Time-Depth Functions for Basins of the Great Australian Bight

by

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ABSTRACT

The seismic stacking velocity data in the Great Australian Bight are for calculating depths and sediment thicknesses. This work presents time-depth relationships computed from a database of unfiltered stacking velocities and compares these with depths from sonobuoy P-wave velocities and exploration well sonic logs. The comparison suggests that a maximum sediment thickness over-estimate for the Ceduna Sub-basin of about 15% below 4 s two-way-time below sea floor can be expected from the depths derived from stacking velocities. For sediment thickness calculations down to ~4 s two-way travel time (TWT) below sea floor, stacking velocity data give comparable depths to those obtained from wells sonic logs. A piece-wise formula is offered which scales the time-depth function for the Ceduna Sub-basin in order to compensate for the depth overestimate inherent in using stacking velocities to calculate total sediment thickness. Megasequence boundary depths are calculated for the Ceduna Sub-basin to further illustrate data quality.

INTRODUCTION

The basins of the Great Australian Bight (GAB, Figure 1) have received increasing attention over the past decade, particularly by Geoscience Australia in it's efforts to promote them as a frontier of petroleum exploration (Stagg *et al.,* 1990, Totterdell *et al.,* 2000), and by industry to evaluate petroleum prospects (Sommerville, 2001). The Ceduna Sub-basin is the most substantial depocentre within the area. This study estimates a maximum sediment thickness of 15-20 km based on reflection stacking velocities and refraction data. In an endeavour to further the understanding of structural relationships and improve constraints on sediment thickness and lithological parameters, a seismic velocity database has been compiled by Geoscience Australia.

This paper presents an overview of the stacking velocity[1] data presently available in the area, and assesses their quality with reference to well sonic log and sonobuoy refraction data. A future aim is to standardise and improve metadata for seismic velocity information (such as whether velocities are obtained from migrated or un-migrated data), extend the database to national coverage, and take advantage of the Government's new data access policy to deliver these data via the internet.

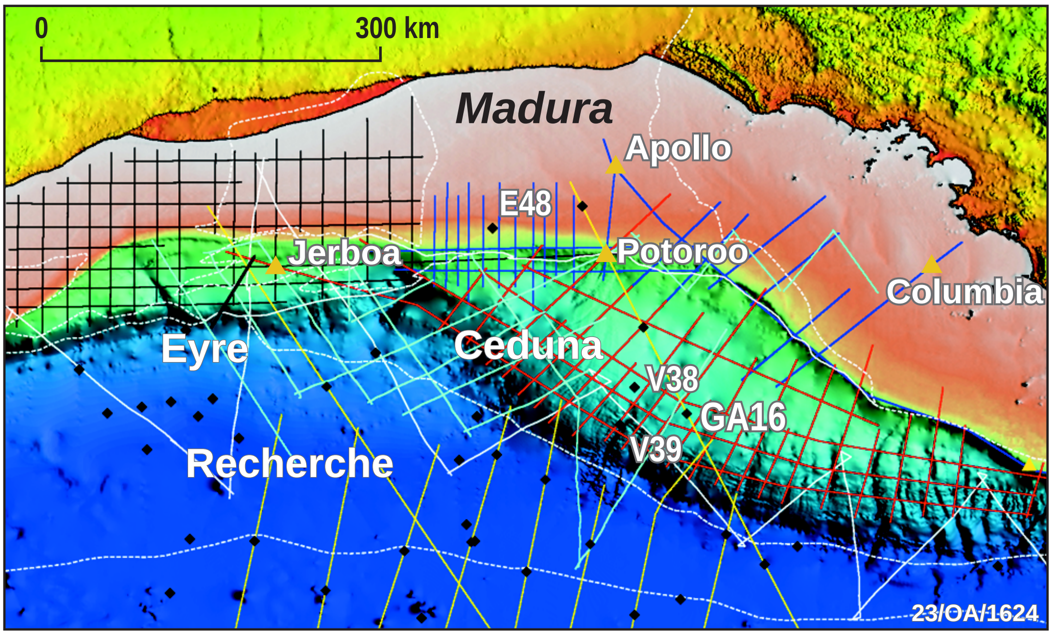

Figure 1. Location map showing data coverage for the study in the area 31°S-37°S, 125°E-135°E with bathymetry and topography as background. Refraction stations (◆). Petroleum exploration wells (▲) Jerboa-1, Potoroo-1, Apollo-1, Columbia-1. Seismic surveys 65 (aqua), 199 (yellow), 215 (red), 216 (blue), 1001 (white), 1187 (black). Dashed white lines are boundaries for Ceduna Sub-basin, Recherche Sub-basin, Eyre Sub-basin and Madura Shelf.

