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Pore geometry as an indicator of depositional texture and velocity variations in chalks

By

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Abstract I

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Pore Geometry as an Indicator of Depositional Texture and Velocity Variations in Chalks

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SUMMARY

The complex pore geometry in carbonates makes their velocity behavior difficult to predict. Integration of geology information can help to make a predictive pattern for pore geometry and as a result for velocity. In this paper, based on available diagenetic models for chalks, an integrated modeling strategy is developed for velocity variation in a mineralogically uniform chalk. It can be shown that different depositional texture in chalks can be expressed by different depositional pore aspect ratio. This depositional aspect ratio transforms to other aspect ratio by post-depositional processes. This transformation of pore aspect ratio in chalks can be predicted from geology information and mostly from foraminifer s contents and sorting information of the sediment.

Mechanical compaction and cementation although both decrease porosity with depth but may increase the velocity by different rates, since one makes more compliant pore throats while another one close cracks and makes stiffer pore bodies, respectively. These show the relevance of pore geometry consideration in velocity interpretation, since some variations in velocity data may results from pore geometry (depositional texture) and its transformation (post-depositional process) through different diagenetic environments rather than mineralogy, fluid or porosity.

Introduction

Understanding the correlation between seismic parameters and reservoir properties are important for exploration and production studies. In this paper, we address the relevance of selecting textural parameters resulted from diagenesis in carbonates. In particular a modeling strategy is discussed for a set of well data from Leg130 site 807 of Ocean Drilling Program (ODP) for chalks as deep basin carbonates. Pore aspect ratio is an implication of pore geometry in rocks which has application ranges from hydrocarbon reservoir characterization to environmental issues. In velocity modeling as the choice of pore aspect ratios are crucial but for a fixed velocity quite a wide range of aspect ratios are applicable in a uniform mineralogical rock. There are some qualitative and quantitative methods for describing the various aspects of pore space and assessment of the porosity distribution which has their own advantage and disadvantage. In this study, we have tried to link pore aspect ratio at various depths to depositional and post-depositional processes in chalks. It uses the changes in microstructure during burial and links it to a pore aspect ratio transformation.

Chalk deposition and porosity

Chalk deposition as with other carbonates, is very sensitive to changes in oceanographic conditions and such changes result in variations in reservoir properties. The influence of depositional on reservoir properties can be linked to texture and mineralogy (Fabricius et al., 2007) and in a mineralogically uniform chalk, just to the texture. Texture is a category that includes several features of the constituent particles like, size, sorting, packing, fabric, shape and roundness (Gutierrez et al., 2002). Dunham (1962) accounts for particle size and sorting by dividing particles into grains (in chalks foraminifers>20µm) and mud (in chalks coccoliths<20µm). Packing (cubic to rhombohedral) also plays an important role in diagenetic potential and reservoir property variations for a given rock type. Based on these definitions and observations of other authors (e.g. Fabricius, 2003), it is possible to link different porosity type and pore-aspect ratio in chalks as follows.

- **Grain porosity:** refers to intragrain porosity (inside foraminifers) and is insensitive to pressure changes. It represents the very stiff pores. For instance, grainstones have higher amounts of grain porosity and stiffer pores than packstone, wackstone and mudstone.
- **Matrix porosity:** refers to interparticle porosity (between coccoliths, foraminifers or both in mud-supported and/or grain-supported rock types). It ranges from stiff to compliant pores and is strongly dependent on overburden pressure. Due to their complex morphology, these pore spaces are normally considered as relatively large nodes connected by narrow throats.
  - ✓ **Matrix porosity/pore body:** This is the main and stiffer part of interparticle porosity. It contains most of the matrix porosity.
  - ✓ **Matrix porosity/pore throat:** The connection between two pore bodies in interparticle porosity is considered as a pore throat. The number, size and distribution of the pore throats control many of the resistivity, flow and capillary-pressure characteristics of the rock.

