Velocity-depth trends in Mesozoic and Cenozoic sediments from the Norwegian Shelf: Discussion

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Storvoll et al. (2005) present log data from 60 wells on the Norwegian Shelf to investigate velocity-depth trends in sedimentary rocks. They present an interesting analysis of, e.g., the sonic-log velocities of overpressured Jurassic sediments and of source rock intervals. The authors do, however, reach the conclusion that "no general velocity-depth function can be used when performing more accurate analyses like depth conversion of seismic data, pore-pressure prediction, or basin modeling" (Storvoll et al., 2005, p. 359). This conclusion is surprising for two reasons: first, because it is not tested by the authors, and second, because the article presents very good evidence for the existence of normal velocity-depth trends for shale (i.e., functions that describe how sonic velocity increases with depth in relatively homogenous, sedimentary formations as porosity is reduced during normal compaction).

The authors present log data from three areas along the Norwegian Shelf (but no examples of pressure versus depth): the northern North Sea, Haltenbanken, and the Barents Sea (about 60°N, 65°N, and 72°N, respectively). The main figures show velocity measurements versus depth for several wells in the three study areas (their figures 6, 8, 12). The authors compare the data with a linear velocity-depth trend: $V_p = 1477 + 0.57 \times Z$, which is similar to the normal velocity-depth trend for marine shale dominated by smectite-illite published by Japsen (2000):

$$V_p = 10^6/(460\ e^{-Z/2175} + 185)$$

where V_p is velocity in meters per second, and Z is depth in meters below seabed or ground level. This trend is almost identical to that developed by Scherbaum (1982) for Lower Jurassic shale in the Northwest German Basin and to that presented by Hansen (1996) based on data for Cretaceous–Cenozoic shales on the Norwegian Shelf (for depths less than about 2.5 km [1.6 mi]). It is interesting that the presented shale data plot very close to the shale trend for all three areas.

- In the northern part of the northern North Sea study area, Upper Triassic to Paleocene sediments "closely follow" the linear shale trend from about 2 to 4 km (1.2 to 2.5 mi) depth (citation from Storvoll et al., 2005, p. 365, see their figure 6; the interval labeled "3N"). These sediments are dominated by the shales of the Upper Cretaceous Shetland Group, and the close match between the data and the shale trend is noted by the authors, but not discussed any further.
- On Haltenbanken, the western part of the study area is characterized by highly overpressured Jurassic shales, but the plot of the log data from the eastern part (where most wells are from an area of transitional Jurassic pressure) shows that the Middle to Upper Jurassic and Cretaceous shales plot fairly close to the linear shale trend (up to 500 m [1600 ft] deeper) from almost 2 to 4 km depth (1.2 to 2.5 mi) (4E, their figure 8).
- In the Barents Sea case, a plot of velocity versus depth corrected for erosion shows a clear shale trend from about 1.5 to 3.5 km (0.9 to 2.2 mi) depth (marked by the authors) that is subparallel to the linear shale trend, only at a somewhat greater depth (up to 400 m [1300 ft] deeper, their figure 12). The authors thus use estimates of exhumation based on shale velocities (Liu et al., 1992), but they do not discuss the offset between the erosion-corrected trend, the general trend. A possible explanation could be that Liu et al. (1992) used a too deep reference line and, thus, overestimated the exhumation.

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Manuscript received May 9, 2005; provisional acceptance June 1, 2005; revised manuscript received June 23, 2005; 2nd revised manuscript received September 23, 2005; final acceptance September 29, 2005.
DOI:10.1306/09290505084

Velocity-depth data for shale from all three areas thus appear to be uniform over kilometer-thick sections: they show a steady velocity-depth gradient that is very close to that suggested for general shale trends. The depth shift (or burial anomaly) of the data relative to the linear shale baseline for the above-indicated intervals is less than 500 m (1600 ft), and this is equivalent to a moderate overpressure of less than 5 MPa (725 psi) for undercompacted sediments (see Japsen, 1998). Analysis of the log pattern is needed to estimate whether the data represent shale with similar characteristics as the data used as reference, but the depth-shift caused by overpressure is commonly a first-order effect compared to many second-order velocity variations caused by minor lithological differences (see Japsen, 1999).

