From two-way time to depth and pressure for interpretation of seismic geometries and velocities offshore

Alexey Goncharov
Geoscience Australia
GPO Box 378 Canberra ACT 2601 Australia
Alexey.Goncharov@ga.gov.au

SUMMARY

The effect of water and rock loading on seismic velocities and consequently on interpreted geometries is often underestimated in offshore studies. Direct comparative analysis of interval velocity patterns between areas of significantly different water depth and thickness of rock overburden requires various pressure related changes in velocity to be accounted for. Presentation of velocity models as a function of pressure rather than two-way time, or depth, emerges as a possible solution. An accurate velocity model is essential for meaningful time-to-depth conversion of interpreted seismic horizons. Ideally, it should be based on integration of seismic velocities from well log measurements, refraction seismic surveys and from stacking of multi-channel marine reflection data. In some cases velocities derived from stacking of high quality long streamer marine reflection seismic data correlate reasonably with well log measurements and velocities derived from refraction seismic studies, and provide clues to reasonable depth conversion and lithology interpretation.

Key words: time-depth conversion, seismic velocity, pressure effects.

INTRODUCTION

The effect of water and rock overburden on seismic velocities and consequently on interpreted geometries is often underestimated in offshore studies. However, direct comparative analysis of interval velocity patterns between areas of significantly different water depth and thickness of rock overburden requires various pressure related changes in velocity to be accounted for. There are controversies in the methodology and application of a water depth adjustment to seismic velocities (Goncharov and Nelson, 2010), and the presentation of velocity models as a function of pressure rather than two-way time or depth, emerges as a possible solution. To illustrate this I use data and interpretation of the 2008/09 seismic survey (GA 310), acquired by Geoscience Australia as part of the Offshore Energy Security Program, to examine the effect of variable water depth and rock overburden on seismic velocities of the southwest Australian margin, including the Wallaby Plateau (Figure 1). Five seismic lines were acquired across the Plateau using an 8 km long solid streamer and a 4290 cubic inch airgun array with 106-fold recording.

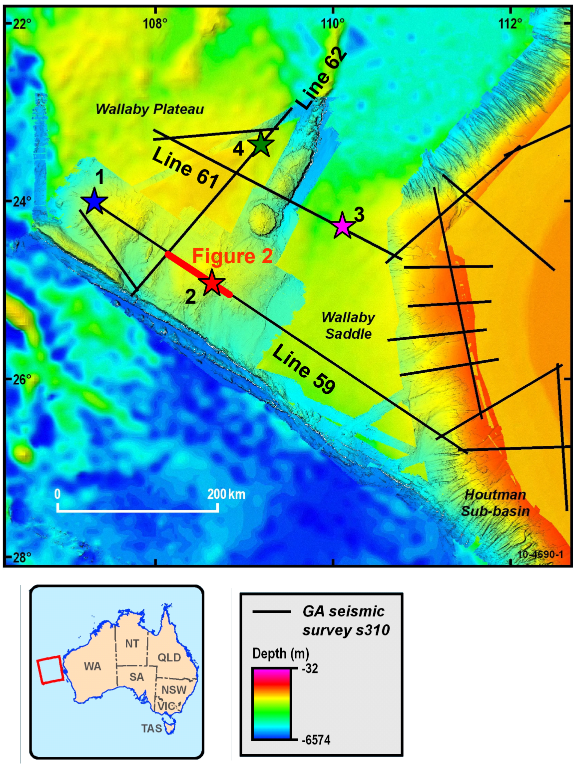

Figure 1. Study area and location of seismic sections. Background bathymetry from satellite measurements (low resolution) and ship-board SWATH data (high resolution). Locations marked 1 to 4 correspond to SDRS/DDRS areas 1 to 4 represented by accordingly colour coded graphs in Figure 6.

Interpretation of these reflection profiles reveals seismically distinctive divergent dipping reflector sequences (DDRS) (Goncharov and Nelson, 2010). The DDRS packages are ~30-50 km wide and up to ~6-7.5 km thick, with generally smooth upper surfaces and concordant to onlapping divergent internal reflectors (Figure 2). The DDRS are similar to seaward-dipping reflector sequences (SDRS) described beneath the Wallaby Saddle by Symonds et al. (1998), on other volcanic margins globally (e.g. Planke et al., 2000; White at al., 2008), and also identified on other GA 310 lines. Both DDRS and SDRS can be used as examples to illustrate the effects of water and rock loading on seismic velocities and on interpreted geometries offshore.