Chalk diagenesis

Chalk diagenesis has been addressed by many authors (e.g. Fabricius, 2003). They described diagenetic models that show sediment changes from ooze at sea bottom to compacted lime at large depths. The different induration of the sediments through depth make different intervals named as ooze, chalk and limestone (e.g. Kroneke et al. 1991). In the ooze interval, mechanical compaction is the dominant process, while at the end of this interval meniscus cementation or contact cements can make a strong framework that may prevent more porosity reduction. Chalk interval is the place where mechanical compaction, recrystallization,

chemical compaction and marine cementation may be active. They will reduce porosity and change rock elastic properties. Lime interval starts when huge amounts of cements are introduced into the rock. This occluding cementation will reduce porosity by filling in the pore bodies and pore throats. Early hydrocarbon introduction, strong contact cement and high pore pressure may halt diagenesis and keep high porosity for chalks even in deep burial intervals (e.g. Grutzner and Mienert, 1999).
Foraminifera's wall breaks during burial diagenesis. This changes the grain porosity to matrix porosity. Compaction and cementation in different depths will cause porosity reduction in different ways for either type of porosities. Such effects have significant impact on pore aspect ratio and velocity.

Effective medium modeling

Sonic velocity is a function not only of total porosity, but also of the predominant pore type (e.g. Wang, 1997) and as discussed earlier, different pore aspect ratios can be assigned to different textures in chalks. This shows that sonic velocity can be used as a texture indicator in chalks. Deep burial diagenesis changes porosity as well as pore type with increasing depth, temperature and time in a way initial contact points (high porosity) changes to circles of finite

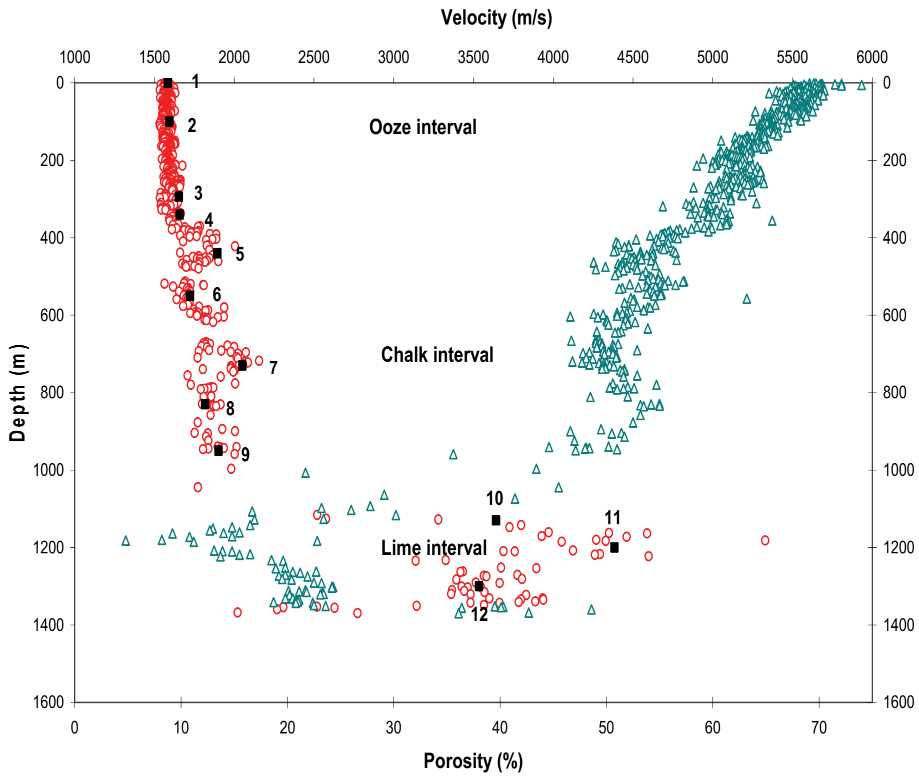

Figure 1 Real P-velocities (Red circles), porosities (Green triangles) and modeled P-velocities (Black square) of site 807 Leg 130 of the Ocean Drilling Program (ODP).

area (low porosity) by diagenesis. These dynamic changes in pore type result in velocity variabilities that do not follow the regular depth-wise pattern. ODP/Leg130 data site 807 is chosen to evaluate and apply pore aspect ratio transformation strategy on velocity calculation.

