive and maximum flooding surfaces, and within systems tracts (Fig. 4).

**Sequence boundaries**

Diagenetic alterations related to sequence boundaries include mechanical clay infiltration and formation of kaolinite and intragranular porosity in the underlying deposits. Mechanical clay infiltration occurs into sand deposits (commonly HST foreshore and shoreface sands) below sequence boundaries owing to the percolation of muddy river waters below incised valleys and by crevassing and flooding of interfluve areas (papers IV and V) (Fig. 5). Mechanical clay infiltration is expected to be more pervasive during dry climates owing to the lower position of the water table (i.e., thick vadose zone), which act as a barrier for the infiltration of clays (Moraes and De Ros, 1990). The relatively thin zone (= 1 m) of mechanically infiltrated clays in the studied sandstones of the Cretaceous of the U.S.A. (paper V; Walker, 1976; Moraes and De Ros, 1990) is possibly because of the contemporary humid climate. The preservation potential of mechanically infiltrated clays in sandstones below sequence boundaries is low where sequence boundaries coincide with wave ravinement surfaces (transgressive surface) (Fig. 5), because of the reworking of the underlying sands (papers IV and V).
Fig. 4 - Cartoon indicating sequence stratigraphic location to where distribution of diagenetic alterations are detailed. For legend refer to Figure 2.
Fig. 5 - Diagram showing the distribution and evolution of diagenetic alterations in sandstones below sequence boundaries and within incised valleys. Note that the zone with mechanically infiltrated clays is thin (or absent) below the ravinement surface. Refer to Figure 4 for location in a sequence stratigraphic framework.

Sand deposits below subaerially exposed sequence boundaries may also be subjected to percolation of meteoric water, which typically results in dissolution of unstable framework grains (e.g., micas and feldspars) and formation of intragranular porosity and kaolinite (Fig. 5). The absence of both kaolinite and intragranular porosity below sequence boundaries in the Carboniferous sandstones of Ireland (paper II) is attributed to the contemporary semi-arid climatic conditions, which inhibit their formation, owing to the limited volume of meteoric water (paper IV),
and short subaerial exposure time of these sandstones. Favorable conditions for the formation of intragranular porosity and kaolinite occur below unconformities with much longer subaerially exposure time than sequence boundaries in the sequence stratigraphic sense (Van Wagoner et al., 1990) and during humid climates, such as encountered during the development of the early Cretaceous Cimmerian unconformity in the North Sea (paper VII). In this case, unconformity related diagenetic alterations occur up to 200 m below the unconformity. This deep zone of alteration is also attributed to regional uplift during formation of the unconformity, which created a hydraulic head, and hence enabled deep penetration of meteoric waters (paper VII).

Parasequence boundaries, transgressive surface, and maximum flooding surface
Diagenetic alterations related to these surfaces include: (i) carbonate cementation (calcite, dolomite, and siderite) and formation of pseudomatrix in lag deposits, (ii) calcite, pyrite, and kaolinite cementation in sandstones below and above parasequence boundaries with coal deposits, and (iii) formation of glaucony.

