PSSediment Compaction and Rock Properties*

Knut Bjorlykke[1], Jens Jahren[1], Nazmul Haqui Mondol[1], Oyvind Marcussen[1], Delphine Croize[1], Christer Peltonen[1], and Brit Thyberg[1]

Search and Discovery Article #50192 (2009)
Posted June 29, 2009

*Adapted from poster presentation at AAPG International Conference and Exhibition, Cape Town, South Africa, October 26-29, 2008

[1] Department of Geoscience, University of Oslo, Oslo, Norway (mailto:knut.bjorlykke@geo.uio.no)

Abstract

Compaction of sediments is driven towards lower porosities and higher densities as a function of increasing stress and chemical reactions. Mechanical processes are controlled by the effective stress and chemical compaction by dissolution and precipitation of solids. Chemical compaction is a function of thermodynamics and kinetics and silicate reactions are very slow and sensitive to temperature. Chemical compaction of siliceous sandstones is modelled based on the assumption that the precipitation of quartz and other cements are the rate limiting steps. This is therefore a function of temperature and nearly independent of the stress.

Quartz cementation is probably also important in the compaction of siliceous mudstones. The kinetics of carbonate precipitation is much faster and less dependent on temperature and probably more dependent on effective stress (pressure solution) and stylolite formation. Carbonate compaction is however poorly understood and the relation between stress and both mechanical and chemical compaction is difficult to model. Experimental compaction of artificial and natural samples provides valuable constraints on the mechanical compaction processes. The compressibility and the velocity vary considerably with changes in primary sediment composition, particularly in mudstones. Modelling of mechanical and chemical compaction requires detailed input about mineralogy and textural relations which are difficult to predict prior to drilling. We have therefore used well data and mineralogical analyses from the North Sea Basin to establish compaction and velocity trends for different lithologies and burial histories. This provides a basis for prediction of porosity and density for basin modelling and velocity distributions for seismic modelling and interpretations.

Sediment Compaction and Rock Properties

Knut Bjørlykke, Jens Jahren, Nazmul Haque Mondol,
Øyvind Marcussen, Delphine Croizé, Christer Peltonen & Brit Thyberg

Department of Geosciences, University of Oslo
P.O. Box 1047, Blindern, Oslo, Norway
E-mail: knut.bjorlykke@geo.uio.no

1. Abstract

Compaction of sediments involves complex processes causing reduced porosity, increased density and other physical properties such as bulk modulus and velocity. Mechanical compaction processes are controlled by the effective stress and laboratory tests provide useful data on the mechanical compressibility of sediments with different mineralogical and textural compositions and fluid properties. In deep cold basins mechanical compaction is the most critical factor. Experimental compaction of artificial and natural samples provides valuable constraints on the mechanical compaction processes. The compressibility and the velocity vary considerably with changes in primary sediment composition, particularly in mudstones. Coarse grained clays consisting mostly of kaolinite are more compressible than fine grained clays such as smectite and illite.

Chemical compaction occurs by dissolution and precipitation of solids and are controlled by thermodynamics and kinetics. Constraints on mass transport by fluid flow and diffusion indicate that diagenetic reactions are isochemical particularly at greater depth. Silicate reactions are very slow and sensitive to temperature. At temperatures above (80-100°C) quartz cementation and clay mineral alterations stiffens the rocks so that it siliceous sediments becomes “overconsolidated” preventing further mechanical compaction. Compaction at greater depth must therefore be modelled as a function of temperature integrated over time.

The kinetics of carbonate precipitation is much faster and less dependent on temperature and probably more dependent on effective stress (pressure solution) and stylolite formation. Carbonate compaction is however poorly understood and the relation between stress and mechanical and chemical compaction is difficult to model.

Chemical compaction of siliceous sandstones is modelled based on the assumption that the precipitation of quartz and other cements are the rate limiting steps. This is therefore a function of temperature and nearly independent of the stress. Modelling of mechanical and chemical compaction requires detailed input about mineralogy and textural relations which are difficult to predict prior to drilling. Prediction of reservoir and other rock properties should be based both on the analysis of provenance, facies and burial history.