Another aspect of the analysis is that it depends on estimates of exhumation based on shale velocity data, although the authors conclude that ''no general velocity-depth function can be used'' (Storvoll et al., 2005, p. 359). On the list of what such functions cannot be used for, the authors do not specifically include exhumation estimates, but the physics behind depth conversion, pore-pressure prediction, and exhumation estimation based on velocity-depth trends is the same, that is, for some sediments and over a certain stress range, the increase of velocity is controlled by effective stress (caused by mechanical compaction or pressure solution).

The youngest sediments in the northern North Sea and on Haltenbanken are dominated by sands and shales and show a clear, rather high velocity increase for depths shallower than about 1 km (0.6 mi) (Storvoll et al., 2005, their figures 6 [1N and 1S] and 8 [1W and 1E]). This sand-dominated, uppermost part of the overburden is normally compacted and has higher velocities than the shale trend and has similar characteristics to that of the central North Sea (cf. Japsen [1999]).

The underlying, Paleogene smectitic sediments from these two areas are characterized by relatively low velocities compared to the overlying normally compacted sediments, causing a distinct velocity inversion (Storvoll et al., 2005, their figures 6 [2N and 2S] and 8 [2W and 2E]). The authors are, however, caught in the classic chicken-and-egg situation when they conclude that these low velocities are caused mainly by high smectite content, although they also find that smectite reduces permeability and, thus, favors overpressure generation. They report that overpressure is present in the Cenozoic sediments in both areas, but they do not compare the velocity-depth data with pressure-depth profiles, nor do they investigate whether the velocity inversion in the smectitic sediments could be related to overpressure increasing with depth. Without any argument, the authors conclude that velocity-depth data cannot be used for pore-pressure prediction. The reader is, however, informed that the overpressure in the Cenozoic sediments can be up to 10 MPa (1450 psi) in the northern North Sea, which is in very good agreement with the deviation of up to 1 km (0.6 mi) between the velocity-depth data for the smectitic sediments and the linear shale trend (cf. Japsen, 1999; Storvoll et al., 2005, their figure 6).

A plot of density versus depth for wells in the western part of Haltenbanken reveals a pronounced density inversion for the lower part of the Cenozoic section (Storvoll et al., 2005, their figure 10) similar to that observed for the velocity-depth data. The plot shows a normal compaction trend down to about 1.4 km (0.9 mi) where density is up to approximately 2.4 g/cm^3 and, below that, a decrease to about 1.8 g/cm^3 at a depth of about 2 km (1.2 mi). Such low densities are likely to reflect significant overpressure, but this is not discussed.

A key point in the article is the function of smectite-illite transition and initial precipitation of quartz cement for increasing sonic log velocities. The effect of overpressure on velocity is, however, never addressed, so the specific influence of the chemical processes does not become clear for the reader. No direct evidence is presented to support that these processes actually occurred in the places drilled by the wells studied (''is probably caused by'' and ''may also contribute to,'' p. 372), nor is any distinction made between how the effects could be different for shale and sandstone. The argumentation is further complicated because the onset of these processes is recorded at different depths throughout the manuscript: 2.5–3 km (1.6–1.9 mi) (p. 372), >3 km (1.9 mi) (same page), and 2–2.5 km (1.3–1.6 mi) (p. 377).

Estimation of pore pressure from velocity-depth data from shale intervals is a well-established geophysical discipline that cannot be eliminated without proper argumentation (cf. Hottmann and Johnson, 1965; Magara, 1978; Chapman, 1983; Dutta, 1990). The unclear analysis presented by Storvoll et al. (2005) is probably caused by their lacking distinction between the two main mechanisms that generate overpressure at basin scale: disequilibrium compaction and volume expansion related to hydrocarbon generation (Osborne and Swarbrick, 1997). In the North Sea, for example, volume expansion of hydrocarbons is the dominating process in the Jurassic source rock intervals, whereas compaction disequilibrium is the main overpressure-generating process in the overburden. Here, the giant Ekofisk field has long provided the proof that disequilibrium compaction is important because porosities of up to 45% are found in the Upper Cretaceous–Danian chalk at depths of 3 km (1.9 mi) only because an overpressure of about 17 MPa (2500 psi) prevents the chalk from reaching normal compaction for that depth (e.g., Scholle, 1977; Japsen, 1998). The porosities in the overburden sediments thus depend on the vertical effective stress (lithostatic load minus pore pressure), and as sonic velocity is directly correlated with porosity, deviations from velocity-depth trends for shale (or chalk) intervals will be a measure of overpressure.

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