Parasequence boundaries, transgressive and maximum flooding surfaces are commonly marked by a lag deposit formed by wave reworking of the substrate and accumulation of winnowed sediments during transgression (Posamentier and Allen, 1999). The detrital composition of such lags, which is in partly controlled by the type of substrate below the lag, is of great importance for the type of diagenetic alterations. Starting from a landward to a basinward location, the same lag will possibly vary in detrital composition from mud intraclast-rich to bioclast-rich (Fig. 6). Lags rich in mud intraclasts will potentially have abundant pseudomatrix (paper V), which is formed by mechanical compaction, which results in deformation and squeezing of mud clasts and other ductile grains into adjacent pores (Fig. 6). Lags rich in carbonate bioclasts, however, will be pervasively cemented by calcite, dolomite and/or siderite (papers II and III) (Fig. 6). Carbonate cementation in such cases occurs because of the presence of carbonate bioclasts, which act as nuclei and source of ions for cementation. Carbonate cement growth is favored by the prolonged residence time in which sediments stay under the same geochemical conditions, close to the sea floor, as a consequence of the low sedimentation rates encountered at parasequence boundaries (papers I and II). Siderite, in particular, is formed in a more distal extent of calcite and dolomite cemented lags (Fig. 6), possibly because of the lower amounts of organic matter and, thus prolonged suboxic diagenesis (paper III). Factors controlling the formation of calcite rather than dolomite (and vice-versa) in such lag deposits are, however, uncertain. Calcite and dolomite may, in some cases occur together, cementing the same lag. It has been observed, however, that dolomite tends to form during periods of overall transgression of the shoreline (i.e., TST), particularly when associated with deltaic deposits showing low wave influence. Calcite, on the contrary, is more common in lag deposits formed during overall regression, and associated with deltaic deposits with strong wave influence (e.g., early HST; paper II).
Fig. 6 - Diagram illustrating the distribution of diagenetic alterations in lag deposits at parasequence boundaries in proximal, intermediate, and distal locations. Refer to Figure 4 for location in a sequence stratigraphic framework.
Parasequence boundaries are eventually marked by marine deposits on top of coal layers (Van Wagoner et al., 1990). The near-surface and burial diagenesis of organic matter in these coal deposits may result in the formation of pyrite concretions, stratified calcite (up to 3 m thick), and kaolinite in the under- and overlying sandstones (paper III) (Fig. 7). Pyrite concretions form in sandstones above and below the coal deposits because of sulfate reduction, which is enhanced by the abundant organic matter in the coal layers and by large volumes of sulfate-charged seawater supplied during transgression (paper III). Stratified calcite occurs in sandstones on top of coal deposits at parasequence boundaries and disappears in both the landward and basinward terminations of the coal deposits (Fig. 7). It forms because of the alteration of organic matter, and consequent increase in the carbonate alkalinity of pore waters. Kaolinite is formed mainly in sandstones below coal deposits at parasequence boundaries. Meteoric waters percolating through coal or peat usually become strongly acidic due to the presence of CO₂ and organic acids produced during microbial alteration of organic matter. These acidic meteoric watersfavor the dissolution of silicates grains (e.g. feldspars and micas) and formation of kaolinite in sandstones beneath the coal layer (paper III) (Fig. 7).

In contrast to kaolinite, glaucony is typically encountered along the outer shelf extension of parasequence boundaries, transgressive and maximum flooding surfaces. At these surfaces, glaucony can be accumulated by mechanical, wave or tidal reworking (allochthonous glaucony; cf. Amorosi, 1995) or be formed in situ (authochthonous glaucony). The latter is formed by: (i) low sedimentation rates owing to low siliciclastic input to the shelf, and (ii) moderate amounts of organic matter to establish a mildly reduced condition, i.e. Fe^{2+} = Fe^{3+} (nitrate- and manganese-reducing, suboxic condition; Berner, 1981) for a prolonged time (Amorosi, 1995, 1997; paper IV). As the lowest sedimentation rate is encountered at the maximum flooding surface, there is an overall systematic upwards increase in the volume of glaucony from the transgressive surface, through parasequence boundaries of the TST, to the maximum flooding surface (Amorosi and Centineo, 2000; paper IV). The volume of glaucony decreases upwards, however, from the maximum flooding surface to parasequence boundaries of the HST. The occurrence of glaucony at parasequence boundaries, transgressive and maximum flooding surface make these surfaces a fairly reliable regional stratigraphic markers, such as in the Cretaceous to Oligocene glaucony-rich successions of northern-central Europe (Robaszynski et al., 1998; Vandenberghe et al., 1998).

**Systems tracts**

Certain diagenetic alterations are more likely to occur in the LST, TST, or HST. Sandstones of LST, in particular fluvial deposits in incised valleys, commonly contain abundant kaolinite and grain dissolution owing to a more effective meteoric water circulation, if compared to typical estuarine or marine deposits LST lowstand wedge, TST and HST (papers I, III, and VI) (Fig. 5). Contemporary humid climatic conditions
Fig. 7 - Diagram showing the distribution of diagenetic alterations in sandstones under- and overlying parasequence boundaries with coal layers. Refer to Figure 4 for location in a sequence stratigraphic framework.
promote extensive percolation of meteoric waters through the LST sandstones, and thus enhance dissolution of silicates and formation of kaolinite. During semi-arid climates, however, when the supply of meteoric water is limited, kaolinite is of minor importance or absent (paper II). Instead, clay minerals commonly occurring in the LST alluvial sandstones are mechanically infiltrated smectitic clays, which will eventually evolve to grain-coating chlorite and/or illite during burial diagenesis (papers I and IV). Formation of illite instead of chlorite is favored by contemporary albitization of detrital K-feldspars (paper II) (Fig. 5). In some cases, however, the widespread occurrence of grain-coating chlorite in both LST fluvial and TST estuarine, incised valley sandstones indicates that its formation was possibly neither related to mechanical clay infiltration nor to a particular depositional facies or systems tract (paper VI).