Sediment Compaction and Rock Properties

Knut Bjørlykke, Jens Jahren, Nazmul Haque Mondol,
Øyvind Marcussen, Delphine Croizé, Christer Peltonen & Brit Thyberg

Department of Geosciences, University of Oslo
P.O. Box 1047, Blindern, Oslo, Norway
E-mail: knut.bjorlykke@geo.uio.no

2. Introduction

Sediment compaction is critical for basin modeling since it determines the rate of density and velocity increases as a function of depth for different lithologies. Rock physical properties vary greatly as a function of primary sediment composition and burial history. Sediment compaction is driven towards higher density (lower porosity) by mechanical compaction following the laws of rock and soil mechanics and by chemical compaction controlled by thermodynamics and kinetics (Fig. 1). The primary sediment composition is a function of provenance and sedimentary facies and the distribution of clay minerals are different in the proximal and distal facies. Each lithology has a different compaction trend and the changes in physical properties as a function of depth reflect both changes in the primary composition and mechanical and chemical compaction processes. The observed trends may be rather different from exponential curves (Fig. 2). These two compaction processes are principally very different and must be modeled separately also when predicting reservoir properties (Fig. 3).

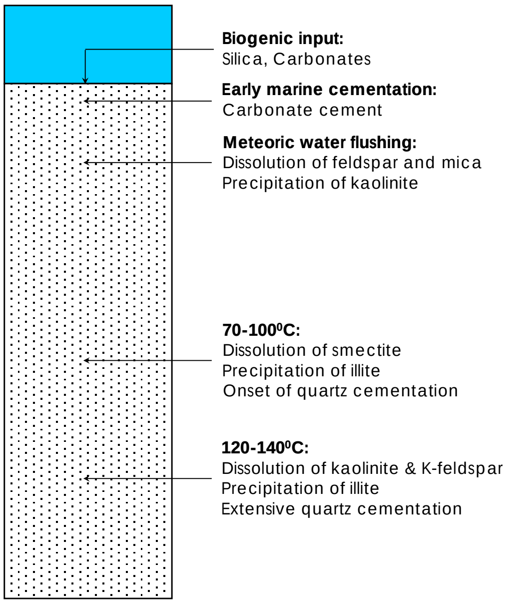

Fig. 1. Main diagenetic processes for sandstones and clays. Near surface diagenesis is geochemically open due to ground water flow or evaporation. Burial diagenesis occur in a closed system due to limited fluid flow and diffusion.

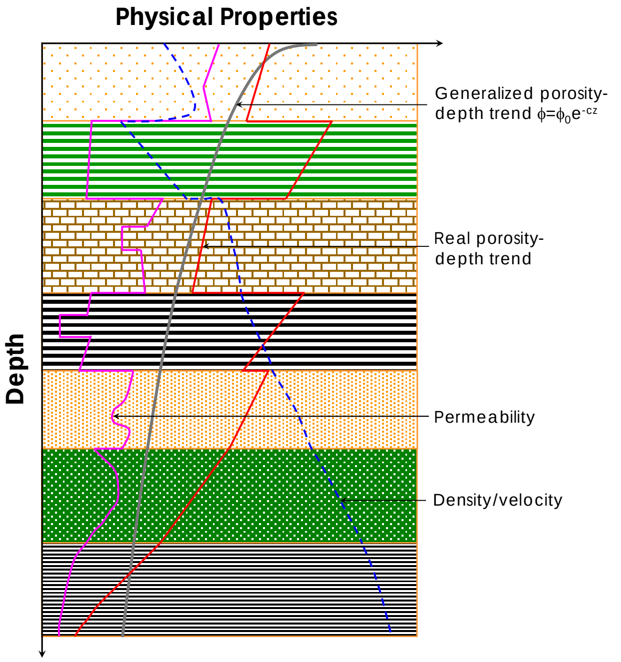

Fig. 2. A lithological unit will compact as functions of increasing stress and temperature so that the porosity will decrease at a rate controlled by the initial composition of sediments. Increased porosity can only result from shallow meteoric water leaching and uplift and extension.

