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Time-Depth Functions for the Otway Basin
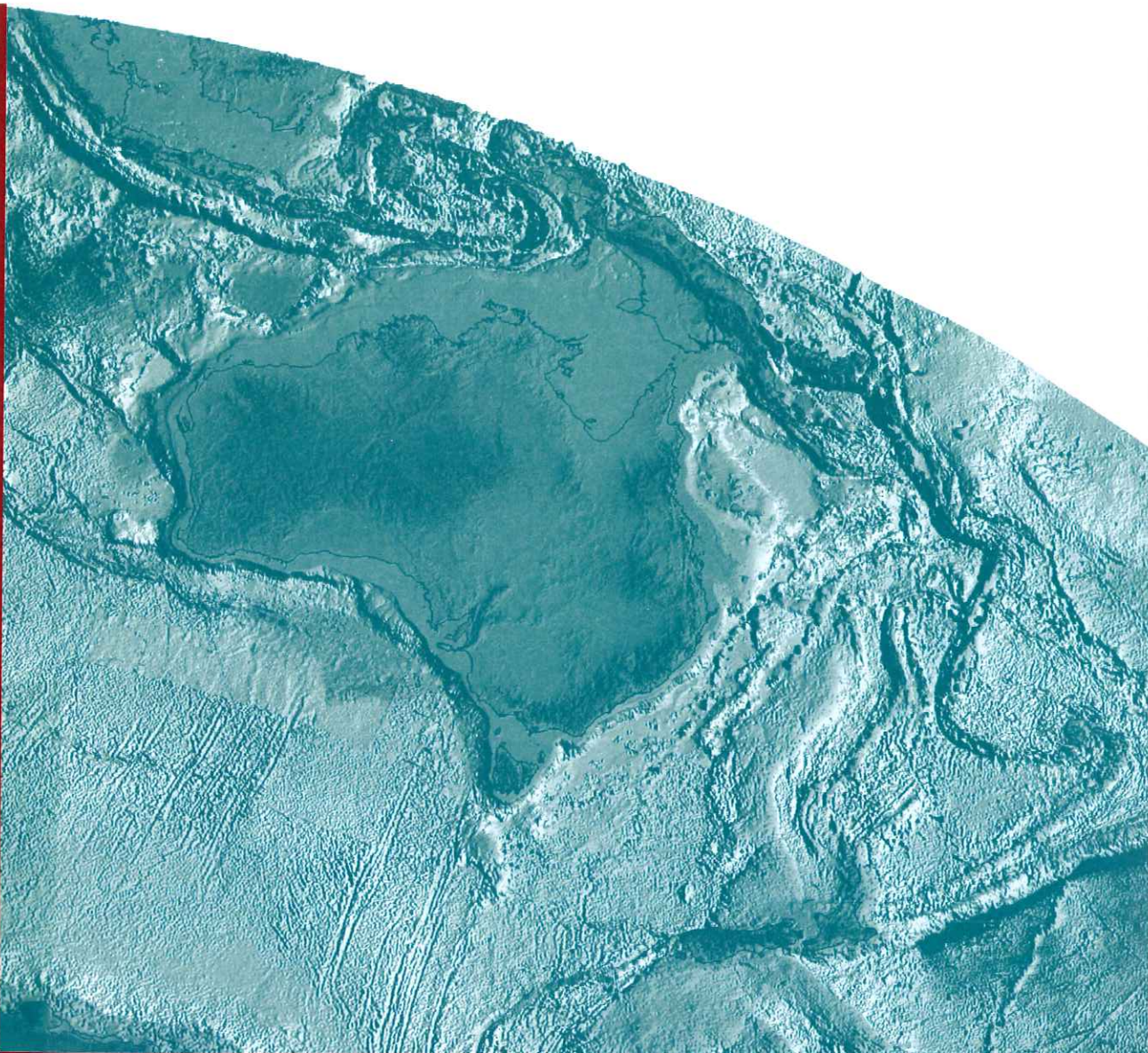
Peter Petkovic

TIME-DEPTH FUNCTIONS FOR THE OTWAY BASIN

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ABSTRACT

The seismic stacking velocity data in the Otway Basin are for calculating depths and sediment thicknesses. This work presents time-depth relationships computed from unsmoothed stacking velocities and compares these with functions obtained from sonobuoy refraction data and exploration well sonic logs. The comparison suggests that a total sediment thickness over-estimate for the Otway Basin of about 20% can be expected from the depths derived from stacking velocities alone. On the other hand, for sediment thickness calculations down to ~1.5 s two-way travel time below sea floor, stacking velocity data give comparable depths to those obtained from the sonic logs. A piece-wise formula is offered which scales the time-depth function for the Otway Basin in order to compensate for the depth overestimate inherent in using stacking velocities to calculate total sediment thickness.