The TST and early HST paralic sandstones have higher potential to be cemented by carbonates (notably calcite) than, for instance, late HST and LST deposits (paper II) (Fig. 8). This is because marine transgression (i) prevents rivers from progradation, suppressing a fluvial signature in the delta fronts, and (ii) causes trapping of coarse-grained sediments in estuaries, reducing the sediment flux to the shelf (Emery and Myers, 1996), which will lead to a higher degree of wave reworking of sands on the shelf. Wave reworking results in a more effective incorporation of carbonate bioclatics into the sand deposits, which act as potential sources and nuclei for later carbonate cementation.

The TST and early HST are preferential sites for the occurrence of coal deposits (Ryer, 1981; Cross, 1988; Shanley and McCabe 1993). Thus, diagenetic alterations related to coal at parasequence boundaries, such as the formation of pyrite, stratabound calcite, and kaolinite, will potentially be more common or extensive along TST and early HST parasequence boundaries (paper III). Pseudomatrix in lag deposits at parasequence boundaries will be laterally most extensive in the TST, because the shoreface advances most landwards onto fine-grained, delta-plain and backshore deposits (paper V).

Paralic sandstones of the late HST and possibly the LST lowstand wedge (excluding fluvial deposits within incised valley) tend to develop fluvial-dominated deltas owing to progradation in response to a decrease in the rate of relative sea level rise (Emery and Myers, 1996). This will favor the formation of pellets and grain-coating or pore-lining berthierine or odinite, adjacent to river-mouths (Hornibrook and Longstaffe, 1996; Kronen & Glenn, 2000; paper IV) (Fig. 8). The relatively high burial rates of such sediments below the seafloor promote a rapid establishment of the post-oxic, Fe-reducing geochemical conditions, which favour berthierine formation. The formation of berthierine in such deposits is possibly enhanced by abundant supply of iron oxides and hydroxides (Odin and Matter, 1981) and a low sulphate concentration in pore-waters (i.e., less Fe$^{2+}$ is incorporated in Fe-sulphides), owing to mixing of marine and meteoric waters during shoreline progradation (paper IV). Berthierine is a potential precursor for the formation of grain-coating
Fig. 8 - Diagram showing the distribution of diagenetic alterations in wave-dominated, transgressive systems tract (TST), and in fluvial-dominated, highstand systems tract (HST) deltaic sandstones. The TST sandstones are likely to contain more carbonate bioclasts (BC) than HST sandstones, which are prone to have more siliciclastic grains (QZ = quartz, and K-F = K-feldspar). Refer to Figure 4 for location in a sequence stratigraphic framework.
chlorite (chamosite) during burial diagenesis in late HST and LST lowstand wedge sandstones (papers II and IV) (Fig. 8).

3 EVOLUTION OF RESERVOIR QUALITY IN SANDSTONES

The integration of diagenesis and sequence stratigraphy allowed elaboration of a general, predictive model for evolution of reservoir quality in sandstones and distribution of fluid flow baffles and barriers in siliciclastic sequences (Fig. 9). This model comprises preferential sites for cementation, thus porosity and presumably permeability destruction, or for dissolution, thus porosity and possibly permeability enhancement. Porosity of sandstones beneath subaerially exposed sequence boundaries, for instance, is commonly enhanced because of the dissolution of micas and feldspars, accompanied by the formation of smaller volumes of kaolinite, as a result of meteoric water percolation (paper IV). It has been demonstrated, however, that porosity and permeability of sandstones beneath subaerially exposed sequence boundaries can be deteriorated because of the mechanical infiltration of clay minerals, which may result in the formation of baffles or barriers for fluid flow (paper V) (Fig. 9). The precise prediction of porosity destruction or enhancement below sequence boundaries is difficult because it involves parameters such as climate, duration of subaerial exposure, and type of deposits below the sequence boundary. Humid climatic conditions will favor the dissolution of framework grains and porosity enhancement, while arid to semi-arid climatic conditions will favor mechanical clay infiltration and porosity deterioration (paper IV). Both processes, dissolution of framework grains and mechanical clay infiltration, will be inhibited by short subaerial exposure times and obliterated by pronounced erosion at sequence boundaries by waves (i.e., ravinement) during succeeding transgression.