Velocity is modeled by using a self-consistent approximation of effective moduli (Mavko et al., 1998). Based on variations observed in real velocity data, twelve depth points are chosen to be modeled (Table 1). Bulk modulus, shear modulus and density for solid phase (calcite) and fluid phase (water) are chosen as 71 GPa, 30 GPa, 2.71 g/cm^3 and 2.3 GPa, 0 GPa, 1.02 g/cm^3, respectively. For each point one aspect ratio is considered based on the depositional and post-depositional history of the rock. Results are shown in Figure1 and are compared with real velocity measurements. Information related to each of the modeled points is presented in Table 1.

No.	Depth (m)	Φ (%)	Aspect ratio concentration-F(α) (%)				V_{pm} (m/s)	V_{pr} (m/s)	Description
			α= 1	0.1 / 0.8	0.01	0.001			
1	0	72	32	55 (0.1)	13	0	1584	1575	Critical porosity
2	100	65	30	63 (0.1)	6	1	1594	1575	Mechanical compaction
3	290	63	28	65 (0.1)	6.5	0.5	1653	1655	Contact cementation
4	340	58	20	72 (0.2)	6	2	1658	1960	Compaction
5	440	52	46	48 (0.2)	5	1	1894	1900	Higher fraction of forams
6	550	51	15	67 (0.3)	9	9	1723	1680	High pore throats
7	730	50	48	47.5(0.4)	4	0.5	2052	2050	Higher fraction of forams
8	830	50	28	57 (0.4)	12	3	1818	1850	High pore throats
9	950	46	28	62 (0.5)	7	3	1902	1900	Reduce forams
10	1120	20	10	35 (0.8)	55	0	3642	3700	Huge occluding cements
11	1200	13	0	84 (0.2)	16	0	4384	4500	Well-sorted limestone
12	1300	21	0	79 (0.8)	21	0	3535	3500	

Table 1 Properties of different depth modeled velocity points. Φ is porosity in percentage, α is the aspect ratio and F (α) is concentration of aspect ratio α in percentage of total porosity. V_{pm} is modeled P-wave velocity in m/s and V_{pr} is the mean real velocity in m/s.

Pore aspect ratio interpretation

At sea bottom (point one), grain porosity (α=1) is calculated from foraminiferal contents. At this point foraminiferal content is about 31% (Kroenke et al., 1991) and about 80% of each foraminifera is empty (Schlanger and Douglas, 1974). This means about 32% percent of total porosity is intragrain porosity. The rest of the porosity will be matrix porosity which is divided into pore body (α=0.1) and pore throats (α=0.01). These matrix pore aspect ratios will change by mechanical compaction and cementation toward more compliant and stiffer pores, respectively. Overburden pressure and dissolution break forams walls and this changes grain porosity (α=1) to matrix porosity (α=0.1 and α=0.01). Mechanical compaction reduces porosity in the ooze interval as well as pore aspect ratio of most compliant parts of the porosity. This is described by introducing a new aspect ratio (α=0.001) into the system at point two.

At points three and four foraminiferal content reduces from 25% at point two to 23% and 15% and as a result grain porosity reduces from 20% to 18% and 15%, respectively. Mechanical compaction is the dominant diagenetic process, in this area while at some higher depth contact cementation starts to create stiffer pore bodies. They mostly affect compliant pores (α=0.01) and reduce their amount, while mechanical compaction reduces their aspect ratio (to α=0.001). At point five and seven foraminiferal contents increases probably due to the higher productivity of foraminifera at deposition time. This induces poor sorting in the sediment (grain size) and decreases matrix porosity that results in changes from mudstone to packstone. By increasing depth at points six, eight and nine (chalk interval) foraminiferal again start to decrease and as a result grain porosity decreases. Compaction and marine cementation are the dominant diagenetic processes in this area. They reduce matrix porosity and mostly pore throats (compliant parts) while the pore body amount is almost the same. Cementation increases the aspect ratio of pore bodies, while mechanical compaction decreases aspect ratio of pore throats. Limestone interval starts by introducing huge amount of cement into the matrix and especially pore bodies. This will result in a sharp increase in velocity. Most of the velocity fluctuation in this interval is a result of porosity changes but still the effect of sorting can be observed. There are no grains (foraminiferal content) at this depth so that sorting mostly refers to packing. Geology report of this site (Kroenke et al., 1991) mention point eleven as well sorted limestone compared to points ten and twelve. This means point eleven has cubic packing while points ten and twelve have rhombohedric packing. Cubic packing has lower coordination number (4) as well as lower frame stiffness. This makes less pore throat concentration and less pore body aspect ratio for point eleven. These sorting differences may result from primary sedimentation or winowing during deposition. This change in sorting is identified by the pore aspect ratio in Table 1.

