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GR Focus Review

Sonic velocity of chalk, sandstone and marine shale controlled by effective stress: Velocity-depth anomalies as a proxy for vertical movements

Peter Japsen

Geological Survey of Denmark and Greenland (GEUS), Denmark

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ABSTRACT

Sonic velocities of sedimentary rocks can provide a simple measure of the vertical movements of the rocks relative to the earth's surface. During progressive burial histories when effective stress increases, sonic velocities of many sedimentary units of uniform lithology show a progressive increase that defines a baseline or a normal velocity-depth trend. Departures from such a trend may reflect velocities that are low relative to depth (positive burial anomaly) due to overpressuring or velocities that are high relative to depth (negative burial anomaly) due to deeper burial followed by exhumation. Maps of such anomalies across the North Sea Basin based on data from about 1000 wells for the Upper Cretaceous–Danian Chalk Group and for the overlying, lower Cenozoic, shale-dominated deposits, reveal an east–west oriented, sinusoidal pattern that vary between -1 and $+2$ km with a wavelength of about 1000 km. The anomalies primarily reflect two physical processes that cause deviations from normal compaction. (1) Removal of up to 1 km of sediments along the western and eastern margins of the basin due to Cenozoic uplift of the British Isles and Scandinavia. (2) Overpressure of up to 20 MPa in the formations below the mid-Miocene unconformity in the central North Sea due to disequilibrium compaction. In order to define such patterns with confidence it is essential that sonic velocity data are compared with well-constrained, normal velocity-depth trends for suitable lithologies; e.g. baselines for chalk, marine shale and sandstone that are reviewed here. The mechanisms behind such vertical movements as those observed for the North Sea Basin are debated, but the material presented here documents the tectonic nature of these processes by revealing their variation in time and space.

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1. Introduction

Estimates of overpressure and amount of exhumation based on sonic data for a sedimentary formation rely on identification of a normal velocity–depth trend for the formation (Fig. 1). Such trends (or baselines) predict what the sonic velocity of a relatively homogeneous, brine-saturated sedimentary formation will be at a given depth during normal compaction of a sedimentary unit. Compaction is 'normal' when the fluid pressure of the formation is hydrostatic and the formation is at maximum burial depth, i.e. the thickness of the overburden has not been reduced by exhumation. The definition of such trend lines for different lithologies is thus critical for the success of this approach, but their definition is far from trivial because many sedimentary units in basins such as the North Sea Basin are not normally compacted over vast regions. During almost two decades, I have been involved in the study of velocity-depth relations for different sedimentary formations (Japsen, 1998, 1999, 2000; Japsen et al., 2007a, 2011, 2012b),

and here I take the opportunity to review the formulation of these baselines (Fig. 2A) and also to update the velocity-depth relation for chalk based on the recent discovery of the chalk compaction front (Japsen et al., 2011).

The observation that the acoustic velocity of sediments increases with depth is as old as exploration geophysics (Slotnick, 1936), and numerous studies have used sonic velocities for estimating exhumation and amount of overpressure due to undercompaction (Hottmann and Johnson, 1965; Herring, 1973; Magara, 1978; Chapman, 1983; Bulat and Stoker, 1987; Marsden, 1992; Hillis, 1995; Hansen, 1996; Al-Chalabi, 1997b; Corcoran and Doré, 2005; Mavromatidis, 2006; Holford et al., 2009a,b; Tassone et al., 2014a,b; Baig et al., 2016). Estimates of exhumation and overpressure have been based on sonic data from marine shale in many of the world's sedimentary basin, but sonic data for the Upper Cretaceous–Danian Chalk Group (or Shetland Group in the Norwegian sector) of the North Sea Basin have also been used to estimate exhumation (Herring, 1973; Hansen, 1996; Bulat and Stoker, 1987; Hillis, 1995; Hansen, 1996) ('chalk' refers to the lithology and 'Chalk' to the North Sea Chalk). Japsen (1998) was the first to estimate overpressure in the North Sea Chalk based on sonic data for this formation.