Parasequence boundaries, transgressive and maximum flooding surfaces are common sites of porosity destruction in adjacent sandstones and in associated lag deposits because of the great potential for cementation (calcite, dolomite, siderite, and/or pyrite; papers II, III, and IV) and formation of pseudomatrix (paper V). These surfaces can, thus, form potential baffles and barriers for fluid flow, and create reservoir compartments between sandstone bodies of adjacent parasequences (Fig. 9). Important factors controlling the formation of pseudomatrix and cementation of sandstones in the vicinity of parasequence boundaries include the presence of coal and lag deposits. Coal deposits favor concretionary pyrite and stratabound calcite cementation in the under- and overlying sandstones (paper III). Lags will be carbonate cemented (calcite, dolomite or siderite) if bioclast-rich (paper II), or will contain abundant pseudomatrix if rich in mud intraclasts (paper V). These lags are not formed (thus no fluid flow baffles or barriers) in areas protected from waves, such as within estuaries (paper III), in places where the transgressive surface does
not coincide with the ravinement surface (Dalrymple et al. 1992), or in a landward position of the maximum landward advance of the coast (Fig. 9).

Regarding systems tracts, the TST and early HST paralic sandstones are prone to be subjected to porosity deterioration owing to carbonate cementation than LST and late HST deposits. This is because TST and early HST deposits are more likely to incorporate carbonate bioclasts into the sand framework, which act as nuclei and source of ions for carbonate cementation (paper II)(Fig. 9). Late HST deltaic deposits are prone to have grain coating berthierine, which will eventually evolve to chlorite during burial diagenesis and possibly act as inhibitor for development of quartz overgrowths (paper II). Transformation of grain coating smectitic clays into illite in LST fluvial deposits during burial diagenesis is favored by contemporary albition of detrital K-feldspar (Paper II). The fluvial LST sandstones commonly have more intragranular porosity than TST and HST sandstones, because of the most efficient circulation of meteoric waters in the former (papers I, III, IV, VI).

![Cartoon showing the spatial distribution of potential sites for porosity destruction (cementation, formation of pseudomatrix and mechanical clay infiltration), formation of baffles and barriers for fluid flow, or potential sites for porosity enhancement (grain dissolution and formation of intragranular porosity). Porosity enhancement may also occurs in sandstones lying below incised valleys. LST, TST, and HST refer to lowstand, transgressive, and highstand systems tracts, respectively.](image)
Paper I – The spatial and temporal distribution patterns of diagenetic alterations in siliciclastic sequences are controlled by a complex array of interrelated parameters that prevail during eodiagenesis, mesodiagenesis and telodiagenesis. The spatial distribution of near-surface eogenetic alteration is controlled by the depositional facies, climate, detrital composition, and relative changes in sea-level. The most important eogenetic alterations in continental sediments include silicate dissolution and the formation of kaolinite, smectite, calcrete and dolocrete. In marine and transitional sediments, eogenetic alterations include the precipitation of carbonate, opal, microquartz, Fe-silicates (glaucony, berthierine and nontronite), sulphides and zeolite. The eogenetic evolution of marine and transitional sediments can probably be developed within a predictable sequence stratigraphic context. Mesodiagenesis is strongly influenced by the induced eogenetic alterations, as well as by temperature, pressure and the composition of basinal brines. The residence time of sedimentary sequences under certain burial conditions is of key importance in determining the timing, extent and patterns of diagenetic modifications induced. The most important mesogenetic alterations include feldspar albitisation, illitisation and chloritisation of smectite and kaolinite, dickitisation of kaolinite, chemical compaction as well as quartz and carbonate cementation. Various aspects of deep-burial mesodiagenesis are still poorly understood, such as: (i) whether reactions are accomplished by active fluid flow or by diffusion, (ii) the pattern and extent of mass transfer between mudrocks and sandstones, (iii) the role of hydrocarbon emplacement on sandstone diagenesis, and (iv) the importance and origin of fluids involved in the formation of secondary inter- and intragranular porosity during mesodiagenesis. Uplift and incursion of meteoric waters induce telogenetic alterations that include kaolinitization and carbonate-cement dissolution down to depths of tens to a few hundred metres below the surface.