GEOMETRIES IN TWO-WAY TIME AND DEPTH

An accurate velocity model is essential for meaningful time-to-depth conversion of interpreted seismic horizons. Ideally, it should be based on the integration of seismic velocities from well log measurements, refraction seismic surveys (with sonobuoys or ocean-bottom seismographs) and from stacking of multi-channel marine reflection data. Unfortunately there are no wells or refraction measurements in the area of interest, and only stacking-derived velocities can be utilised for depth conversion. Generally, these velocities may differ from true propagation velocities and will not match velocities measured by seismic logs (Al-Chalabi, 1994).

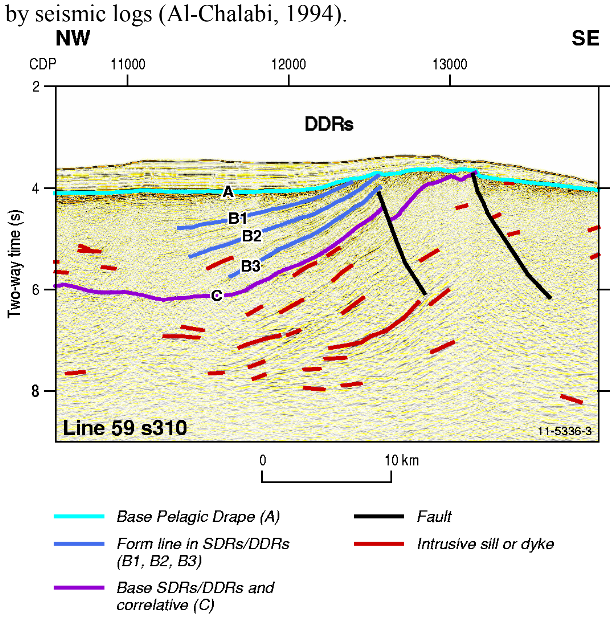

Figure 2. Interpreted seismic section along line 59 of survey 310 illustrating divergent dipping reflector sequence (DDRS) on Wallaby Plateau. Line location shown in fig. 1.

However, stacking velocities in this study were derived from long (8 km) streamer 106-fold data, and picked on traces after pre-stack time migration, and 4th order normal move-out (NMO) corrections were applied. Therefore, distortions to velocities due to insufficient curvature of NMO curve at short offsets, structural dip, and ray bending due to stratification are assumed to be largely suppressed and root mean squared (RMS) velocities are assumed to be close enough to average velocities. The following arguments show that these assumptions are valid.

Firstly, stacking-derived velocities from survey GA 310 were compared to velocities measured in the nearby Herdsman-1 well. Time-depth functions of the stacking-derived and well velocities, calculated for depth conversion of interpreted seismic horizons show a high degree of correlation. Even in the deepest part of the well, where maximum mismatches between stacking-derived and well velocities could be expected, the stacking and well time-depth functions have an average deviation of only 5% and do not deviate by more than 7.5%. This result is valid for all velocity analysis locations within an 8 km radius (i.e., streamer length) of the well. Secondly, a comparison of stacking-derived velocities with velocity functions derived from 2D ray tracing of data recorded by sonobuoys in the Mentelle Basin also show reasonable correlation. The sonobuoy data have offsets of up to 20 km, much larger than the maximum 8 km offset of the GA 310 survey.

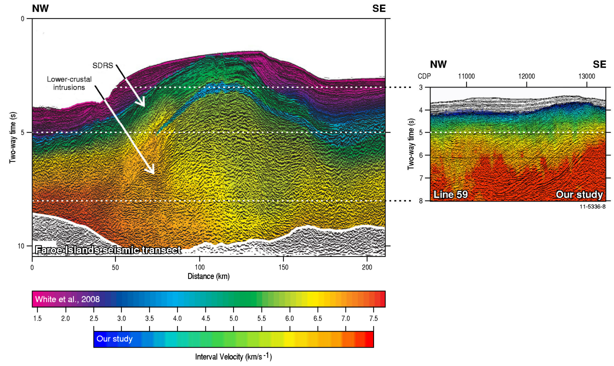

Figure 3. Interval velocities (colour coded) over reflection seismic along the Farøe Islands transect in the North Atlantic crossing SDRS (after White at al., 2008, left panel) compared to the southern margin of the Wallaby Plateau from this study (right panel, same section as in Fig. 2).