E-mail address: pj@geus.dk.

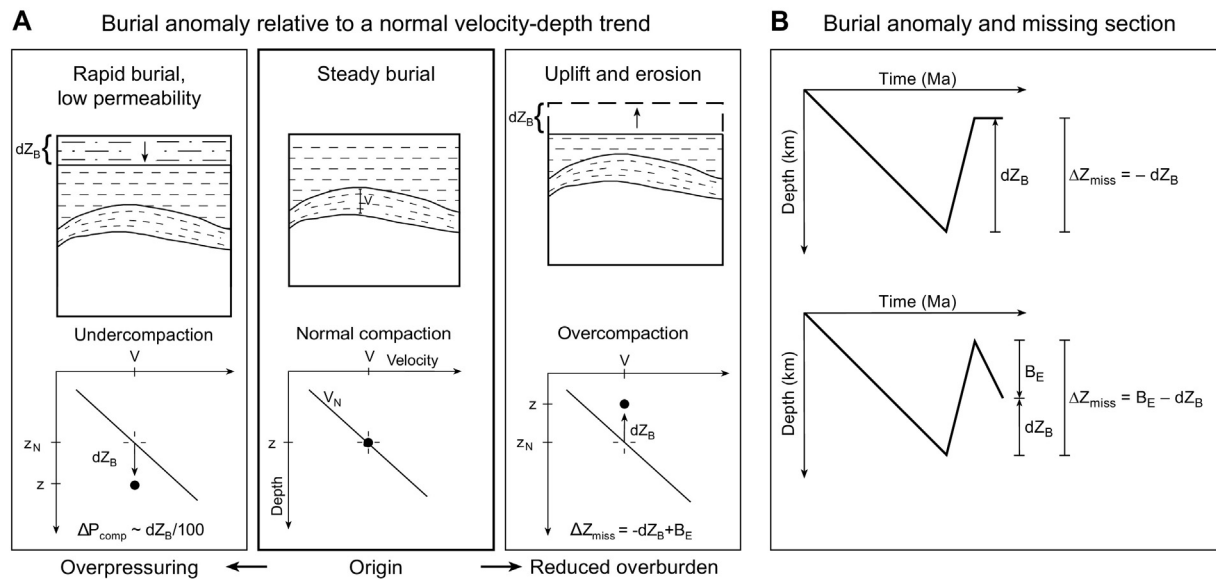


Fig. 1. A: Burial anomaly, dZ_B , relative to a normal velocity–depth trend, V_N , for a sedimentary formation. In the North Sea Basin, burial anomalies of ± 1 km for pre-Miocene formations result from late Cenozoic exhumation along basin margins and overpressuring due to rapid, late Cenozoic burial in the basin center. Left: Rapid burial and low permeability cause undercompaction and overpressure, ΔP_{comp} , and velocities that are low relative to depth (positive dZ_B) (Eq. (4)). Right: Exhumation reduces the overburden thickness and causes overcompaction expressed as velocities high relative to depth (negative dZ_B). The normalized depth z_N is the depth corresponding to normal compaction for the measured velocity (cf. Terzaghi's principle; Terzaghi and Peck, 1968). B: Schematic burial diagram illustrating that post-exhumational burial, B_E , will mask the magnitude of exhumation, ΔZ_{miss} , relative to the depth anomaly, dZ_B , (Eq. (2)). Slightly modified from Japsen (1998).