INTRODUCTION

The Otway Basin (Figure 1) has been of considerable interest over the past decade to Geoscience Australia and state surveys in their efforts to promote frontier petroleum exploration (Blevin *et al*, 1995; Moore *et al*, 2000, Woolands & Wong, 2001; Boult & Hibburt, 2002, Bernecker & Moore, 2003) and to industry in evaluating petroleum prospects (Power et al, 2000). A study by SRK Consulting commissioned by Geoscience Australia (Teasedale, *et al*, 2002) suggests a maximum sediment thickness of up to 13 km based on a proprietary method which depends on magnetic depth estimates. In an endeavour to further the understanding of structural relationships within the basin and improve constraints on sediment thickness and lithological parameters, a seismic velocity database has been compiled by Geoscience Australia.
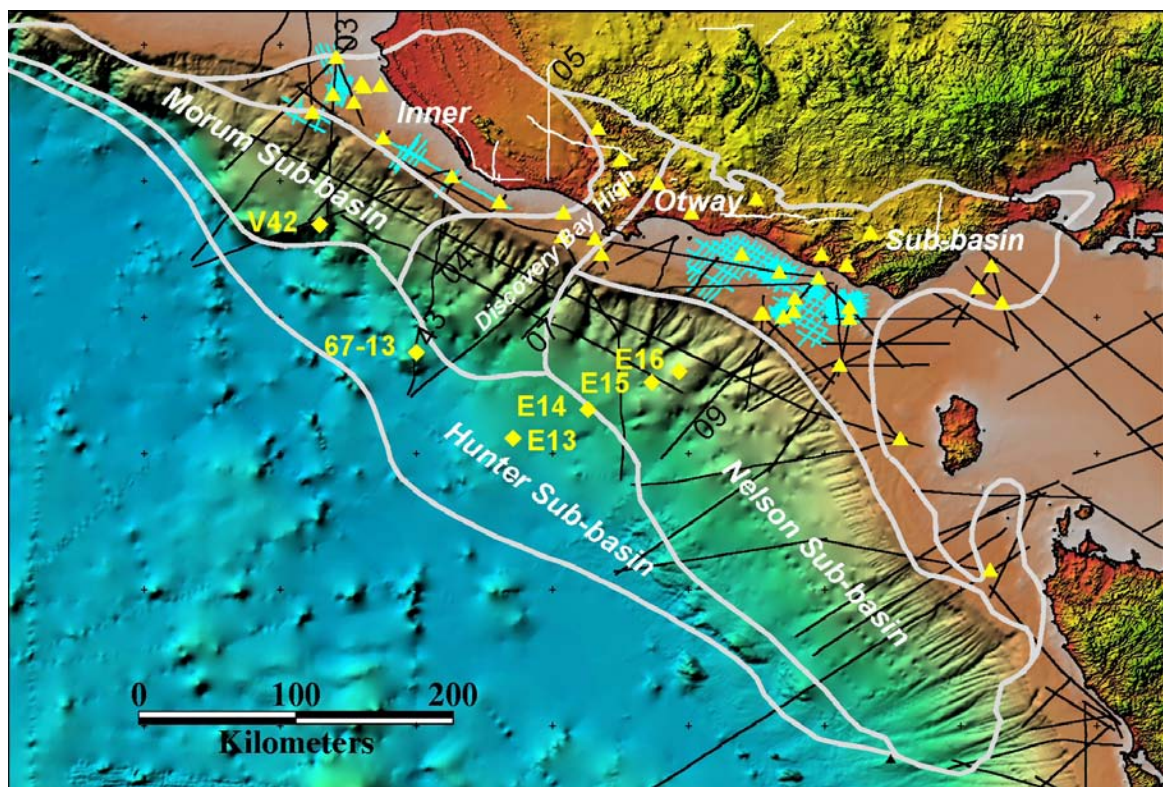
Figure 1. Location map showing data coverage for the study in the area 36°45'S - 42°30'S, 137°00'E - 145°30'E **with bathymetry and topography as background. Refraction stations (◆). Petroleum exploration wells (▲) for which sonic logs were available to this study. Seismic surveys BMR92OT (white), 40, 48, 78, 137, 148, 172 (black), 2300 (mauve). Boundaries for Hunter Sub-basin, Morum Sub-basin, Nelson Sub-basin, Discovery Bay High and Inner Otway Sub-basin (after Moore *et al* 2000) are in grey. Geoscience Australia seismic lines 03, 04, 07, 09 (survey 137), 43 (survey 48), and 05 (BMR92OT) were depth converted using the stacking velocities.**

This report presents an overview of the stacking velocity data presently available in the area, assessing their quality with reference to well sonic log and sonobuoy refraction data. A future aim is to standardise and improve on metadata about sesimic 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.

DATA COMPILATION

The region selected for the compilation (36°45'S - 42°30'S, 137°E - 145°30'E) includes onshore, shelf and deep-water areas of the Otway Basin as part of the southern margin of Australia. Sources of stacking velocity data and comparison data from well logs and refraction probes are listed in Table 1, with locations shown in Figures 1 & 2.

Type	Source
Stacking velocities	Surveys 40, 48, 78, 137, 148, 172, 2300(OH91), BMR92OT5
Wells	see list in Table 2 and Figure 2
Refraction	67-13, V42, E15, E16