Thirdly, interval velocities from this study do not show systematic differences, at least down to 6s two-way time, from the velocities interpreted within similar geological structures from observations with ocean-bottom seismographs along the Farøe Islands transect of White et al. (2008) in the North Atlantic which crosses an SDRS (Fig. 3). The above three examples are taken as an indication that the stacking-derived velocities from survey GA 310 are reasonable for time-to-depth conversion, and for examining the effects of water and rock pressure on seismic geometries and velocities.

However, where seismic velocities are derived from poorer quality and shorter streamer reflection data, refraction measurements remain essential, and delivery in 2014 of the Australian Geophysical Observing System (AGOS), that will include ocean-bottom seismographs, is seen as an important initiative recently funded through the Australian Government's Education Investment Fund.

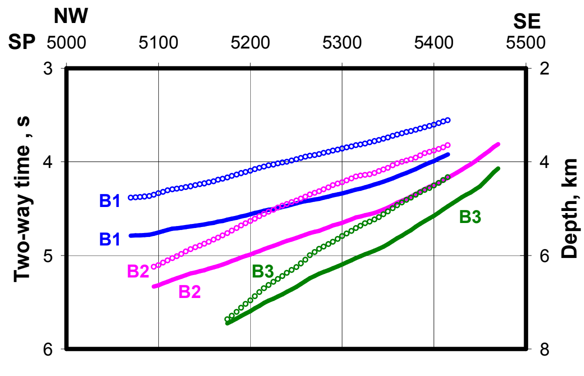

Figure 4. Two-way time (solid lines) and depth (circles) interpretation of the seismic section along line 59 (same as in figure 2). Note the dramatic change of form lines geometries within DDRS between the time and depth sections.

Seismic velocities in the study area vary vertically and horizontally (Figure 3, right panel). As a result, the geometries of interpreted seismic horizons are represented differently in two-way time and depth. For example, the shape of reflections (form lines of Figure 2) within DDRS/SDRS changes from convex downward in two-way time to convex upward in depth (Figure 4), changing the interpretation of this sequence to be consistent with the geological model for formation of seaward dipping wedges of flood basalts (Planke and Edholm, 1994).

PRESSURE EFFECTS ON SEISMIC VELOCITY

The comparative analysis of velocity variation patterns (e.g., for lithology interpretation) between areas of significantly varying water depth requires the adjustment of velocities for the effect of the water layer pressure. There is no consensus as to the method for undertaking this correction. The method of Goncharov and Nelson (2010) is not ideal for a number of reasons (e.g., unknown water saturation of rock below sea floor), and is open to further debate. More complications arise when comparing seismic velocities between areas where the thickness of rock overburden above the target interval varies as well as water depth. For example, velocity at 3 s two-way time at the 50 km mark of the Farøe Islands seismic transect of White et al., (2008) is 2.2 km/s, while velocity at the same two-way time at the 105 km mark is 3.8 km/s (Figure 3). While this difference is large, it can be attributed to differences in water and rock thickness between the two locations: the 3 s two-way-time interval at the 50 km location is composed almost entirely of water, while the same 3 s two-way time interval at the 105 km location is made up of ~ 1 s of water and ~2 s of high velocity rock. Due to differences in the density of water and rock, the pressure at 3 s two-way times at the 50 km and 105 km locations will be significantly different.

To translate velocities expressed as a function of two-way time into velocities expressed as function of pressure, depths corresponding to two-way times at which velocities are reported were calculated, and then interval velocities were translated into interval densities using the experimental regression between velocity and density (Brocher, 2005). After that pressure at any depth can be calculated, and the vertical velocity profile at any location where velocities are reported can be presented as a function of pressure.

Comparison of velocity-pressure profiles at the 50 km and 105 km locations on the Farøe Islands, show that the pressure difference between these two locations at the 3 s two-way time mark is ~100 MPa. A comparison of these two velocity-pressure profiles to the Cenozoic terrigenous rock reference model of Averbukh & Nikolayev (1990), also presented in the pressure domain, shows that the 2.2 km/s velocity at the 50 km location can correspond to exactly the same Cenozoic terrigenous lithology as 3.8 km/s velocity at the 105 km location at 3 s two-way time (Figure 5). This counter-intuitive conclusion means that on the basis of velocity values alone it would not be possible to distinguish the rock lithology between units of very different seismic velocity located at the same two-way time level.

Obviously, the deeper parts of any section will be more affected by pressure differences resulting from the split of overburden into water and rock components. Therefore, in the SW Australian Margin examples comparing interval velocities in deeper sections of the SDRS and DDRS is the most appropriate to understand how translation of velocity data into the pressure domain affects lithological interpretation. To make such an assessment, the lowermost interval of DRRS/SDRS bounded by the interpreted seismic horizons B3 and C (see Figure 2), was selected. Interval velocities within this interval for selected DDRS/SDRS areas, originally presented as functions of two-way time, were expressed as functions of depth, and then pressure.