Paper II - The distribution of diagenetic alterations in the fluvial, deltaic and shallow marine, arkosic to subarkosic sandstones (average Q:2F:8L:2) of the Mullaghmore Formation (Carboniferous, NW Ireland) can be predicted within a sequence stratigraphic framework. Eogenetic calcite ($\delta^{18}$O$_{PDB} = -13.3\%_o$ to $-6.5\%_o$, $\delta^{13}$C$_{PDB} = -3.0$ to +3.4\%, and $^{87}$Sr/$^{86}$Sr = 0.706721 to 0.709227) and ferron dolomite (FeCO$_3 = 8-12$ mol\%; $\delta^{18}$O$_{PDB} = -14.2\%_o$ to $-7.8\%_o$, $\delta^{13}$C$_{PDB} = -1.4\%_o$ to $-1.0\%_o$, and $^{87}$Sr/$^{86}$Sr = 0.709051 to 0.709167) occur in bioclast-rich, transgressive lag deposits at parasequence boundaries and transgressive surfaces, and in wave-influenced, deltaic, highstand systems tract (HST) deposits. Mesogenetic illite, chlorite, baroque dolomite (FeCO$_3 = 16$ mol\%; $\delta^{18}$O$_{PDB} = -14.2\%_o$ to $-12.7\%_o$, $\delta^{13}$C$_{PDB} = -3.8\%_o$ to $-1.0\%_o$), quartz and calcite ($\delta^{18}$O$_{PDB} = -15.7\%_o$ to $-12.5\%_o$, $\delta^{13}$C$_{PDB} = -5.8\%_o$ to $-3.7\%_o$, and $^{87}$Sr/$^{86}$Sr = 0.709016 to 0.709122) were formed mainly in the bioclast-poor deposits, which were not pervasively cemented by carbonates during near-surface eodiagenesis. These
deposits include fluvial, incised-valley sandstones of lowstand systems tract (LST), and fluvial-dominated, deltaic sandstones of transgressive systems tract (TST) and HST. Illite is the dominant diagenetic clay mineral in the fluvial, incised-valley sandstones of LST, possibly because of simultaneous albitionization of K-feldspars. Conversely, chlorite, dominates in the fluvial-dominated, deltaic sandstones of TST and HST, because of the presence of suitable precursor clays.