Table 1. Data sources used in the compilation. Surveys 40, 48, 78, BMR92OT by Bureau of Mineral Resources (BMR); 137, 148, 172 by Australian Geological Survey Organisation; 2300(OH91) by Western Geophysical. Sonobuoys V* and E* by Lamont-Doherty Geophysical Observatory from surveys Vema 33 (Talwani, et. al. 1979) and Eltanin 37 (Houtz and Markl, 1972) respectively; 67-13 by BMR (Williamson et. al., 1989).
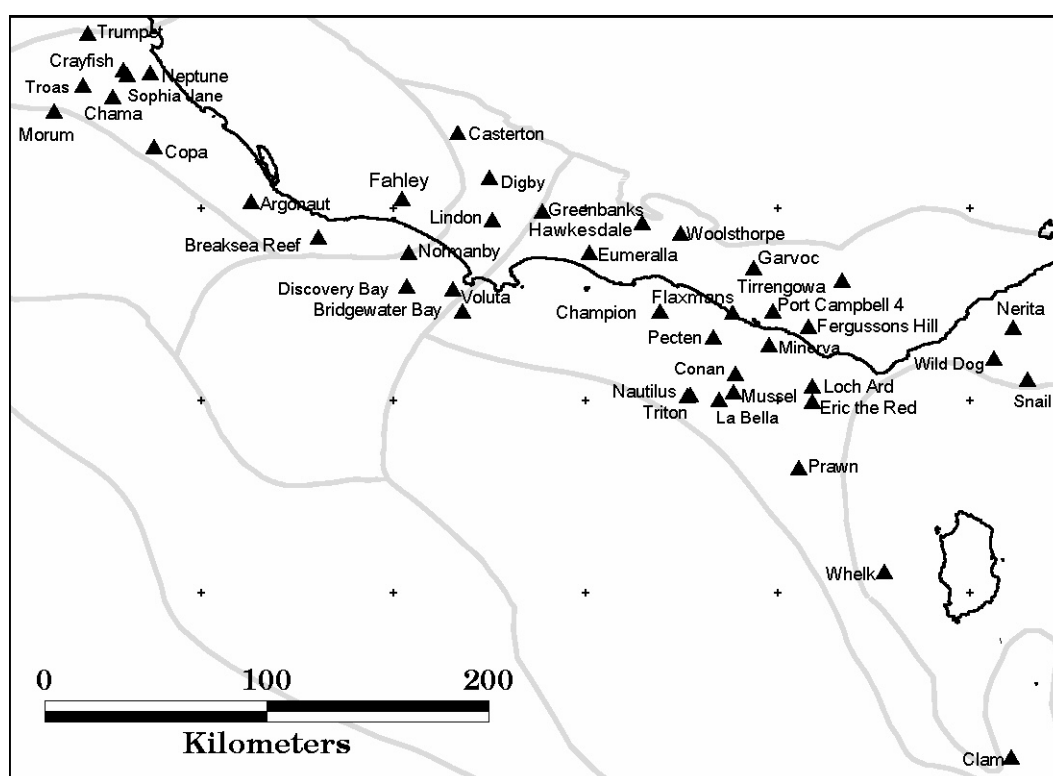

Figure 2 - Locations and names of wells used in this study. The map covers 37°S - 41°S, 139°E - 144°30'E. Sub-basin boundaries in grey as for Figure 1.

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Various formats are used for representation of stacking velocities, including 'PROMAX' (Landmark Graphics), 'WESTERN' (Western Geophysical) and 'DISCO' (Cogniseis) although there is no standard. Geoscience Australia uses the latter for processing convenience. The first step in the study was to convert files to Disco format, and edit gross errors. Interval velocities were calculated from the stacking velocities by assuming their equivalence to rms velocities and using Dix's equation (Dix, 1955). Depth below sea floor to each point in the velocity functions was computed from the interval velocities. Thin intervals shorter than 100 ms, travel times greater than 10 s and interval velocities greater than 7 km/s were excluded as suspect, and the results plotted against two-way travel time through the sediments shown in Figure 3.

ANALYSIS AND COMPARISONS

Depth as a simple power function of time

The depth-time plot in Figure 3 is an amalgamation of stacking velocity data for all surveys across the area. The form of the distribution suggests a simple power law relationship, and this trend was fitted by least-squares technique using software developed by Hyams (1997). 95% of depths fall within 1.6 km (twice the standard error) of the trendline given by the function:

$$D = a\,T^{\,b} \qquad\qquad ①$$

where a = 1.19, b = 1.37, D is the depth below sea floor (km), and T is the two-way travel time through the sediments (s).
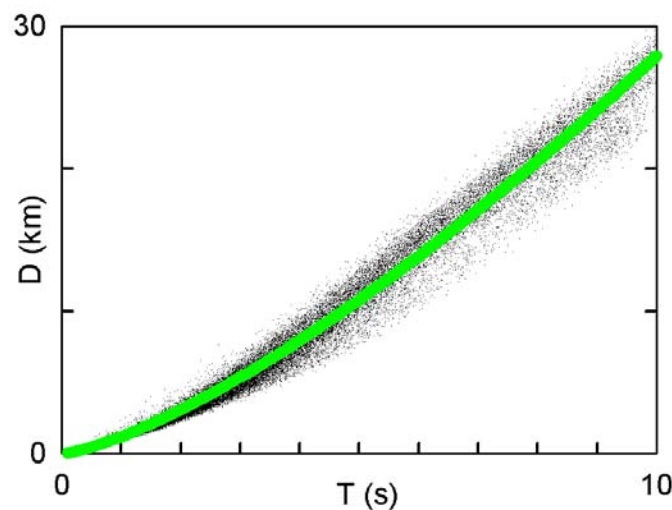
Figure 3. Depth vs time plot calculated from stacking velocity functions with no smoothing for whole of Otway Basin dataset. D **is depth below sea floor (km);** T **is two-way travel time below sea floor (s). Interval velocities were calculated using Dix equation assuming equivalence of stacking velocity and rms velocity. The best fit power function for the distribution is** $D = 1.19\,T^{\,1.37}$ **which gives a standard error of 0.82 km.**