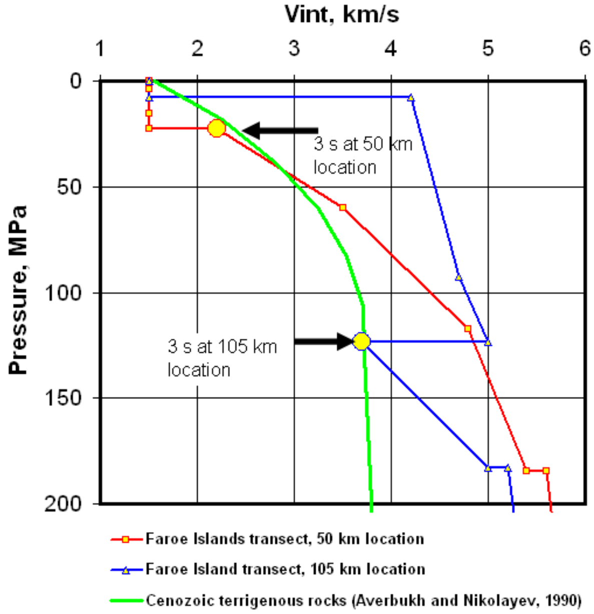

Figure 5. Seimic velocity profiles at select locations along the Farøe Islands transect (Figure 3, left panel) as functions of pressure. Points marked by arrows correspond to constant two-way time of 3 s at these locations.

Four identified DDRS/SDRS areas marked in Fig.1 were selected for analysis of interval velocity behaviour in the pressure domain because they cover the broadest possible range of the B3-C overburden's splits into water and sediment components. The selected B3-C interval velocities are analysed as functions of two-way time, depth and pressure at mid-interval (Figure 6) to characterise their variation with horizon deepening. Analysis of the B3-C interval velocities expressed as functions of two-way time (Figure 6a) shows very large variation between areas selected for analysis, e.g. interval velocities at 6 s differ by almost 2.0 km/s between areas 2 and 4, and differences exceeding 1.0 km/s are observed between areas 1 and 3. However, it would be a mistake to make conclusions about the lithological differences between these areas on the basis of the two-way time representation. Translation of the same interval velocity data set into the depth domain shows that areas 1, 3 and 4 conform to the same pattern of velocity variation with depth. Corresponding graphs overlap substantially and jointly form a distinctive trend (Figure 6b). Only area 2 falls off this trend with velocities in it systematically higher (by ~0.2 km/s) than those in areas 1,3,4, but still increasing with depth roughly at the same rate as in other 3 areas. Again, it would be a mistake to attribute these differences in velocity values and similarities in velocity gradients to differences in rock composition between areas 1,3,4 versus area 2 because these velocities are not adjusted for variation in water depth and rock overburden thickness above the target interval B3-C. So, the apparently obvious conclusion that rock lithology within this interval in areas 1, 3 and 4 is similar, and that area 2 is likely to have a different lithology from the first three, is premature. Translation of the B3-C interval velocity data set into the pressure domain, indeed, results in a different picture (Figure

6c). Now areas 2, 3 and 4 are on the same trend of velocity-pressure variation, and area 1 stands apart. So, finally, rock lithology within this interval in areas 2, 3 and 4 appears similar, and area 1 is likely to have a different lithology from the first three.