Physical parameters of sedimenray rocks: Interpreting compaction trends from well logs for different lithologies

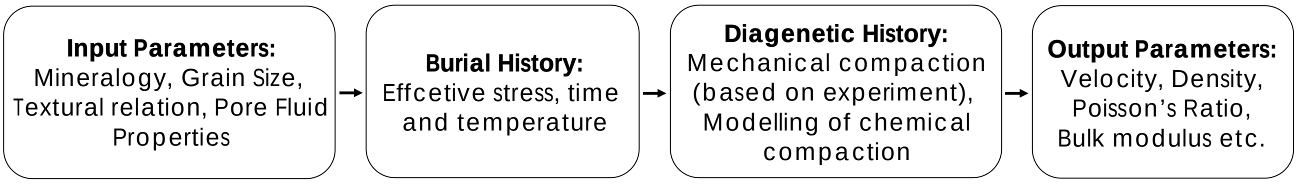
Input Parameters: Mineralogy, Grain Size, Textural relation, Pore Fluid Properties → **Burial History:** Effcetive stress, time and temperature → **Diagenetic History:** Mechanical compaction (based on experiment), Modelling of chemical compaction → **Output Parameters:** Velocity, Density, Poisson’s Ratio, Bulk modulus etc.

Fig. 3. Forward medelling: Physical properties of sedimentary rocks.

Sediment Compaction and Rock Properties

Knut Bjørlykke, Jens Jahren, Nazmul Haque Mondol,
Øyvind Marcussen, Delphine Croizé, Christer Peltonen & Brit Thyberg

Department of Geosciences, University of Oslo
P.O. Box 1047, Blindern, Oslo, Norway
E-mail: knut.bjorlykke@geo.uio.no

3. Compaction of sands and sandstones

Compaction of sands is a function of the mechanical strength of the grains. Well sorted quartz rich sandstones are more compressible than well sorted fine grained quartz sand (Fig. 4). It has been shown that coarse grain sands are more fractured than the fine grained sand and this may be due to higher stress per grain contact. Softer carbonate grains such as ooids are less compressible because the grain contact becomes relatively large at low to moderate stress (Fig. 5). Quartz cementation (T>80-100°C) causes an increase in rocks strength resulting in an "over consolidation" (Fig. 6 and 7). Further compaction is therefore mostly chemical at a rate which is mostly a function of temperature.

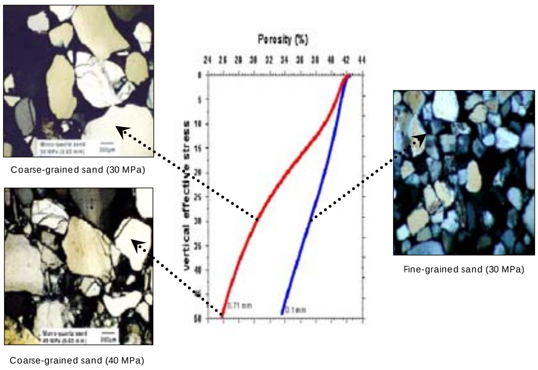

Fig. 4. Porosity loss in sands due to mechanical compaction. Fine-grained sand compact more than coarse-grained sand (Chuhan et al., 2002, Marine & Petroleum Geology). .

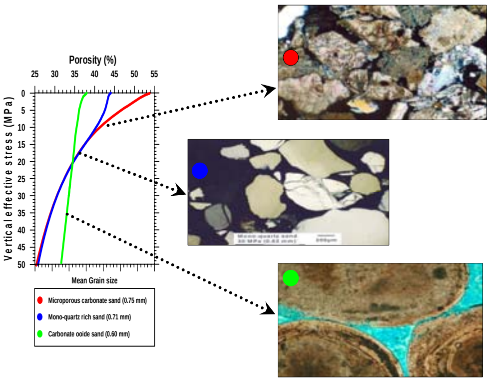

Fig. 5. Experimental compaction of quartz sand and carbonate ooids. Carbonate ooids have lower compressibility than quartz sands (Chuhan et al., 2003, Canadian Geotechnical Journal).

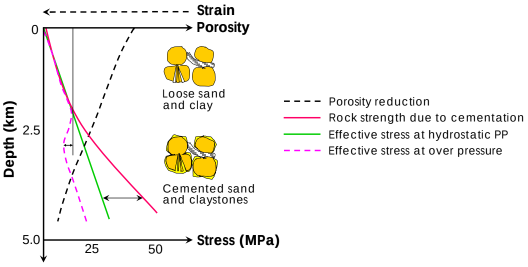

Fig. 6. Compaction of sands (Bjørlykke et al. 2004, Coupled thermo-hydro-mechanical-chemical processes in geosystems, Elsevier publication).