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[1] The stacking velocity is calculated during seismic processing from normal moveout and used to maximise the reflection coherence in common-midpoint stacking. The stacking velocity is dependant upon the offset range, and becomes more poorly determined with increasing depth (Sheriff, R.E., 1991).

DATA COMPILATION

The region selected for the compilation (31°S - 37°S, 125°E - 135°E) includes the Eyre and Ceduna Sub-basins and adjacent shelf and deep-water areas of the southern margin of Australia (Figure 1). Sources of stacking velocity data and comparison data from well logs and refraction probes are listed in Table 1.

In the petroleum industry, various formats are used for the representation of stacking velocities, including 'PROMAX' (Landmark Geophysics), 'WESTERN' (Western geophysical) and 'DISCO' (Cogniseis) as there is no standard. Geoscience Australia uses 'DISCO' for processing convenience and conversion to this format, together with editing gross errors, was the first step in the study. Interval velocities were calculated from the stacking velocities by assuming their equivalence to RMS velocities and by using Dix's equation (Dix, 1955).

Type	Source	Locations
Stacking velocities	GA surveys 65, 199, 215 (DWGAB), 216 (HRGAB), 1001 (Shell Petrel), 1187 (JA90); Total 22,000 km	14871
Wells	Apollo, Columbia, Jerboa, Potoroo	4
Refraction	V8,10-16,18,19,21,32-40; E41,48,51; GA1-18	41

Table 1. Data sources used in the compilation. Surveys 65, 199, 216, 216 by Geoscience Australia, 1001 by Shell, 1187 by Japan National Oil Corporation. Sonobuous V* and E* by Lamont-Doherty Geophysical Observatory from surveys Vema 33 and Eltanin 53 respectively; GA* by Geoscience Australia from survey 199. Alternative or common names for surveys are in parentheses.

Depths below sea floor to each of 198,813 points in the velocity functions were computed from the interval velocities. Thin intervals less than 100 ms, travel times greater than 10 s and interval velocities greater than 8 km/s were excluded. The results were then plotted against TWT through the sediments (Figure 2).

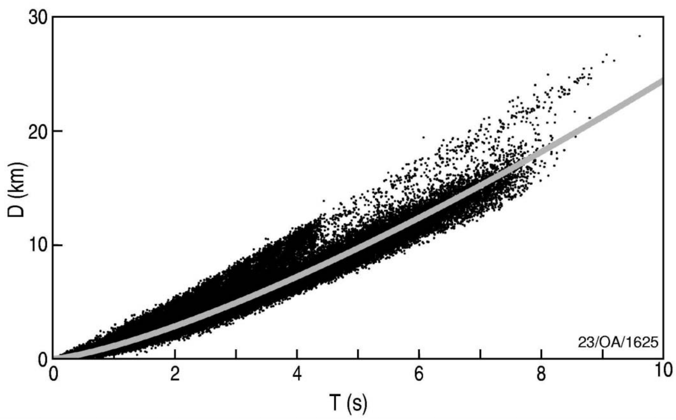


Figure 2. Depth vs time plot calculated from 14,871 stacking velocity functions with no smoothing. D is depth below sea floor (km); T is TWT below sea floor (s). Interval velocities were calculated using Dix equation assuming equivalence of stacking velocity and RMS velocity. The distribution about the trendline $D = 1.194\ T^{1.33}$ has a standard error of 0.87 km and correlation coefficient of 0.97.

ANALYSIS AND COMPARISONS

Figure 2 shows calculated time-depth points distributed within an envelope with an upper boundary of approx. 6 km/s interval velocity and a lower boundary of approx. 4.5 km/s interval velocity when measured at 5 s TWT. Following Faust (1950), a power law depth-time function can be fitted by least-squares technique to these data using software developed by Hyams (1997). 95% of depths fall within 1.8 km (twice the standard error) of the trendline given by the function:

$$D = 1.194\ T^{1.33}$$

where D is the depth below sea floor in km, and T is the TWT in seconds through the sediments. Figure 3 gives the average velocity function derived from this trendline.

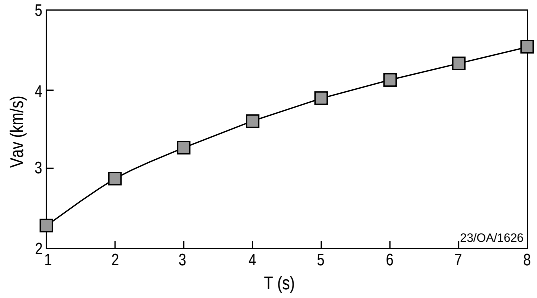


Figure 3. Average velocity (Vav) vs TWT below sea floor (T) derived from the best-fit function in Figure 2.