The power law for this type of data is an empirical relationship first developed from velocity measurements of sands and shales in 500 North American wells by Faust (1950). In his study, shallow data (< 600 m) were excluded as well as all calcareous sediments. Faust found b = 1.2, and interval velocity (V_{int}, m/s) as a function of depth of burial (d, m) and age (A, millions years):

$$V_{int} = 46.6 \, (\, d \, A \,)^{1/6} \qquad \qquad ②$$

Faust's empirical relationship (1) appears to model the data satisfactorily. However V_{av} ➠ 0 as T ➠ 0, which is unrealistic. Therefore at shallow depths an alternative model, perhaps linear, may be more appropriate. Figure 4 gives the average velocity derived from this model, for the range of values where it may be reliable.
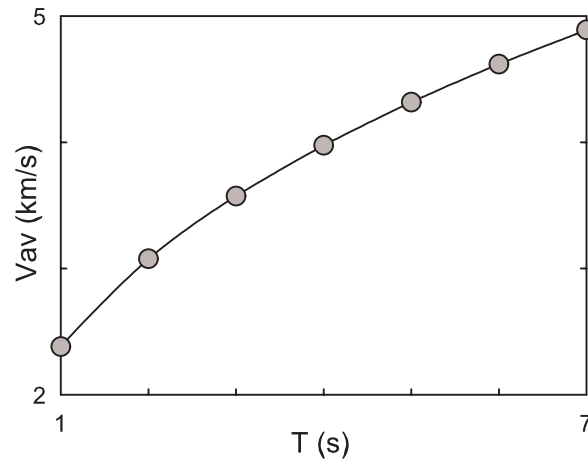
Figure 4. Average velocity (V_{av}) vs two-way travel time below sea floor (T) derived from best fit function in Figure 3, may be expressed as $V_{av} = 2.38 \, T^{\,0.37}$.

Figure 5 shows a comparison of the best-fit time-depth power function from stacking velocities (1) to one obtained using Faust's interval velocity prediction (2). For the latter, a uniform age profile from 0 to 150 Ma is assumed for the top 10 km of sedimentary section. The maximum time corresponds approximately to the onset of deposition of the Casterton Formation in Late Jurassic/Early Cretaceous (Boult & Hibburt, 2001). The maximum depth approximates maximum sediment thickness in the Otway Basin given by Teasedale *et al* (2002). The diagram indicates that stacking velocity data overestimate depth compared to Faust's work by about 15%. That is to say, applying a correction factor of 0.85 to the 'a' coefficient in (1) is enough to bring the curves into coincidence.

Figure 5 - A comparison of stacking velocity derived depth-time curve (circles) with Faust's model based on North American well log analysis (squares). The difference corresponds to a scale factor of 0.15 .

Time-Depth Functions for Selected Otway Basin Wells
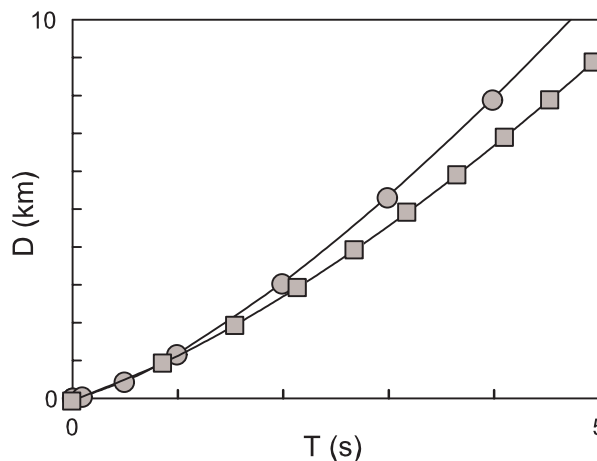
Figure 5 points to a commonly held understanding that stacking velocities give over-estimated and increasingly unreliable interval velocities with increasing depth. In this section, the same data will be compared to velocities from wells from the study area. The Otway Basin is not sampled by wells beyond the edge of the shelf, however the velocities calculated from sonic logs for the offshore Inner Otway Sub-basin (Appendix 1) show close agreement with the stacking velocity derived data taken from proximal shotpoint locations from intersecting sesimic lines. Panel 4 of Appendix 4 describes the software and method used to locate proximal stacking velocity functions.

Sonic logs are characteristically noisy. Bad sonic logs can result from instrumental and environmental noise and wave attenuation due to various conditions, resulting in characteristically spiky data as shown in Appendix 1. To clean up the raw data, some edits were applied, followed by a median filter of 241 points (window length about 4 cm) across all the data. This gave a reasonable result for the purposes of this study. Panel 4 of Appendix 4 describes the software and method used to clean up the sonic log data.

Appendix 2 contains a set of plots of velocity *vs* depth and depth *vs* time comparing despiked sonic log and stacking velocity data. To calculate the depth *vs* time from a sonic log requires continuous velocity measurement, however the shallowest part of the section is usually not logged. In this study, the velocity assigned to the shallowest part of the section where no measurements are available is the average of the shallowest reliable measured value and the projected velocity at zero depth (usually about 1.8 km/s). There is considerable difficulty in applying this procedure automatically because of the noisy character of the sonic log, even after de-spiking. Therefore, the average velocity for the unlogged shallow section was estimated by graphical means and inspection.

Following this, best-fit power functions were calculated for the depth *vs* time data for the offshore wells (Appendix 2) and onshore wells (Appendix 3) using SigmaPlot (SPSS,

2003). The '*a*' coefficient and '*b*' exponent as defined in equation (1) for each well are listed in Table 2.