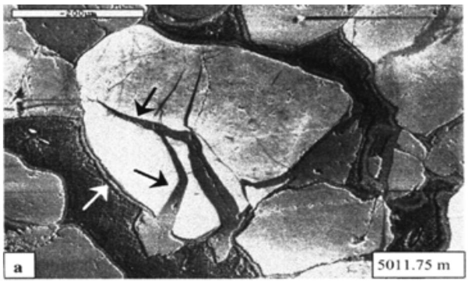

Fig. 7. CL image of Tilje Formation (Haltenbanken area, offshore Norway) showing numerous fractures healed by quartz cement (black arrows) but chlorite coating (white arrow) prevented quartz cementation (Chuhan et al. 2002, Marine & Petroleum Geology).

4. Compaction of clays

Compaction of clays is strongly influenced by the clay mineralogy, pore fluid composition and burial history (Fig. 8). Experimental compaction shows that smectitic clays are less compressible and has lower velocities and permeabilities than kaolinitic clays (Fig. 9 and 11). The physical properties of mudstones vary greatly with depth and mineralogy plays a significant role to control compaction (Fig. 12, 13 and 14). The low compressibility of fine grained clays like smectite is due to the total stress is distributed on a very large number of clay contacts (Fig. 9). The smectite to illite reaction (Fig. 8) may produced significant amounts of micro-quartz cement (Fig. 10), which may have contributed to the increase in velocity without significantly reducing the porosity or increasing the density of the mudstones.

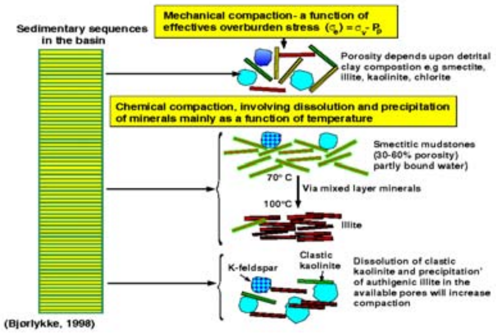

Fig. 8. Schematic representation of mechanical and chemical compaction of mudstones (Bjørlykke, 1998, Clay Minerals).

Sediment Compaction and Rock Properties

Knut Bjørlykke, Jens Jahren, Nazmul Haque Mondol,
Øyvind Marcussen, Delphine Croizé, Christer Peltonen & Brit Thyberg

Department of Geosciences, University of Oslo
P.O. Box 1047, Blindern, Oslo, Norway
E-mail: knut.bjorlykke@geo.uio.no

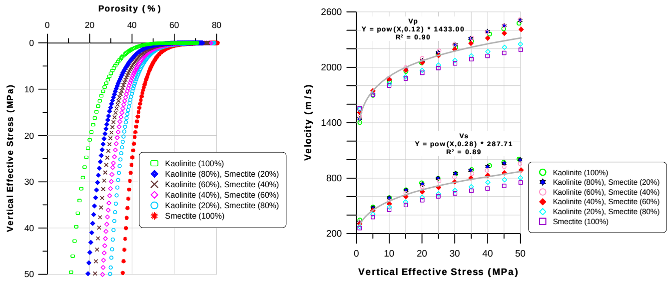

Fig. 9. Porosity and velocity versus effective stress of brine-saturated smectite -kaolinite mixtures (Mondol et al., 2007, Marine & Petroleum Geology).

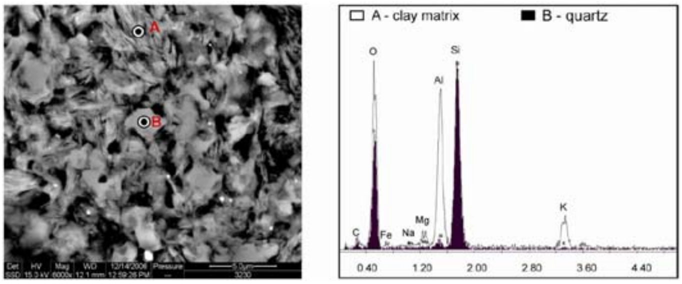

Fig. 10. FEG-SEM backscatter electron imaging and EDS; A) clay matrix; B) micro-crystalline authigenic quartz (Peltonen et al., 2008, Petroleum Geoscience).