**Paper III -** Study of the coal bearing, Rio Bonito Formation, early Permian, Paraná Basin (southern Brazil), revealed that the distribution of diagenetic alterations and related porosity evolution can be constrained in a sequence stratigraphic framework. The Rio Bonito Formation consists of lowstand systems tract (LST), deltaic (subarkose, Q\textsubscript{85}F\textsubscript{10}L\textsubscript{05}, average porosity = 10.8 %) sandstones, transgressive systems tract (TST), estuarine (subarkose, Q\textsubscript{86}F\textsubscript{10}L\textsubscript{02}, average porosity = 9.3 %) sandstones, and LST, TST and highstand systems tract (HST) shallow-marine (subarkose to quartzarenites, Q\textsubscript{82}F\textsubscript{13}L\textsubscript{07}, average porosity = 9.2 %) sandstones. Conglomeratic lag deposits occur at parasequence boundaries (sublitharenites, Q\textsubscript{87}F\textsubscript{04}L\textsubscript{09}) and at sequence boundaries and transgressive surfaces (sublitharenites, Q\textsubscript{80}F\textsubscript{13}L\textsubscript{07}). Diagenetic alterations that can be linked to sequence stratigraphy include: (a) calcite ($\delta^{13}$C\textsubscript{PDB} = -7.7‰ to -3.6‰ and $\delta^{18}$O\textsubscript{PDB} = -16.7‰ to -8.6‰) and pyrite cementation in sandstones in the vicinity of TST parasequence boundaries and transgressive surfaces, (b) formation of kaolinite and grain dissolution below sequence and parasequence boundaries and in the LST deltaic sandstones, and (c) siderite (average MgCO\textsubscript{3} = 7.8 mol%, CaCO\textsubscript{3} = 3.3 mol%, MnCO\textsubscript{3} = 3.7 mol%, and FeCO\textsubscript{3} = 85.3 mol%; $\delta^{13}$C\textsubscript{PDB} = -5.1‰ and $\delta^{18}$O\textsubscript{PDB} = -12.2‰) cementation in LST shoreface sandstones, and in sandstones and lag deposits in the vicinity of parasequence boundaries and transgressive surfaces. Some of these diagenetic alterations, such as tightly calcite cemented (> 20 vol%) sandstones above parasequence boundaries of the TST, can be detected in resistivity wire line logs. Cementation by ankerite (average FeCO\textsubscript{3} = 21 mol%, MgCO\textsubscript{3} = 21.3 mol%, CaCO\textsubscript{3} = 55.7 mol% and MnCO\textsubscript{3} = 1.8 mol%; $\delta^{13}$C\textsubscript{PDB} = -4.7‰ to -3.3‰, and $\delta^{18}$O\textsubscript{PDB} = -12.5‰ to -7.5‰), quartz, feldspars, and chlorite show no obvious distribution pattern according to the sequence stratigraphic framework.

**Paper IV -** The distribution pattern of early diagenetic clay minerals such as kaolinite, smectite, palygorskite, glaucony and berthierine, as well as of mechanically infiltrated clays and mud intralasts, is predicted in siliciclastic rocks using a sequence stratigraphic approach. Changes in relative sea-level and in sediment supply/sedimentation rate, together with the climatic conditions prevalent during and right after deposition of sediments control the type, abundance and spatial distribution of clay minerals by influencing the pore-water chemistry and the duration over which the sediments are submitted to a certain set of geochemical conditions. Diagenetic clay mineral distribution is constrained along sequence and parasequence boundaries, and within parasequences, parasequence sets and systems tracts.
**Paper V** – In this paper, we discuss the sequence stratigraphic distribution and origin of diagenetic clay minerals of the Upper Cretaceous sandstones of the Ferron Sandstone (Mancos Shale Formation) and the Tibbet Canyon (Straight Cliffs Formation) members. Mechanically infiltrated clays (up to 5 vol%) occur mainly in shoreface sandstones of the highstand systems tract lying immediately below (< 1 m) sequence boundaries. These sandstones also contain variable amounts of kaolinite. Kaolinite is, however, most abundant in distributary channels of delta plain and incised valley sandstones. Pseudomatrix (deformed mud and silt intraclasts owing to mechanical compaction; 5 to 20 vol%) occurs in lag deposits associated with parasequence boundaries, developed on delta plain and backshore, mud and silt deposits. The amounts and distribution pattern of these diagenetic clays in the vicinity of sequence and parasequence boundaries can have important consequences for reservoir quality evolution of sandstones about these surfaces.

**Paper VI** - Gas reservoirs of the Upper Miocene, Abu-Madi Formation (present-day depth ≈ 3350 m, temperature ≈ 116°C), the Nile Delta Basin, Egypt, consist of lowstand systems tract (LST) fluvial and transgressive systems tract (TST) estuarine sandstones deposited within an incised valley. These sandstones have a wide range of porosity (2 to 29%) and permeability (0.01 to 6071 mD), which reflect both depositional facies and diagenetic controls. Diagenetic events that influenced the reservoir-quality evolution include primarily the formation of extensive grain-coating Fe-Mg chlorite, local calcite cementation (δ¹⁸O = -13.5‰ to -6.0‰, δ¹³C = -14.3‰ to -1.0‰, and ⁸⁷Sr/⁸⁶Sr = 0.707124 to 0.708181), mechanical compaction of ductile grains, pressure dissolution of quartz, and quartz cementation. The chlorite coatings have preserved reservoir quality by inhibiting quartz cementation. However, high intercrystalline microporosity in the chlorite may account for the high water saturation (15-30%) encountered in the reservoirs. The TST estuarine sandstones have on average lower permeability than LST fluvial sandstones due to the finer grain-size and higher amounts of deformed ductile grains (e.g., micas, glaucony and mud clasts). Other diagenetic events that have little influence on reservoir quality include the more frequent formation of kaolin in the LST fluvial sandstones and formation of pyrite in the TST estuarine sandstones.