Well	TD (m)	a	b	E	N
all onshore Otway	-	1.23	1.28	0.15	187,775
all offshore Otway	-	1.21	1.24	0.09	423,297
all Otway Basin	-	1.22	1.24	0.12	611,072
Inner Otway NW					
Argonaut	3707	1.06	1.36	0.03	22,631
Breaksea Reef	4468	1.17	1.30	0.04	26,493
Chama	2748	1.07	1.40	0.01	13,387
Copa	3857	1.11	1.38	0.03	22,521
Crayfish	3196	1.18	1.28	0.03	19,517
Fahley*	3211	1.15	1.33	0.01	7,998
Morum	2439	1.15	1.23	0.02	13,152
Neptune	2436	1.20	1.23	0.03	14,927
Sophia Jane	2430	1.00	1.36	0.03	14,117
Troas	3506	1.05	1.42	0.03	18,410
Trumpet	2256	1.22	1.23	0.03	13,579
Inner Otway SE					
Bridgewater Bay	4200	1.26	1.20	0.03	24,254
Champion	1882	1.22	1.21	0.00	4,147
Clam	1622	1.31	1.24	0.01	8,635
Conan	1870	1.21	1.22	0.01	4,980
Eric the Red	1875	1.21	1.23	0.01	9,817
Eumeralla*	3142	1.09	1.38	0.03	18,586
Fergusons Hill*	3546	1.37	1.35	0.02	15,404
Flaxmans*	3514	1.26	1.38	0.00	6,255
Garvoc*	1533	1.12	1.30	0.01	7,985
Hawkesdale*	1774	1.18	1.25	0.02	9,202
La Bella	2735	1.38	1.16	0.01	7,561
Loch Ard	1397	1.19	1.26	0.02	6,559
Minerva	2425	1.22	1.30	0.02	12,152
Mussel	2450	1.34	1.15	0.01	13,239
Nautilus	2011	1.42	1.18	0.01	11,233
Nerita	2042	1.21	1.34	0.02	12,102
Pecten	2850	1.22	1.30	0.04	16,915
Port Campbell*	2597	1.10	1.30	0.02	16,773
Prawn	3193	1.21	1.27	0.03	19,079
Snail	1235	1.06	1.18	0.01	6,463
Tirrengowa*	1273	1.40	1.39	0.00	6,713
Triton	3545	1.38	1.14	0.02	18,387
Whelk	1466	1.28	1.14	0.01	7,756
Wild Dog	1222	1.10	1.15	0.01	5,766
Windermere 2*	3595	1.07	1.44	0.04	21,182
Woolsthorpe*	1971	1.22	1.29	0.01	11,222
Discovery Bay High					
Casterton*	2494	1.32	1.30	0.03	15,402
Digby*	2088	1.45	1.24	0.01	15,403
Discovery Bay	2776	1.23	1.15	0.02	15,421
Greenbanks*	1226	1.14	1.14	0.01	7,077
Lindon*	3011	1.18	1.35	0.03	19,032
Normanby	3306	1.18	1.31	0.01	17,286
Voluta	3974	1.30	1.16	0.02	22,752

Table 2. Statistical summary for time-depth points from despiked sonic logs. The power function $D = a\,T^{\,b}$ was fitted where D is depth below sea floor or ground level (km) and T is two-way travel time below sea floor or ground level(s). E is the standard error (km), N is the number of time-depth pairs and (*) denotes onshore well. TD is total well depth (m). Appendix 1 gives examples of sonic logs

before and after despiking. Appendix 2 shows plots of the depth-time functions from a selection of wells and fitted power curve whose defining parameters are given in the table.

Taking all the onshore and offshore data together, the time-depth function is given by the values in the first three rows of Table 2. Perhaps unexpectedly, the depth-time function for the Otway Basin wells is almost completely coincident with Faust's North American dataset, as presented in Figure 6.
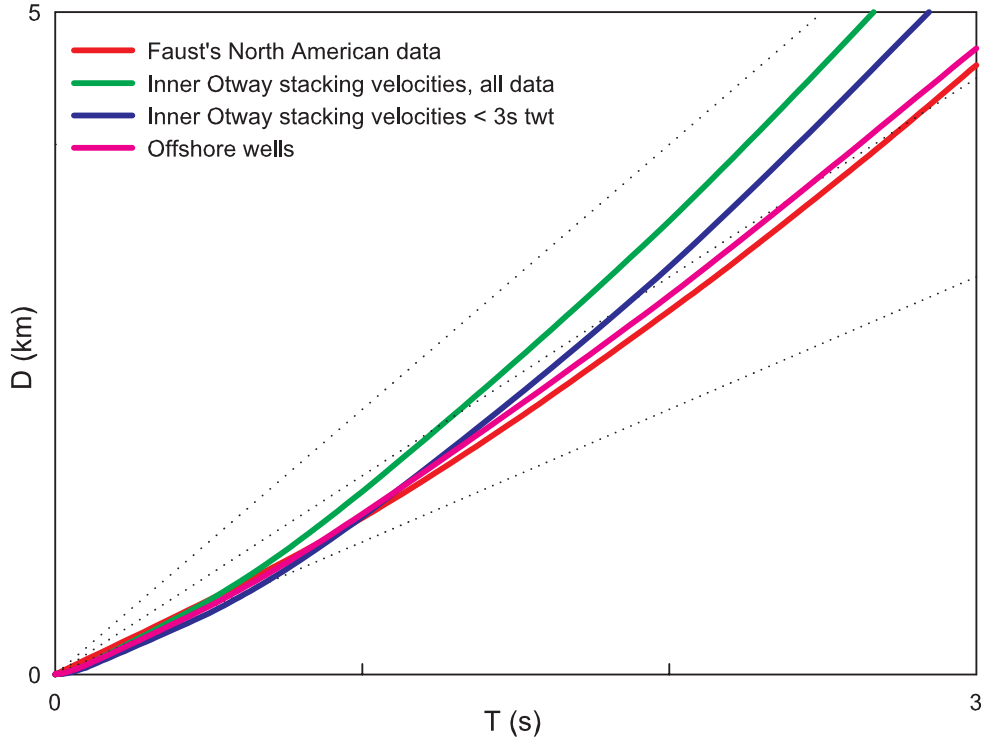