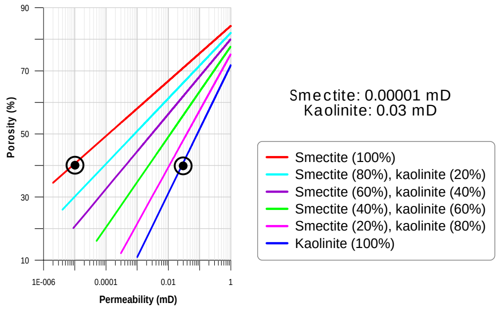

Fig. 11. Porosity-permeability relationships of reconstituted mudstones. The permeability varies by 4-5 orders of magnitude (Mondol et al. 2008, Petroleum Geoscience).

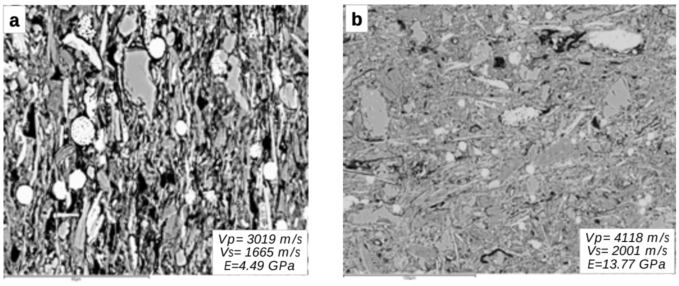

Fig. 12. SEM micrographs of Lange Formation, Holtenbanken, offshore Norway from two different depth a) 2511.42 m and b) 4479.33 m.

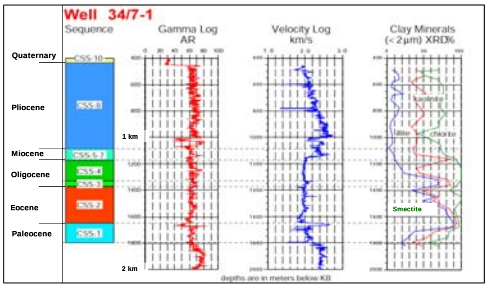

Fig. 13. Relationships between seismic stratigraphic units, velocity and clay mineralogy in well 34/7-1. The Plio-Pleistocene sediments show a strong increase in velocity with depth but this is not the case in the Eocene and Oligocene smectite-rich sediments (Thyberg et al., 2000, Geological Society Special Publication, No. 167.

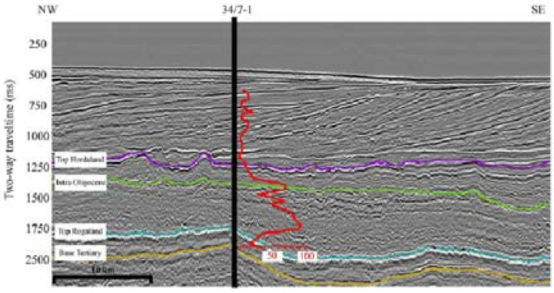

Fig. 14. A seismic section (NVGTI-92-105A) with well tie. Red curve indicates the smectite content. The seismic signature is very different in smectite-rich sequences compared to upper and lower units. (Marcussen et al., 2008, AAPG Bulletin, In press).

5. Compaction of carbonates

Carbonates contain more unstable and reactive components than silisiclastic sediments. In carbonates, the kinetics of precipitation is relatively fast also at low temperatures. Dissolution may then be rate limiting and therefore compaction may be more sensitive to changes stress. Chemical processes involve in carbonate diagenesis can be separated in two groups: early diagenesis and pressure solution. Early diagenesis involves dissolution, mineralogical stabilization of aragonite and magnesium calcite to low-Mg calcite. Sixteen core-plugs from the Marion Plateau were tested with vertical stress of 0-70 MPa, as lateral strain was kept equal to zero. Results show very little strain (Fig. 15). The second important chemical process is the pressure solution. The effect of purely mechanical compaction on carbonate sand was investigated and compared to published porosity–depth trends of carbonate sediments deposited with high porosity (Fig. 16). Experiments, at vertical stress 0–32 MPa, show that mechanical compaction alone can not explain porosity loss in sedimentary basins. The rate of porosity loss in carbonate sediments having high porosity at deposition time is far more important in nature than in experiment.