Conclusion

Microstructure changes have direct relationship with pore aspect ratio transformation. By considering these changes that mostly come from depositional and post-depositional environments, it is possible to find a predictive model for aspect ratio transformation. Such models may help better predicted velocity variations due to textural changes in a mineralogically uniform chalk. Depositional pore aspect ratio for grain porosity, pore body and pore throats may differ in different rock physics models, but their general trend for transformation is the same in different post-depositional environments.

Acknowledgment

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SEG extended abstract:

Rock physics interpolation used for velocity modeling of chalks: Ontong Java Plateau example

By

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Abstract II

Rock physics interpolation used for velocity modeling of Chalks: Ontong Java plateau example

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Summary

Pore geometries of carbonates are more complex than that of siliciclastics. This complexity makes their velocity interpretation and consequently their reservoir characterization more difficult than for sandstones. In this paper, we try to reduce this complexity by combing geological information and rock physics modeling. This strategy leads to a predictive model for pore aspect ratio changes within the whole area. Well and core data from Ontong Java plateau, which has been drilled by DSDP/ODP project are used to examine this approach. The pore texture seems to follow a predictive pattern in chalks of Ontong Java plateau and it can be predicted and modeled by geology information.

Introduction

To create a subsurface image by seismic measurements, we need to understand elastic wave propagation in the subsurface. Based on the interpretation of these images, we wish to extract the types and depths of geological structures and lithologies, as well as fluid information. Such details need a rock physics bridge between seismic data and the lithology and reservoir properties. The major goal of a rock physics model is to understand how lithology, porosity, pore geometry, pore fluid type and saturation, etc. influence on the velocities and attenuations of P and S waves in sedimentary rocks, and vise versa.

The wide spectrum of depositional environments and post-depositional processes in carbonates make their pore structure more heterogeneous than found in siliciclastics. This heterogeneity increases the complexity in velocity modeling and, thus, in understanding their rock physics behavior. Geological based strategies in velocity modeling can help to overcome some of these complexities. In this paper, we tried to model the velocity of Ontong Java plateau by using geology to constrain the rock physics model.

The Ontong Java Plateau is a huge oceanic plateau located in the Pacific Ocean and covers an area of approximately 2,000,000 km² (Figure 1). A sequence of deep sea carbonate sediments from carbonate ooze to chalks to limestones are sampled from this plateau during DSDP and ODP different phases.

Chalk deposition and diagenesis

Chalk sediments mostly occur in the deep basin environments and their physical properties are mainly controlled by overall porosity reduction from burial diagenesis environments (Scholle, 1977).

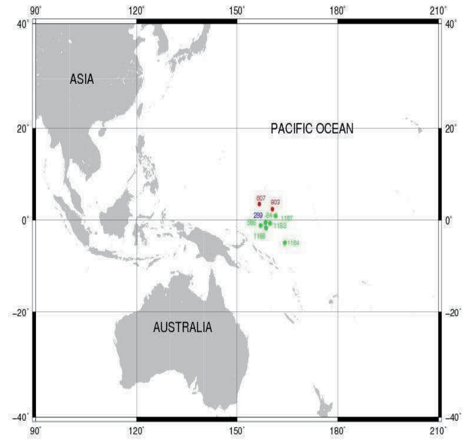

Figure 1: Geographical location of ontong Java plateau and twelve wells used for P-velocity prediction of the plateau.

The majority of carbonate material in modern oceans is dominated by pelagic plants (coccolithophores) and animals (foraminifera, pteropods, and heteropods) (Morse et al, 1990). These deep sea sediments are commonly soft and referred to as pelagic oozes. Their composition may change from place to place due to changing temperature, water chemistry and salinity, latitude, nutrients, carbonate compensation depth (CCD) etc. (Scholle, 1983; Morse et al, 1990; Moore, 2001; Schlager, 2005) and this will result in different seismic velocities (Hamilton et al, 1982; Fabricius, 2003). On the other hand, sorting and texture of these pelagic oozes (Fabricius et al, 2007) as well as introducing different mineralogy (e.g. clay, quartz etc.) into the sediment will also result in velocity variations. This shows the role and importance of the initial conditions with respect to composition, porosity and burial path the sediment has undertaken.