Figure 6. Depth-time relationships for offshore Otway Basin wells available to this study using the values in Table 2 (pink); best-fit power function derived from stacking velocity data shallower than 3 s on shelf (dark blue) using values in Table 3. The divergence of these two curves corresponds to a scale factor of approximately 8% at 2 s and 13% at 3 s. Plotted for comparison are Faust's measurements of North American wells (red), which is in close agreement with the local data. The fourth curve (green) is derived from all stacking velocity data in the Inner Otway area, i.e. down to 16s TWT. The dotted lines show 2, 3 and 4 km/s for reference.

The discrepancy between depth-time functions derived from stacking velocities and those derived from wells is such that the former cannot be extrapolated much below 1.5 s TWT. By inspection of graphs in Appendix 2, and the comparisons shown in Figures 5 and 6, it can be concluded that uncorrected stacking velocities can be used with insignificant error down to typical drilling depths of 1.5 sec TWT, but below that depth, the over-estimate exceeds 5% and becomes significant.

It is unclear whether the data given in Table 2 may be expected to correlate with identifiable geological provinces. Nevertheless, and despite the low number of samples, their distribution is mapped in Figure 7. The most significant feature that correlates with geological boundaries are the high *a* and low *b* values (more closely linear *D-T* relationship) aligning approximately with the Discovery Bay High, and the opposite relationship immediately to the southeast and northwest.   The significance of this

observation is obscure. However it may be argued that the higher linearity of the Discovery Bay High.curves suggests less compressible stratigraphic succession, perhaps lower porosity, and more homogeneous velocity profile. As b → 1, the velocity approaches a constant value throughout the section.
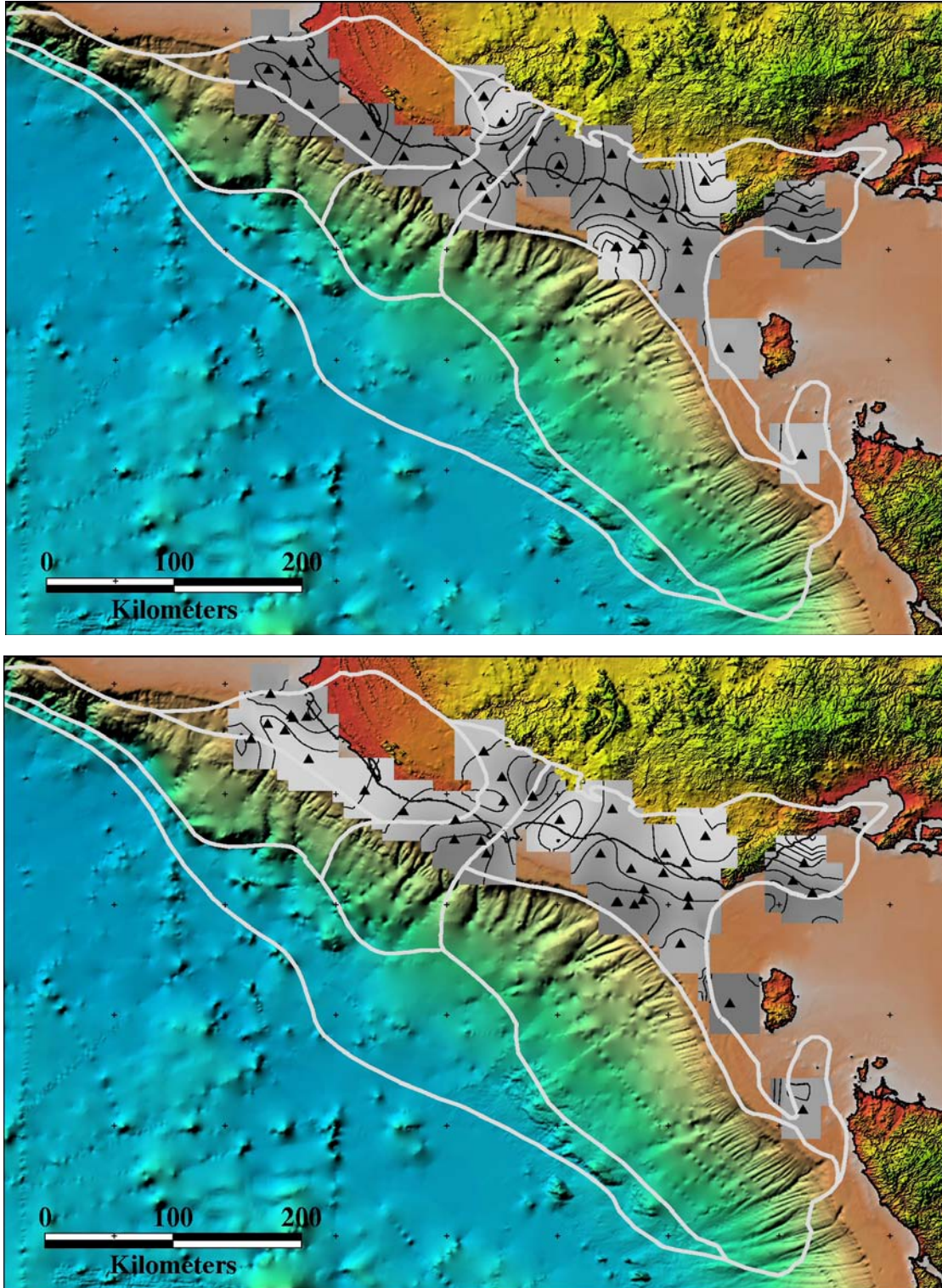