Sediment Compaction and Rock Properties

Knut Bjørlykke, Jens Jahren, Nazmul Haque Mondol,
Øyvind Marcussen, Delphine Croizé, Christer Peltonen & Brit Thyberg

Department of Geosciences, University of Oslo
P.O. Box 1047, Blindern, Oslo, Norway
E-mail: knut.bjorlykke@geo.uio.no

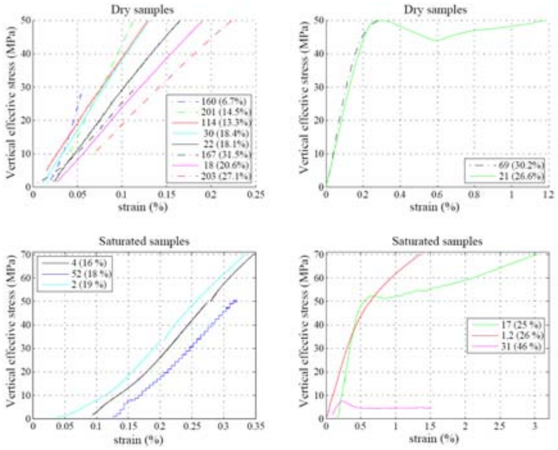

Fig. 15. Stress-strain relationships of sixteen core-plugs from the Marion Plateau, offshore northeast Australia (Croizé et al. 2008, in prep.).

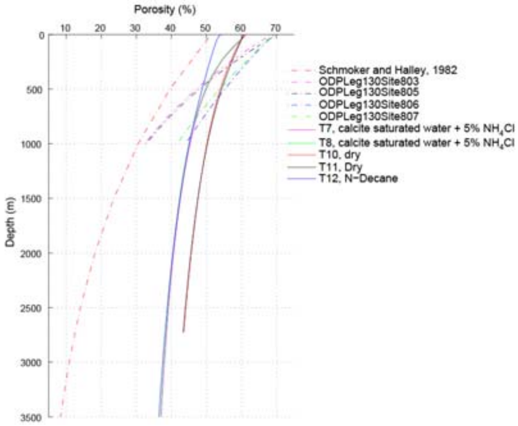

Fig. 16. A comparison of natural compaction trends of carbonates and experimental compaction trends of carbonate sands (Croizé et al. 2008, in prep.).

6. Conclusions

- Burial diagenesis is driven towards higher mechanical and chemical (thermodynamic) stability. The reduction in porosity at a function of stress varies greatly as functions of mineralogy, sorting and grain size and can be tested experimentally.
- Chemical compaction is controlled primarily by the mineralogical and textural composition. In sandstones and siliceous mudstones the rate of compaction is controlled by the kinetics and thereby the temperature. The physical properties of mudstones vary greatly as a function of the clay mineralogy and also the composition of pore fluids.
- Compaction of carbonate is still poorly understood and it is difficult to determine the relative influence of stress and temperature. Mass transfer is constrained by water flow and diffusion rates, particularly at greater depth and diagenetic reaction are nearly isochemical.
- As a consequence the porosity (rock volume) of a given lithology will always decrease during deeper burial. Increases in porosity must be due to dissolution at shallow or extension due to unloading.
- Forward modelling of compaction is very sensitive to small changes in the primary sediment composition. Diagenetic models must be calibrated by well log data for different lithologies.