To give an assessment of data accuracy for practical purposes, the velocity functions were organised into geologically meaningful areas, using zone boundaries as shown in Figure 1 for the Ceduna Sub-basin, Eyre Sub-basin, Recherche Sub-basin and Madura Shelf. Table 2 gives a statistical summary of the distributions about the best-fit power function for each area. The standard error for the estimate improves, and gives a more reliable estimate of the expected error for depth conversion of horizons interpreted from travel time seismic sections.

Area	a	b	E	R	N
Eyre	1.068	1.48	0.59	0.989	5971
Ceduna	1.040	1.38	0.56	0.989	119262
Madura	1.551	1.31	0.71	0.986	31951
Recherche	1.079	1.46	0.37	0.972	14410
All data	1.194	1.33	0.87	0.973	198813
Duntroon	1.249	1.27	-	-	-
Eucla	1.216	1.13	-	-	-

Table 2. Statistical summary for the distribution of time-depth points calculated from stacking velocity functions with no smoothing. The power function $D = a\ T^{b}$ was fitted to the distributions; D and T as defined for Figure 2. E is the standard error (km), R is the correlation coefficient for the fitted curve and N is the number of time-depth pairs. The data for Duntroon and Eucla Sub-basins are from Stagg *et al.* (1990) for comparison.

Stacking velocities are commonly understood to give increasingly unreliable interval velocities with increasing depth. To illustrate this, examine the moveout curves given in Figure 4 for a hypothetical earth model.