Figure 7. Distribution maps of 'a' coefficient (upper image) and 'b' exponent (lower) for selected wells in Inner Otway Sub-basin, from data in Table 2. The light grey represents the higher end of the range. 99% of grid values fall within the ranges: 1.13 < a < 1.41; 1.15 < b < 1.44.

Sub-basin time-depth functions from stacking velocities

Next, the same stacking velocity functions were organised into geologically meaningful areas, using zone boundaries as shown in Figure 1 for the Hunter Sub-basin, Morum Sub-basin, Nelson Sub-basin, Inner Otway Sub-basin and Discovery Bay High. Table 3 gives a statistical summary of the distributions about the best-fit power function of the form (1) for each area. The standard error for the estimate improves and gives a more reliable estimate of the expected.

Area	a	b	E	N
Otway Basin (all data)	1.19	1.37	0.82	53,965
Inner Otway Sub-basin	1.40	1.31	0.61	19,988
Inner Otway + DHB shelf	1.38	1.31	0.63	21,353
Inner Otway + DHB shelf < 3 s TWT	1.18	1.38	0.21	11,581
Nelson Sub-basin	1.04	1.42	0.80	15,083
Morum Sub-basin	1.14	1.37	0.76	9,719
Hunter Sub-basin	1.29	1.39	0.55	1,967
Discovery Bay High	1.14	1.38	0.61	7,208
Eyre Sub-basin	1.07	1.48	0.59	5,971
Ceduna Sub-basin	1.04	1.38	0.56	119,262
Madura Shelf	1.55	1.31	0.71	31,951
Recherche Sub-basin	1.08	1.46	0.37	14,410
Duntroon Sub-basin	1.25	1.27	-	-
Eucla Sub-basin	1.22	1.13	-	-

Table 3. Statistical summary for 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 as described in Figure 3. E is the standard error (km) and N is the number of time-depth pairs. '+ DHB shelf' refers to the continental shelf part of the Discovery Bay High. Duntroon and Eucla from Stagg et al. (1990) for comparison; Great Australian Bight sub-basins from Petkovic (2004)

Refraction Data

Figure 8 shows velocity-depth relationships from refraction records acquired by the Lamont-Doherty Geological Observatory (Konig and Talwani, 1977; Talwani et al. 1979) and the Australian Bureau of Mineral Resources (Williamson et al. 1989). They are comparing to interval velocities calculated from proximal stacking velocity functions. Panel 4 of Appendix 4 describes the method and software used to extract proximal functions. A good match between the two datasets is evident to approximately 4 km below sea level, after which the noise in the stacking velocity-derived depths increases and velocities exceeding 6 km/s predominate. These should be treated with caution as they may be low confidence picks or derive from deep within basement.

Neither sonic logs nor refraction results over the Otway Basin give sufficient resolution spatially or in depth to extrapolate a calibration to stacking velocity time-depth curves. From four sonobuoys in deep water, and proximal stacking velocity functions, the coefficients for best fit power functions are given in Table 3 and time-depth plot for V39