Depositional processes which results in ooze sediments is normally followed by post-depositional processes which change the ooze to chalk and, finally, to limestone. The important diagenetic processes which are involved in deep basin sediments are mechanical and chemical compaction, recrystallization and cementation.

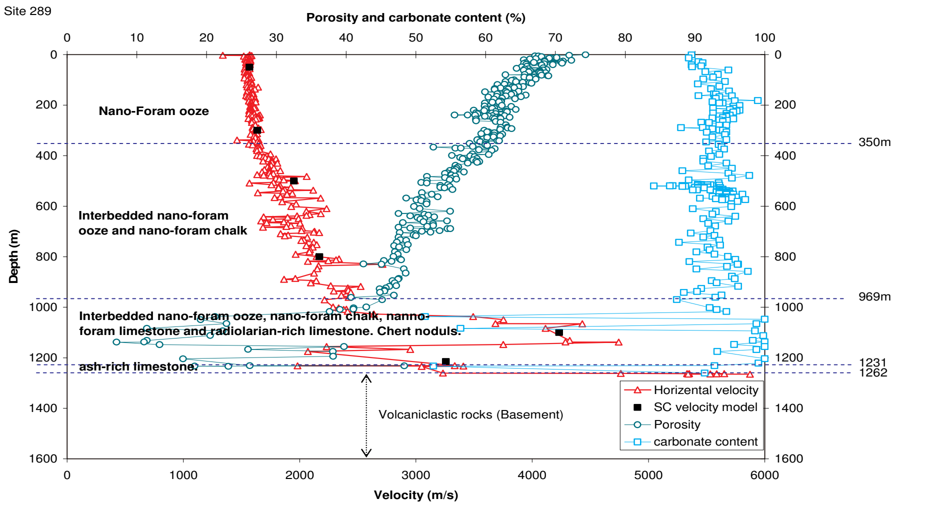

Figure 2: P-velocities (red triangles), carbonate content (blue squares) porosities (green circles) and modeled P-velocities (black square) of site 289 Leg 30 of Deep Sea Drilling Program (DSDP).

Each of these processes effects in different ways, the porosity reduction, texture and mineral changes as well as pore aspect ratio transformation (changes of pore aspect spectrum ratio by increasing depth). The overall effect of these changes can be traced on the velocity variation of deep basin sediments as observed by other authors (e.g. Fabricius 2007).

Porosity in chalks

Since chalk deposition is very sensitive to changes in oceanographic conditions, such changes result in variations in reservoir properties. The influence of deposition on reservoir properties can be linked to texture and mineralogy (Fabricius et al., 2007) and in a mineralogically uniform chalk just to the texture. Texture is a category that includes several features of the constituent particles like, size, sorting, packing, fabric, shape and roundness (Gutierrez et al., 2002). Dunham (1962) accounts for particle size and sorting by dividing particles into grains (in chalks foraminifers>20µm) and mud (in chalks coccoliths<20µm). Packing (cubic to rhombohedral) also plays an important role in diagenetic potential and reservoir property variations for a given rock type. Based on these definitions and observations of other authors (e.g. Fabricius, 2003), it is possible to link different porosity types and pore-aspect ratios in chalks as follows,

- *Grain porosity:* refers to intragrain porosity (inside foraminifers) and is insensitive to pressure changes. It represents very stiff pores.
- *Matrix porosity:* refers to interparticle porosity. It ranges from stiff to compliant pores and is strongly dependent on overburden pressure. Due to their complex morphology, these pore spaces are normally considered as relatively large nodes connected by narrow throats,
  - ✓ *Matrix porosity/pore body:* This is the main and stiffer part of interparticle porosity. It contains most of the matrix porosity.
  - ✓ *Matrix porosity/pore throat:* The connection between two pore bodies in interparticle porosity is considered as a pore throat. The number, size and distribution of the pore throats control many of the resistivity, flow and capillary-pressure characteristics of the rock.