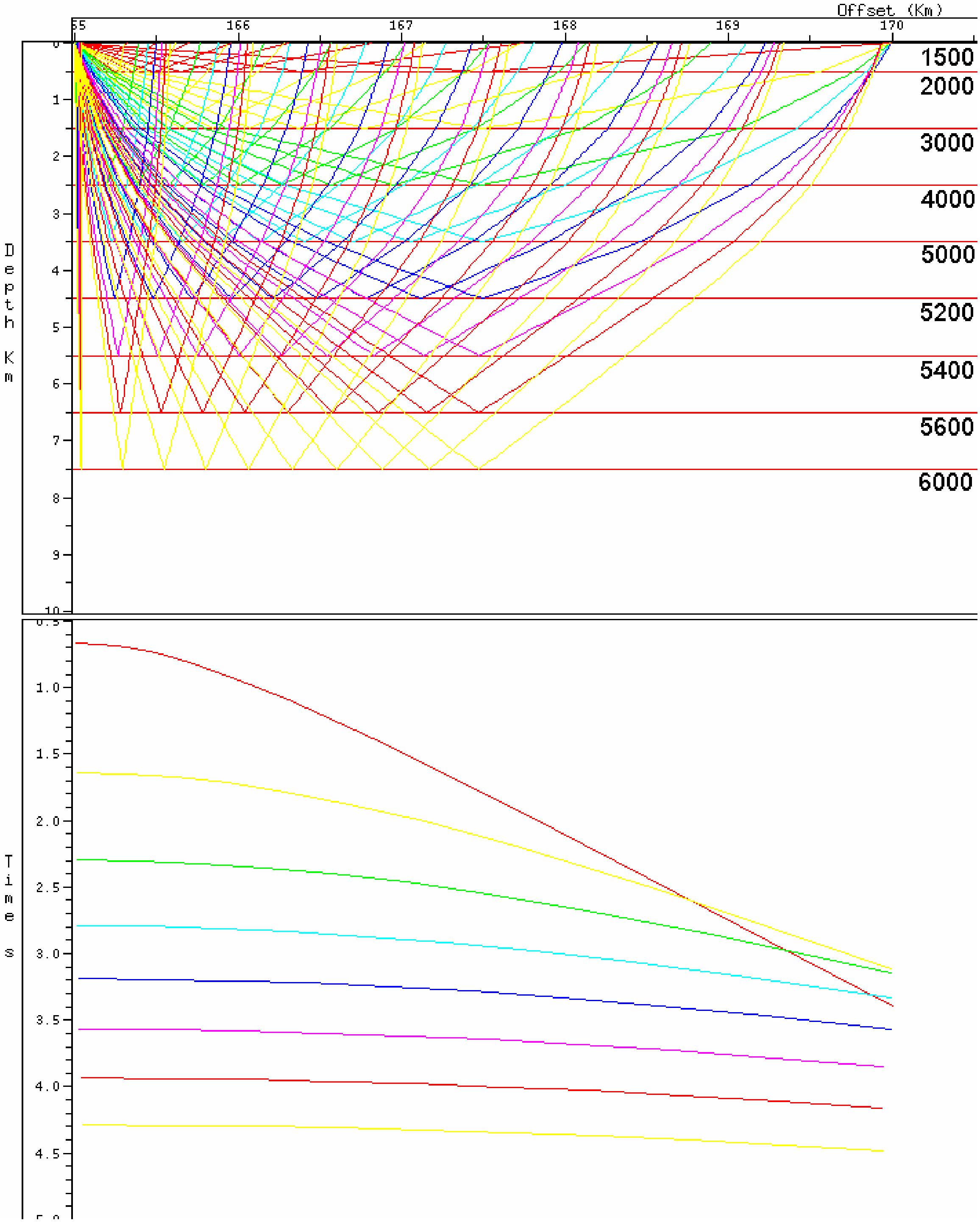


Figure 4. Reflected ray paths (upper) and travel time curves (lower) for a nominal crustal model in 500 m of water with velocities in nine horizontal layers as shown in m/s. The horizontal extent of 5 km corresponds to a typical seismic streamer length. The diagram illustrates how the reliability of stacking velocities decreases with increasing depth as the moveout on the deeper events becomes insignificant for any particular offset.

The small moveout on the deeper events makes the picking of stacking velocities increasingly uncertain. Indeed, if we propose a measure of confidence proportional to moveout, it can be shown that the confidence falls asymptotically to zero with increasing travel time.

The fitting of a smooth curve to the stacking velocity data points in Figure 2 does not reveal this, but merely indicates the uncertainty based on the distribution. A comparison with direct measures of velocity taken from exploration wells and using sonobuoys gives a better insight into the reliability of the stacking velocities for this area.

While the study area is sparsely sampled by wells, the velocities calculated from sonic logs show close agreement with the stacking velocity data taken at proximal shotpoint locations from intersecting seismic lines (Figure 5).

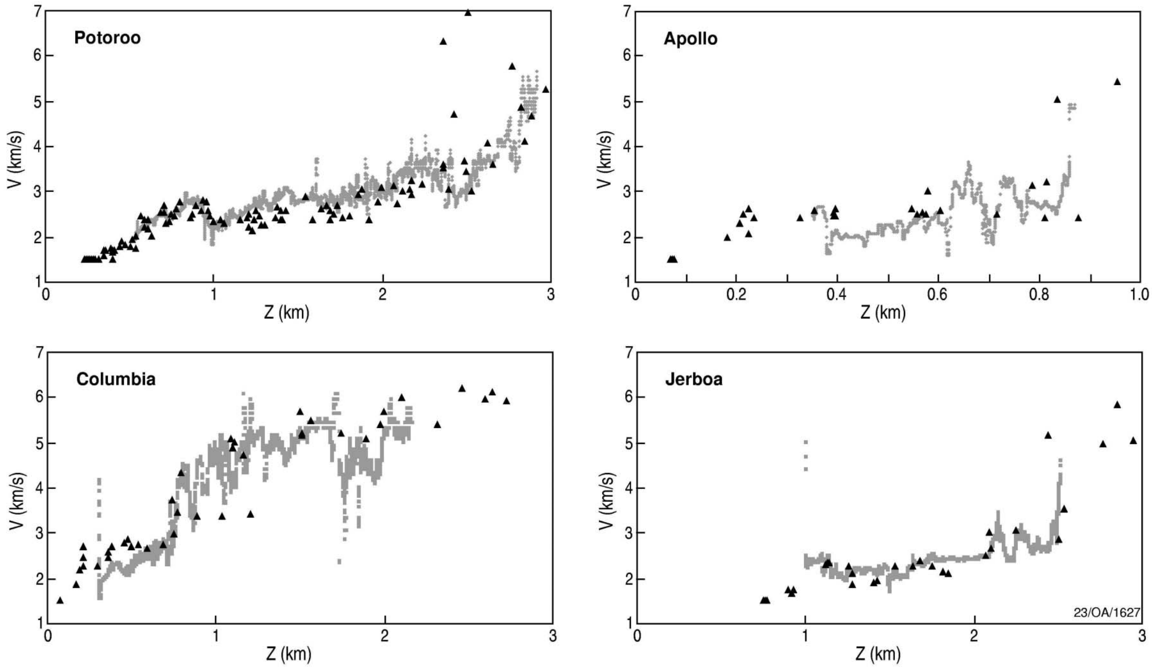


Figure 5. Sonic logs (grey dots) from the four wells with interval velocities calculated from stacking velocity data (▲) near the wells (within 10 km). Interval velocities taken as follows: Potoroo-1 (surveys 199, 215, 216, 1187), Apollo-1 (216), Jerboa-1 (215), Columbia-1 (216). Sonic logs were despiked using a 31 point median filter.