The North Sea Basin is ideal for testing this approach (Fig. 3). First, velocity data are available from hundreds of deep boreholes, and second, thick and fairly uniform sedimentary units extend over much of the region; in particular the lower Cenozoic shales and the underlying Chalk Group. Clastic influx into the North Sea Basin was low during the deposition of the Chalk, which is composed mainly of stable, low-magnesium calcite of coccoliths, the debris of planktonic algae deposited at the bottom of a vast ocean that extended across much of north-west Europe (Scholle, 1977; Ziegler, 1990). Today the Chalk forms a coherent body with an average thickness of about 500 m across the North Sea Basin between the British Isles and southern Scandinavia where the Chalk is at outcrop whereas it is buried below up to 3 km of Cenozoic sediments in the central North Sea. This configuration is due to significant, differential vertical motion across the North Sea since the deposition of the Chalk. The western and eastern margins experienced burial followed by exhumation whereas subsidence and burial continued in the central North Sea and even accelerated in the late Cenozoic (Japsen, 1998).

In this paper, following a discussion of baseline definitions, I summarize evidence from the North Sea Basin for overpressuring and exhumation based on sonic data for the Chalk and its Cenozoic overburden (Japsen, 1998, 1999; Japsen and Bidstrup, 1999; Japsen, 2000; Japsen et al., 2007b, 2010; Green et al., 2017a). The database available for this study is primarily interval velocities for the Chalk and the Cenozoic overburden as measured in about 1000 boreholes from the North Sea Basin, but it is supplemented with data from Jurassic shale drilled in Denmark and from Lower Cretaceous, syn-rift deposits drilled in north-east Brazil. I review how the results of this approach compare with estimates of Chalk overpressure from boreholes and estimates of exhumation derived from palaeo-temperature data (vitrinite reflectance, VR, and apatite fission-track analysis, AFTA, data).

2. Normal velocity-depth trends and velocity-depth anomalies

Disagreement between velocity [m/s] predicted by a normal velocity–depth trend and measured velocity at a given depth may indicate that a formation has become overpressured due to rapid burial (resulting in a lower velocity than expected) or that the overburden has been partially removed subsequent to maximum burial (resulting

in a higher velocity than expected) (Fig. 1A). A velocity–depth anomaly can also be measured along the depth axis as the difference between the depth of an observed velocity and the depth along the baseline predicted for that velocity, the burial anomaly, dZ_B [m] (Japsen, 1998). Burial anomalies can be calculated by expressions presented by Japsen (1998, 1999) or they can be estimated visually by a depth shift of a baseline to fit the sonic log for the formation in question (preferably matching baselines and data for different formations; Japsen et al., 2007a,b, 2010, 2012b).

Several factors make it possible to establish simple velocity–depth relations for certain sedimentary formations. First, acoustic waves are affected by the bulk properties of the rock as they travel through the sediment. Second, acoustic waves are primarily affected by inter-granular porosity rather than by fractures (Rider, 1986). And finally, acoustic wavelengths (up to 10^2 m) are orders of magnitude larger than for example the particles of smectite-illite dominated shale ($\sim 10^{-9}$ m, Weaver, 1989). Relatively few attempts have been made to generalize the relations between sonic velocity and depth for sedimentary formations (Bulat and Stoker, 1987; Hillis, 1995; Al-Chalabi, 1997a; Japsen, 1998, 2000), but Japsen et al. (2007a) presented constraints from rock physics models on velocity–depth relations for shale and sandstone. They suggested that normal porosity at the surface for a given lithology should be constrained by its critical porosity (Nur et al., 1998), i.e. the porosity limit above which a particular sediment exists only as a suspension. Consequently, normal velocity at the surface of unconsolidated sediments saturated with brine approaches the velocity of the sediment in suspension. Furthermore, porosity must approach zero at infinite depth, so the velocity approaches the matrix velocity of the rock and the velocity–depth gradient [$\text{m/s/m} = \text{s}^{-1}$] approaches zero. Consequently, they found that the velocity–depth gradient decreases with depth for sediments with initially good grain contact (such as sand) when porosity is just below the critical porosity. By contrast, initially compliant sediments (such as chalk and shale) may have a maximum velocity gradient at some depth if it assumed that porosity decreases exponentially with depth.

Identification of a normal velocity–depth trend from basin-wide well data involves three steps of generalization, and this may explain differences among trends suggested for identical units by different

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