**Paper VII** - Modal petrographic analysis, textural criteria and petrophysical data were used to unravel the origin and timing of kaolinite formation and its impact on reservoir properties of Triassic sandstones of the Lunde Formation, Snorre Field, northern North Sea. Kaolinite formation occurred by the replacement of detrital feldspar, mica, rock fragments, mud intraclast and pseudomatrix. Some of the kaolinitisation occurred shortly after deposition, but most occurred during the Early Cretaceous regional uplift and formation of the Late Cimmerian unconformity. Kaolinite stable isotopic data (δ¹⁸O SMOW = +13.9‰ to +18.5‰, and δD SMOW = -83‰ to -69‰) support kaolinite formation from Early Cretaceous meteoric waters. Kaolinite content in the sandstones increases from less than 5 to up to 20 vol.% within the first
200 m below the unconformity and average total porosity was enhanced by about 5%. Where mudstones were present between the unconformity and the Triassic sandstones, meteoric water flushing and, hence, kaolinite formation were limited. However, in some cases, kaolinitisation in sandstones buried under thick mudstones was aided by major normal faults that were hydraulically connected to the unconformity surface. The lack of a negative correlation between kaolinite and feldspar contents is attributed to: (i) the presence of other kaolinite sources than feldspar (pseudomatrix, mica, mud intraclast and rock fragments), (ii) the strong variations in the initial detrital mineralogical composition of the sandstones, and (iii) to mass transfer of Si and Al ions on scales greater than that of the thin section.

CONCLUSIONS

This thesis has demonstrated that integration of diagenesis and sequence stratigraphy allows a better prediction of the spatial and temporal distribution of diagenetic alterations in siliciclastic sequences, and contraining of reservoir quality evolution of sandstones. Diagenetic minerals such as calcite, dolomite, siderite, pyrite, kaolinite, glaucony, and berthierine, and formation of pseudomatrix, mechanical clay infiltration, and intragranular porosity showed a systematic distribution in sandstones lying in the vicinity of sequence and parasequence boundaries, transgressive and maximum flooding surfaces, and in sandstones of the lowstand, transgressive, and highstand systems tracts. The main sequence stratigraphic controls on the distribution and type of diagenetic alteration are: (i) detrital composition (mainly the proportion and type of intra- and extrabasinal grains), (ii) pore water chemistry, (iii) presence and quantity of organic matter, and (iv) residence time of the sediments under specific geological and geochemical conditions. Other important parameter, although not controlled by sequence stratigraphy, is paleoclimate.

Near-surface diagenetic alterations related to sequence stratigraphy may exert strong, often predictable influence on the burial diagenesis and related evolution of reservoir quality in sandstones. Parasequence boundaries are, for instance, common sites for pervasive cementation, and thus porosity and permeability deterioration. Sandstones and lag deposits in the vicinity of such surfaces may, thus act as potential diagenetic baffles or barriers (reservoir seals) for vertical fluid flow, and are likely to form reservoir compartments between two juxtaposed sandstones of adjacent parasequences. Porosity of sandstones lying below sequences boundaries can be deteriorated or enhanced (by formation of intragranular porosity), but permeability is commonly deteriorated. Sequence boundaries are, thus, also potential baffles and barriers for vertical fluid flow. Among systems tracts, sandstones of transgressive systems tract are the most prone to have near-surface porosity deterioration owing to
their greatest potential for having carbonate cements. Fluvial sandstones of lowstand systems tract have, however, highest chances for porosity enhancement owing to the formation of intragranular porosity.

Finally, it is suggested here that the hypothesis and principles presented in this thesis should be tested in a larger variety of basinal settings and depositional environments, such as those of continental origin. It is an even greater challenge to apply these concepts to deep water turbidite deposits of lowstand systems tract, which constitute the ultimate frontier for oil exploration.

REFERENCES


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