Figure 6 shows velocity-depth relationships from selected refraction records on the Ceduna Sub-basin and Madura Shelf acquired by the Lamont-Doherty Geological Observatory (Konig and Talwani, 1977; Talwani et al. 1979) and Geoscience Australia (Sayers et al. unpub.), and compares them to interval velocities calculated from proximal stacking velocity functions. A good match between the two datasets is evident to approximately 5 km below sea floor, after which the noise in the stacking velocity-derived depths increases. This is especially in V39 and GA16 where velocities exceeding 6 km/s become common. These high velocities should be treated with caution as they may be low confidence picks or derive from within basement.

Although sonobuoy studies do not themselves provide an absolute measure of sonic velocity, they are the only source of directly measured velocities in deep water. Issues affecting sonobuoy velocity studies are:

- In the older studies, events from the sedimentary section were scarce and investigators were often compelled to use assumed velocities in the shallow section.
- The uncertainty of distinguishing between refraction and wide-angle reflection events. A refraction velocity characterises the earth along a raypath below a velocity discontinuity, while a velocity from modelling a wide-angle reflection characterises the whole section.
- The velocity distribution in the sedimentary column is not likely to be isotropic. This means that the refraction velocity (horizontal orientation) will not be the same as the vertical velocity which the stacking velocity represents.
- The sonobuoy position is generally unknown, resulting in undetermined errors in velocity calculations.
- Sonobuoy measurements are not carried out in reciprocal directions to allow calculation of true velocity in the case of dipping refractors.
- The refraction velocity characterises the earth along a raypath below a velocity discontinuity, as noted above, and interpreters invariably assign a constant velocity for the layer below that. This practice leads to underestimated depth from sonobuoy data, as sonic velocity generally increases with depth.

In view of these issues, any conclusions arising from the comparisons done here must be treated with caution.

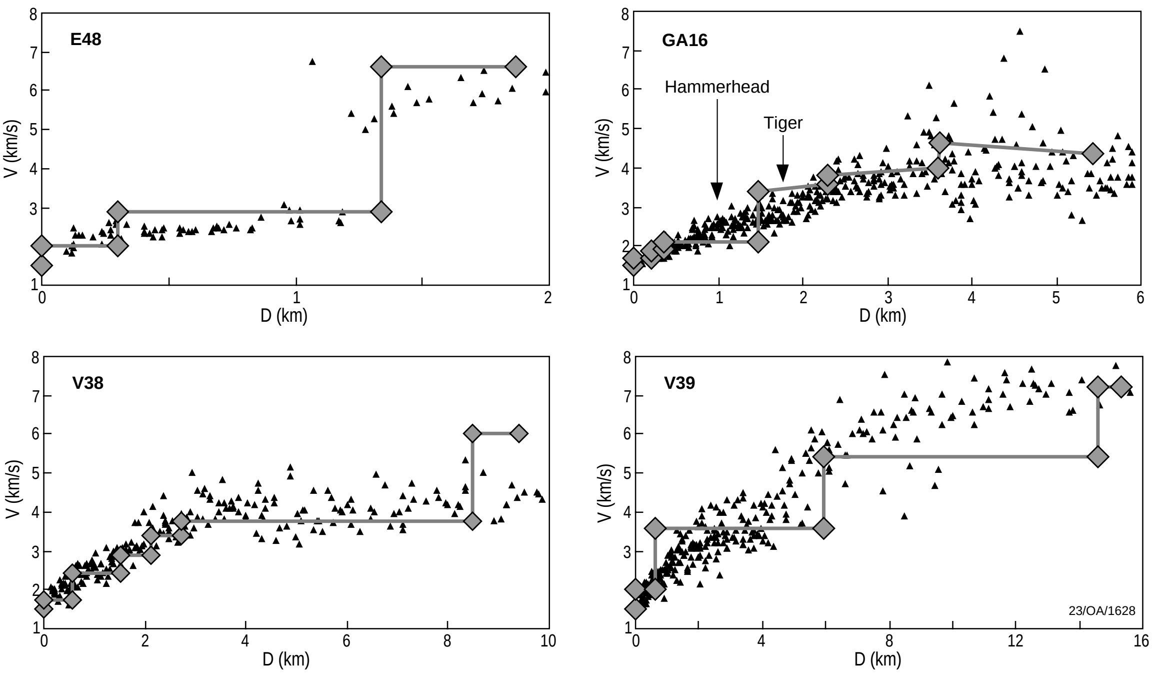


Figure 6. Velocity-depth profiles from sonobuoys (◆) and interval velocities from stacking velocity data calculated from proximal (within 10 km) velocity functions (▲). Interval velocities were taken from these surveys: survey 216 (proximal to E48); 65, 199 and 216 (proximal to GA16); 215 (proximal to V38 and V39). GA16 shows correlation with the Hammerhead (1.9 - 3.0 km, 2.1 km/s) and Tiger (3.0 - 3.8 km, 3.5 km/s) super- sequences.