Ontong Java plateau velocity modeling

We have represented texture by pores of various aspect ratios. For a uniform lithology velocity variations can largely be described by variations in pore fluid and pore aspect ratios. There are some qualitative and quantitative methods for describing the various aspects of pore

geometry and assessment of the porosity distribution which has their own advantage and disadvantage.
It can be shown that pore aspect ratio transformation is predictable and can be modeled in chalks by considering depositional and post-depositional processes (M.R.Saberi et al, personal communication, 2008). In this paper, the procedure of pore aspect ratio modeling in a single well (M.R.Saberi et al, personal communication, 2008) is applied for six wells (sites 288, 289, 807, 1183, 1184 and 1186) on Ontong Java plateau. Then, these aspect ratios were distributed on the whole area by simple geo-statistical methods. These distributed aspect ratios were used to model the velocity at six blind wells (sites 64, 586, 804, 806, 1185 and 1187) and results are compared with their measured velocity.

Stage one: pore aspect ratio modeling

Sonic velocity is a function not only of total porosity, but also of the predominant pore type (e.g. Wang, 1997). Deep burial diagenesis changes porosity as well as pore type with increasing depth, temperature and time in a way initial contact points (high porosity) changes to circles of finite area (low porosity) by diagenesis. These dynamic changes in pore type result in velocity variabilities that do not follow the regular depth-wise pattern. This pore aspect ratio transformation concept can be modeled by using an inverse strategy on real velocity measurements. Sites 288, 289, 807, 1183, 1184 and 1186 are chosen to evaluate and define a pore aspect ratio transformation strategy to be applied in the in the velocity calculation. Velocity is modeled by using a self-consistent approximation of effective moduli (Mavko et al., 1998). Based on variations observed in real velocity data, several depth points are chosen to be modeled for each site. Bulk modulus, shear modulus and density for solid phase (calcite) and fluid phase (water) are chosen as 71 GPa, 30 GPa, 2.71 g/cm3 and 2.3 GPa, 0 GPa, 1.02 g/cm3, respectively. For each point one aspect ratio is considered based on the measured velocity, depositional and post-depositional history of the rock. An example of this method on site 289 is illustrated in Figure 2. Real P-wave velocities are modeled in high carbonate zones. Pore aspect ratios are chosen in a way to reflect depositional and post depositional processes and to hopefully match model velocities to real one.

Stage two: structure and property modeling

To distribute evaluated pore aspect ratio and other well properties (such as porosity, carbonate content etc.) within the whole area a structural model is necessary. Based on well information from twelve sites (seabed depth, ooze and chalk layer thickness as well as the basement depth) drilled on Ontong Java Plateau during DSDP/ODP project (Figure

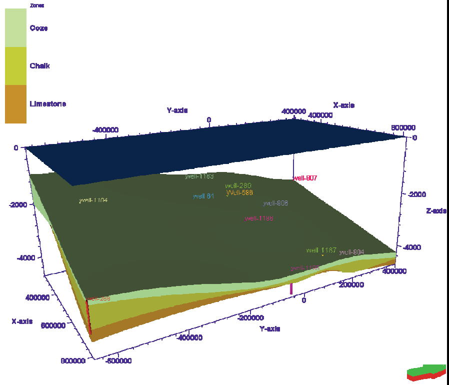

Figure 3: A simple struactural model of Ontong Java plateau build based on well data of twelve sites from DSDP/ODP. Top layer (seabed) is carbonate ooze which change to chalk and finally to limestone by increasing in depth.

1), a simple structural model of the plateau is made. This model shows the thickness variation for ooze, chalk and limestone at different locations (Figure 2) which in some ways reflect different diagenetic processes realm in the area. Later, this structural model used for creating a gridded model (in this case with 194*355*131 nodes) to distribute porosity, total carbonate, foraminifer's content and evaluated pore aspect ratios.
These properties for each well is entered into the model and distributed between all the model cells (8,881,860 cells) with moving average interpolation method to make a 3D model. This method is a simple approach for building for instance a pore aspect ratio transformation model. Since, our rock physic model is suitable for mineralogically uniform chalk, so that cells with carbonate content less that 90% are filtered out from the model. For mixed mineralogy cells, their suitable rock physics model should be applied which later can be combined with this model to predict a velocity model for whole area.