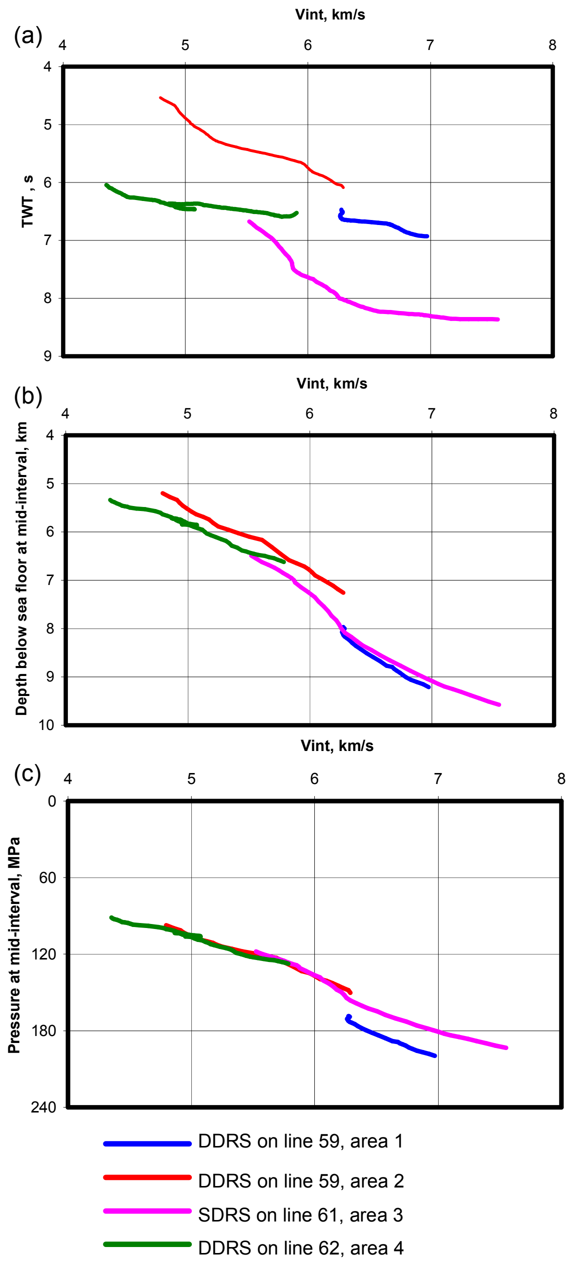

Figure 6. Interval velocity in the lower part of DDRS/SDRS (interval B3 – C in Figure 2, or correlative on other lines) for selected areas (colour coded to locations in Figure 1) as function of (a) two-way time, (b) depth and (c) pressure.

An important methodological conclusion from this analysis is that in the offshore environment presentation of seismic velocities as functions of pressure rather than two-way time, or depth can be recommended to avoid erroneous lithology interpretation.

CONCLUSIONS

- Seismic velocities derived from stacking of high quality long streamer marine reflection seismic data, if properly processed and carefully conditioned, correlate reasonably with well measurements and velocities derived from refraction seismic studies, in some cases down to 6 s two-time, and provide clues to reasonable depth conversion and lithology interpretation.
- Geometries of interpreted seismic horizons in depth change substantially from those interpreted in two-way time, and in some cases will lead to differing geological interpretation.
- The analysis of seismic velocities as functions of pressure rather than two-way time, or depth, is needed to allow meaningful interpretation of seismic velocities offshore in cases of substantial variation in water depth and rock overburden thicknesses.

ACKNOWLEDGMENTS

I thank Fugro Seismic Imaging, in particular Paul O'Neil, for providing access to their in-house velocity processing software MGIVA and technical support. Gabriel Nelson provided interpretation of select seismic lines and advice on geological models for SDRS/DDRS formation. Mike Sexton and Stephen Johnston have reviewed this paper and provided useful remarks. Chris Evenden crafted the figures.

REFERENCES

Al-Chalabi, M., 1994, Seismic velocity - A critique: First Break, v. 12, 589-596.

Brocher, T.M., 2005, Empirical Relations between Elastic Wavespeeds and Density in the Earth's Crust, Bulletin of the Seismological Society of America, v. 95, No. 6, 2081–2092.

Goncharov, A. and Nelson, G., 2010, Seismic Velocity Insights into the Wallaby Plateau. Extended abstracts of the 21st International Geophysical Conference, Sydney, 22-26 August 2010. [CD].

Planke, S. and Edholm, O., 1994, Seismic response and construction of seaward dipping wedges of flood basalts: Vøring volcanic margin. Journal of Geophysical Research, 99, B5, 9263-9278.

Planke, S., Symonds, P.A., Alvestad, E., and Skogseid, J., 2000, Seismic volcanostratigraphy of large-volume basaltic extrusive complexes on rifted margins. Journal of Geophysical Research, v. 105, 19,335-19,361.

Symonds, P.A., Planke, S., Frey, O. & J. Skogseid, 1998, Volcanic evolution of the Northwest Australian continental margin and its implications for basin development, in Purcell, P.G. & Purcell, R.R. (eds), The Sedimentary Basins of Western Australia 2: Proceedings of Petroleum Exploration Society of Australia Symposium, Perth, 1998, 33–54.

White et al., Smith, L.K., Roberts, A.W., Christie, P.A.F., Kusznir, N.J. & iSIMM Team, 2008. Lower-crustal intrusion on the North Atlantic continental margin, Nature, 452, 460–464.