	a	b	E	R
V38	0.948	1.33	0.07	1.000
V38 sv	1.043	1.34	0.27	0.998
V39	1.004	1.40	0.07	1.000
V39 sv	0.837	1.56	0.32	0.997
GA16	0.862	1.49	0.08	0.999
GA16 sv	0.994	1.35	0.22	0.997

Table 3. Statistical summary for distributions of time-depth points from three sonobuoys (V38, V39, GA16) and those calculated from proximal stacking velocity functions (V38sv, V39sv, GA16sv) about the function D = a T ^{b} where D is depth below sea floor (km) and T is travel time below sea floor (s). a,b,E,R defined as in Table 2. For the two deep sonobuoys V38 and V39 the higher b coefficient signifies appreciable over-estimated depth from stacking velocity data, illustrated in Figure 6.

Neither sonic log data nor refraction results over the Ceduna Sub-basin give sufficient resolution spatially or in depth to extrapolate a calibration to stacking velocity time-depth curves. The coefficients for best-fit power functions calculated from refraction data from three sonobuoys in the Ceduna Sub-basin, and proximal stacking velocity functions are given in Table 3. Time-depth plots of the same data for sonobuoy locations V38 and V39 are shown in Figure 7. This illustrates that a depth over-estimate of 15-20% may be expected in the stacking-velocity derived data for this area, for depths exceeding ~4 s travel time below sea floor.

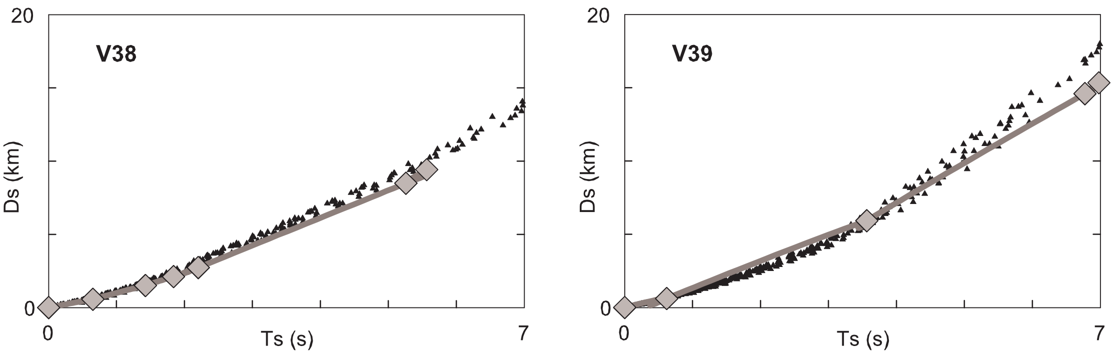


Figure 7. Depth vs time below sea floor for sonobuoys V38 and V39 (◆) and proximal interval velocities from stacking velocities (▲) indicating an over-estimation of depth with increasing depth becomes significant below approximately 4 s.

DEPTH CONVERSION

An interpolated presentation of the stacking velocity data from within the database is given as a horizon consistent format. This was obtained by linear interpolation from stacking velocity locations (approx. 1-2 km apart) to points along major horizons interpreted from the seismic reflection record. This allows direct computation of depth for these horizons and sets up a geological basis for smoothing or editing of the data, if required. For example, McIntosh & Oden (1993) describe a method for smoothing the stacking velocity field using geological considerations, after firstly time-normalising a horizon-consistent interval velocity dataset to remove compaction effects.

Ceduna Sub-basin seismic horizons chosen for depth conversion in this study are equivalent to:

- base of Tiger supersequence, Turonian to Santonian, Figure 8a, (Totterdell *et al*. (2000)
- base of Blue Whale supersequence, mid-Albian to Cenomanian, Figure 8b, (Totterdell *et al*., 2000)
- base of basin fill, equivalent to top basement or base of seismically resolvable Bight Basin succession (Figure 8c).

The grid cell size used in these figures is 0.04° (approximately 4.4 km), while the bathymetry and topography are given in the background for reference using discontinuous and non-linear colour spread. The colour spread for the horizon depths are linear and identical for each image.