Stage three: forward velocity modeling

Sites 64, 586, 804, 806, 1185 and 1187 are chosen for velocity modeling from distributed properties using a self-consistent approximation of effective moduli (Mavko et al., 1998). Comparison between up-scaled measured velocities (arithmetic mean) and modeled velocities are shown in Figure 4.

Discussion on results

Figure 4 shows the comparison between modeled velocity and up-scaled measured velocities.
The modeled velocity (see Figure 4) is almost similar to the measured one. Places with different velocities from the modeled one are mainly related to changes in mineralogy (for instance, in well-1187, a high amount of clay (~70%) and zeolite (~15%) is reported below the depth 4168m in the smear slide analysis). Thus, the modeling can be improved by taking into account more sophisticated mineralogy and 3D pore aspect ratio model. Finding relationship between different porosity types and grain size distribution, carbonate particles and nannofossil as well as foraminifera contents can also help in defining more accurate pore aspect ratio transformation model. The effect of pore aspect ratio on velocity modeling can be removed from the velocity data in order to better reveal the effects of velocity changes with changes in porosity, saturation, pressure etc.

Conclusion

Pore texture can be modeled and related to the changes in micro-facies in rocks, and this has a clear effect on velocity variations. Pore aspect ratios transform with depth which depends on active post-depositional processes. Areas with the same depositional and diagenetic history follow the same trend in pore aspect ratio transformation with depth.

Acknowledgment

This work is made in cooperation with IRIS, Stavanger and supported by Norwegian Research Council under contract 163316.

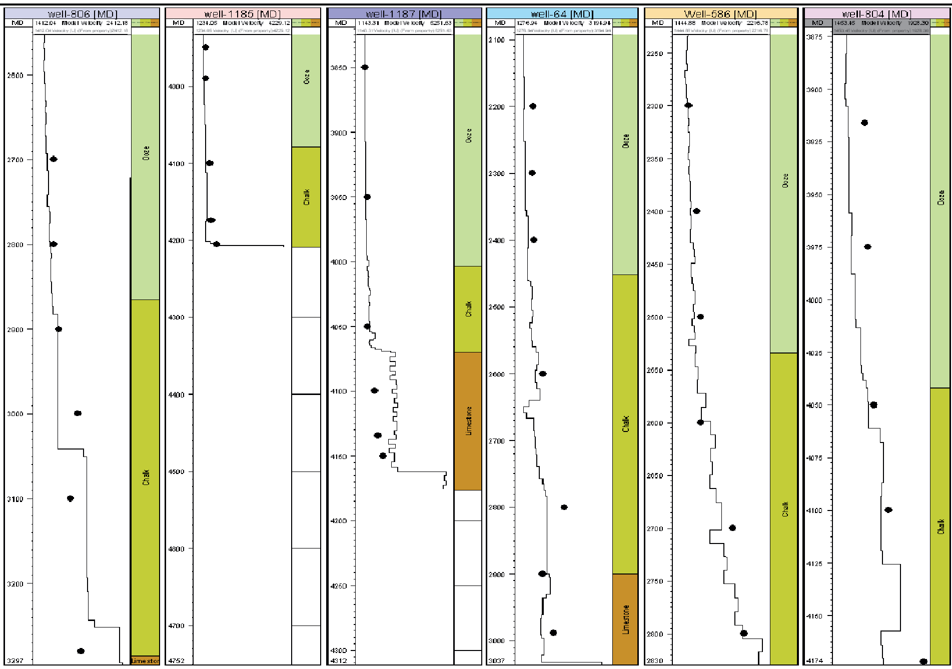

Figure 4: Comparision between modeled velocities (black dots) and up-scaled measured velocities (solid lines) at six blind well locations 806, 1185, 1187, 64, 586 and 804, respectively from the left. 3D pore aspect ratio transformation cube determined from sites 288, 289, 807, 1183, 1184 and 1186 was used to model the pore aspect ratio used in the velocity modeling. Our modeling parameters are suitable for high total carbonate contents (uniform mineralogy) and differences in measured and predicted velocities are mainly realted to changes in mineralogy.

EDITED REFERENCES

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