Stress in passive margin basins with mostly siliceous sediments

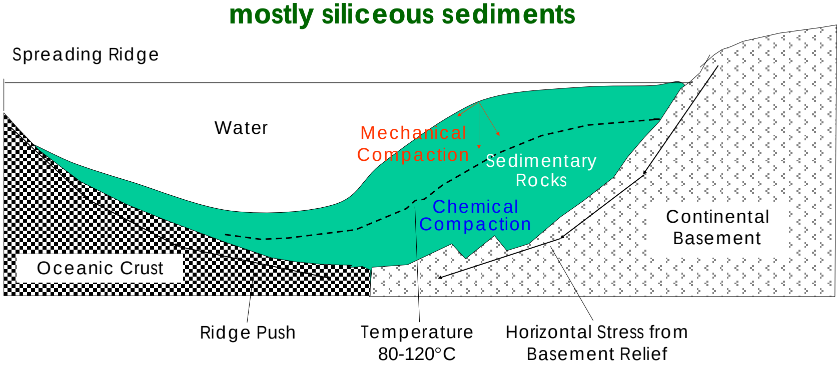

Fig. 17. Schematic diagram in a passive margin basin. Most of the tectonic stress is transmitted through the basement and the well cemented sedimentary rocks. In the case of ice loading the strain rates are relatively high and the response in sediments will be mostly mechanical compaction. Gravitational stress may however be important [modified after Bjørlykke, 2006 (Geological Society Special Publication, No. 253).

Selected References

Bjorlykke, K., 2006, Effects of compaction processes on stresses, faults, and fluid flow in sedimentary basis; examples from the Norwegian Margin: Geological Society Special Publications, v. 253, p. 359-379.

Bjorlykke, K., J. Jahren, N.H. Mondol, 2004, Mechanical and chemical compaction processes in siliceous and carbonate rocks; a comparison: International Geological Congress Abstracts – Congres Geologique International Resumes, v. 1, p. 163.

Bjorlykke, K., L. Grande, and A. Kjeldstad, 2004, Properties of faults in subsiding sedimentary basins; examples from the Haltenbanken offshore Norway and the North Sea: AAPG, Pages; unpaginated.

Bjorlykke, K., Y.G. Gundersen, and J. Jahren, 2004, Compaction driven fluid flow in overpressured compartments: Annual Meeting Expanded Abstracts AAPG, v. 13, 14 p.

Bjorlykke, K., 1998, Clay mineral diagenesis in sedimentary basins; a key to the prediction of rock properties, examples from the North Sea Basin: Clay Minerals, v. 33/1, p. 15-34

Chuhan, F.A., A. Kjeldstad, K. Bjorlykke, and K. Hoeg, 2003, Experimental compression of loose sands; relevance to porosity reduction during burial in sedimentary basins: Canadian Geotechnical Journal = Revue Canadienne de Geotechnique, v. 40/5, p. 995-1011.
DOI: http://dx.doi.org/10.1139/T03-050

Chuhan, F.A., A. Kjeldstad, K. Bjorlykke, and K. Hoeg, 2002, Porosity loss in sand by grain crushing; experimental evidence and relevance to reservoir quality: Marine and Petroleum Geology, v. 19/1, p. 39-53.

Croize, D., K. Bjorlykke, D.K. Dysthe, F. Renard, and J. Jahren, 2008, Deformation of carbonates, experimental mechanical and chemical compaction: Geophysical Research Abstracts, v. 10.

Marcussen, Ø., Thyberg, B.I., Peltonen, C., Jahren, J., Bjørlykke, K. & Faleide, J.I., 2009, Physical properties of Cenozoic mudstones from the northern North Sea: Impact of clay mineralogy on compaction trends, AAPG Bulletin, v. 93, p. 127-150.

Mondol, N.H., Bjørlykke, K., Jahren, J., and Høeg, K., 2007, Experimental Mechanical Compaction of Clay Mineral Aggregates - Changes in Physical Properties of Mudstones during Burial: Marine and Petroleum Geology, v. 24, p. 289-311.

Peltonen, C., O. Marcussen, K. Bjorlykke, and J. Jahren, 2008, Mineralogical control on mudstone compaction; a study of Late Cretaceous to early Tertiary mudstones of the Voring and More Basins, Norwegian Sea: Petroleum Geoscience, v. 14/2, p. 127-138.

DOI: http://dx.doi.org/10.1144/1354-079308-758

Thyberg, B. I., H. Jordt, K. Bjørlykke and J. I. Faleide, 2000, Relationships between sequence stratigraphy, mineralogy and geochemistry in Cenozoic sediments of the northern North Sea: Geological Society, London, Special Publications, v. 167, p. 245-272.
DOI: http://dx.doi.org/10.1144/GSL.SP.2000.167.01.10