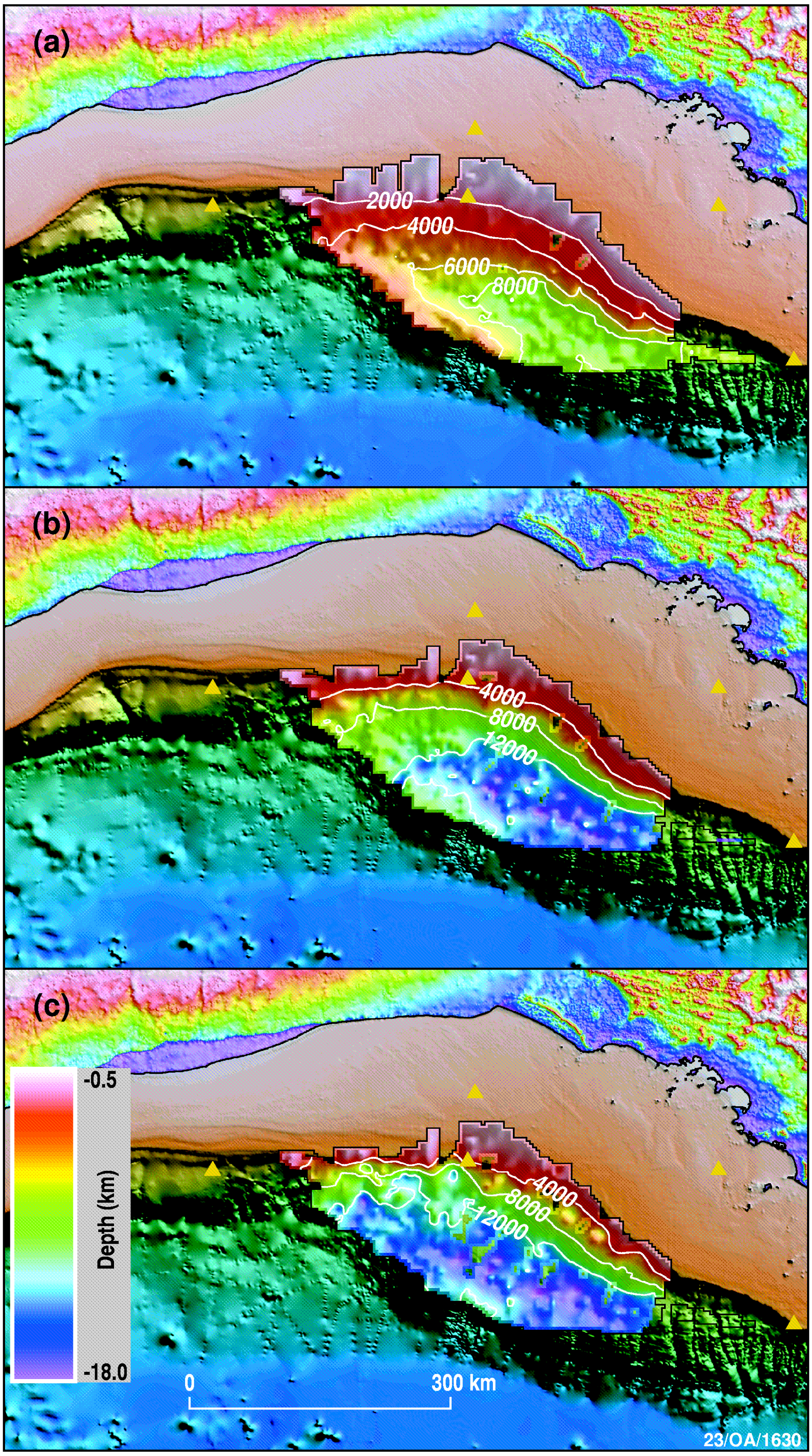


Figure 8. Depth to the base of selected supersequences and the limit of seismic penetration in the Ceduna Sub-basin. data are derived from stacking velocities using a grid cell size of 0.04° (~4.4 km). Bathymetry, topography and location of petroleum exploration wells (▲) are also shown. The colour spread for the horizon depths are linear and identical for each image. Contour interval is 2000 m. (a) Tiger super-sequence (Turonian), maximum depth ~10 km. (b) Blue Whale super-sequence (mid-Albian), maximum depth ~17 km. (c) total sediment or limit of penetration from seismic reflection records, maximum depth ~18 km.

TIME-DEPTH FUNCTIONS

From analysis of stacking velocities, and assuming that shales and sands predominate in the stratigraphic succession, Table 2 gives the best-fit power trendlines for the depth versus time data in each of the defined sub-basins. The power function:

$$d_s = a.t_s^{\,b} \qquad \text{.........①}$$

was fitted to the distributions, after Faust (1950), where the following notation is used:

d_s	depth below sea floor (km)
t_s	TWT below sea floor (s)

To compute depths for this analysis, interval velocities were calculated using the Dix equation (Dix, 1955) assuming equivalence of stacking velocity and RMS velocity.

A comparison of the depths derived from stacking velocities (by-products of processing the reflection seismic record) and those from wells and sonobuoys (direct measurements) indicate that the former are over-estimated in the deeper parts of the section. For the Ceduna Sub-basin the stacking velocity depths are reliable down to 4 s TWT depth below sea floor, but from there the error increases to about 15%[2] at a maximum depth of 7 s two-way time below sea floor. There is insufficient information from 4 s to 7 s to determine if the error increase is linear or otherwise. Below 7 s there is no information about the reliability of stacking velocity depths. The following section develops a piecewise time-depth function which incorporates this observation and adjusts depths accordingly.

Modified time-depth function

To incorporate a correction for the discussed over-estimates into the time-depth curve (equation 1), a linear scale factor will be applied, as there is insufficient information to justify using a higher order correction function. First, the following additional variables are required:

t	TWT from sea level to point in sedimentary column (s)
Z	depth, from sea level, at time t (km)
d_w	water depth, $Z - d_s$ (km)
t_w	TWT through water layer, $t - t_s$ (s)
k	scale factor which adjusts calculated depth to true depth

[2] This amount of over-estimate is close to typically discussed among seismic processors (eg. 20% F. Kroh, Geoscience Australia, personal communication, 2003)

Using the scale factor 'k' to correct the depths, the time-depth function becomes:

$$d_s = k.a.t_s^b$$

So,

$$\begin{aligned} Z &= d_w + d_s \\ &= d_w + k.a.t_s^b \\ &= d_w + k.a.(t - t_w)^b \\ &= d_w + k.a.(t - 4d_w/3)^b \qquad \ldots\ldots \text{②} \end{aligned}$$

(Note that the last step assumes acoustic speed in water of 1.5 km/s.)

Equation 2 gives the depth as a function of travel time, where the scale factor 'k' is a linear adjustment for the error in the stacking velocities.

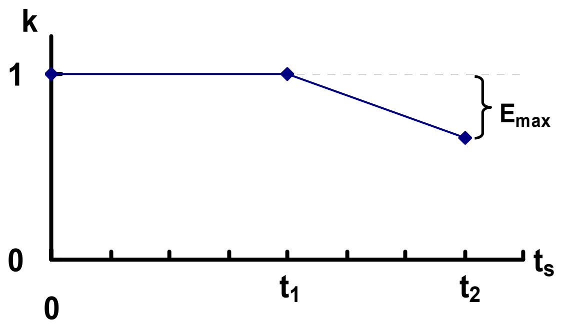
The magnitude of 'k'

When comparing velocities from wells and sonobuoys with stacking velocities it was noted that they agree up to a certain travel time, t_1 . From this point the over-estimate in depth progressively increases to, say, E_{max} at travel time t_2, beyond which we have no information.

In algebraic terminology,

$k = 1$	for $t_s < t_1$,
$k = 1 - E_{max}$	for $t_s = t_2$ and
$k = \varnothing$ (is undefined)	for $t_s > t_2$

Furthermore, we will use a linear interpolation between t_1 and t_2. This may be represented graphically:



and finally, described as the following piecewise function:

$k = 1$	for $t_s \le t_1$
$k = 1 - E_{max}\,(t_s - t_1) / (t_2 - t_1)$	for $t_1 < t_s \le t_2$
$k = \varnothing$	for $t_s > t_2$

If an undefined 'k' is troublesome, such that it leads to too much loss of data, it is suggested that a constant $k = 1 - E_{max}$ be used for $t_s > t_2$ as there is insufficient information to suggest that it becomes smaller than that.

Example for Ceduna Sub-basin

$t_1 = 4$, $t_2 = 7$, $E_{max} = 15\%$, then

$k = 1$	for $t_s \leq 4$
$k = (24 - t_s) / 20$	for $4 < t_s \leq 7$
$k = \varnothing$	for $t_s > 7$

Or, expressed in terms of t,

$k = 1$	for $t \leq t_w + 4$
$k = (24 - t + t_w) / 20$	for $t_w + 4 < t \leq t_w + 7$
$k = \varnothing$	for $t > t_w + 7$

CONCLUSIONS

A stacking velocity database for the basins of the Great Australian Bight can be used with confidence for depth conversion of interpreted megasequence boundaries without need for prior smoothing. Interval velocities derived from the stacking velocities are in agreement with seismic velocities from wells and sonobuoys to a depth of ~4 s TWT below sea floor. Thereafter the depths from stacking velocities diverge to a maximum overestimate of at least 15%.

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