is given in Appendix 2. The latter indicates a depth over-estimate of at 15-20% may be expected in the stacking-velocity derived data for this area for depths exceeding ~4 s travel time below sea floor.
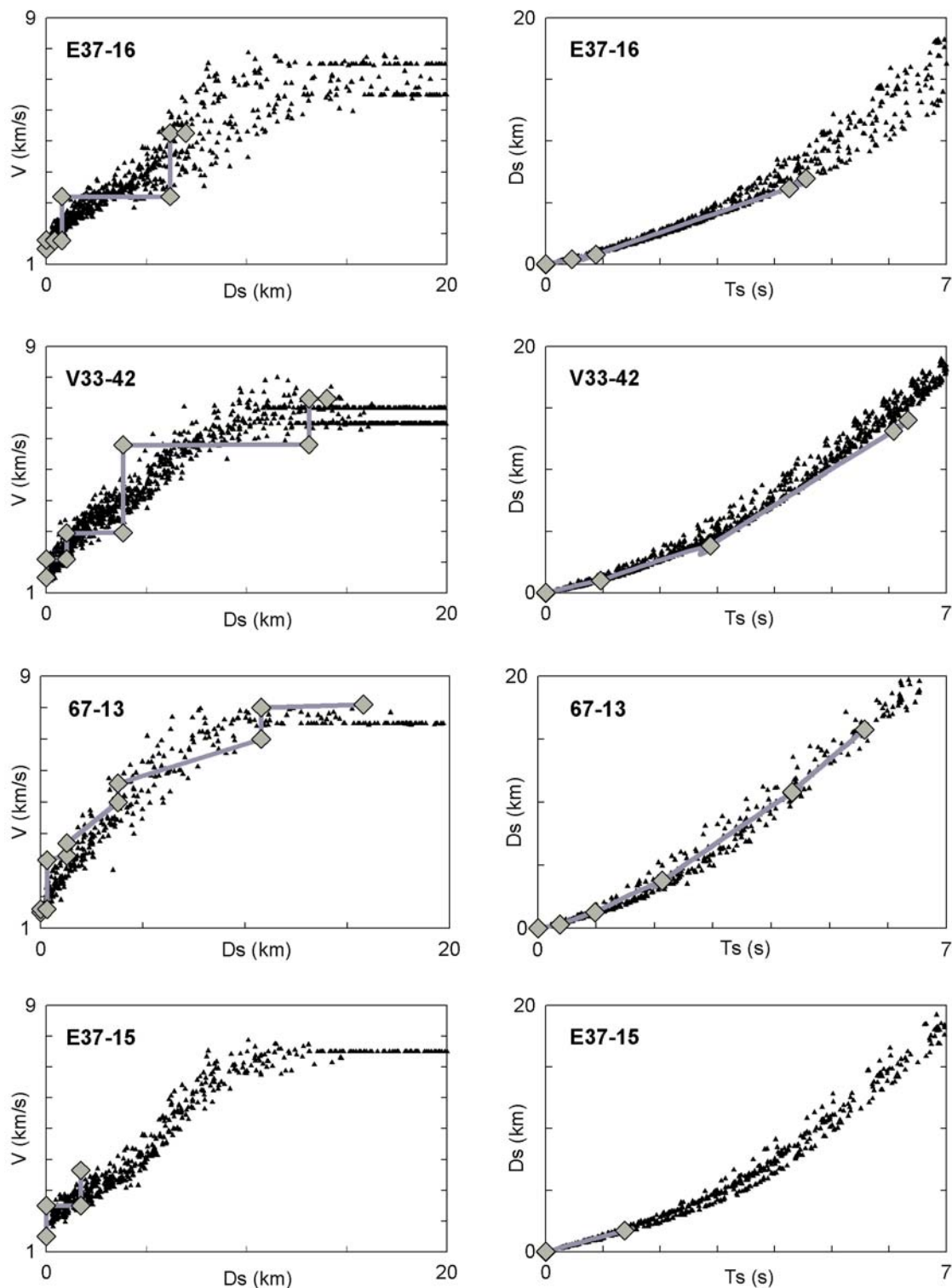

Figure 8. Velocity-depth profiles from sonobuoys (◆) and interval velocities from stacking velocity data calculated from proximal (within 10 km) velocity functions (▲). 67-13 shows good correlation between stacking velocity derived depths and from refraction. V33-42 and E37-16 confirm trends seen in the GAB where stacking velocity depths are overestimated (Petkovic, 2004). E37-15 is inconclusive due to shallow penetration.

	a	b	E	N
E37-15	1.24	1.03	0.00	3
E37-15 sv	0.90	1.54	0.62	613
E37-16	0.95	1.30	0.07	8
E37-16 sv	0.94	1.44	1.14	843
V33-42	0.73	1.60	0.19	8
V33-42 sv	1.06	1.45	0.55	1282
67-13	1.24	1.48	0.05	10
67-13 sv	1.23	1.48	0.68	367

Table 3. Statistical summary for distributions of time-depth points for four sonobuoys and those calculated from proximal stacking velocity functions (sv) about the function $D = a\,T^{\,b}$. D is depth below sea floor (km) and T is travel time below sea floor (s). a, b, E, N defined as in Table 2. The results for sonobuoy E37-15 are not significant due to the small number of points.

DEPTH CONVERSION OF SEISMIC REFLECTION DATA

Several lines from survey 137 were chosen for depth conversion using the stacking velocities as discussed above. As stacking velocity functions are applied individually by the processing software, it is necessary to pre-process the data in order to remove short-period variations between functions and in time. A number of processes were involved (outlined in Appendix 4) consisting essentially of the following three steps:

- reformating velocity data into a consistent format
- smooth stacking velocity data
- apply depth conversion process

The software to perform these tasks was a combination of Cognisies Disco and in-house developed programs. Velocity profiles of before and after smoothing are given in Figure 9 and 10 and the reflection data are given in Figures 11 and 12 for lines 137/03 and 137/09 respectively. Both of these lines show prominent reflection events at the major crustal boundaries including Moho. Note how the casual interpretation of dip of major events can be markedly different on the time section compared to the depth section. When the vertical time scale of the seismic image is re-displayed in depth using the stacking velocities estimated from seismic processing, and speed of sound in water, the resultant image is less distorted and more easily interpreted for structural and geometric information.

It should be noted, however, that distortion still remains after the depth conversion process. The depths obtained from stacking velocities are too great when compared to depths obtained from direct measurement of velocities through refraction probes, as discussed above. This overestimate may be as much as 20%, although there are insufficient data to allow a scaling to be applied with confidence. Therefore, the depth converted seimic profile based on stacking velocities is made available for structural interpretation, with the adjunct proviso of an uncertain overestimate of the vertical scale.
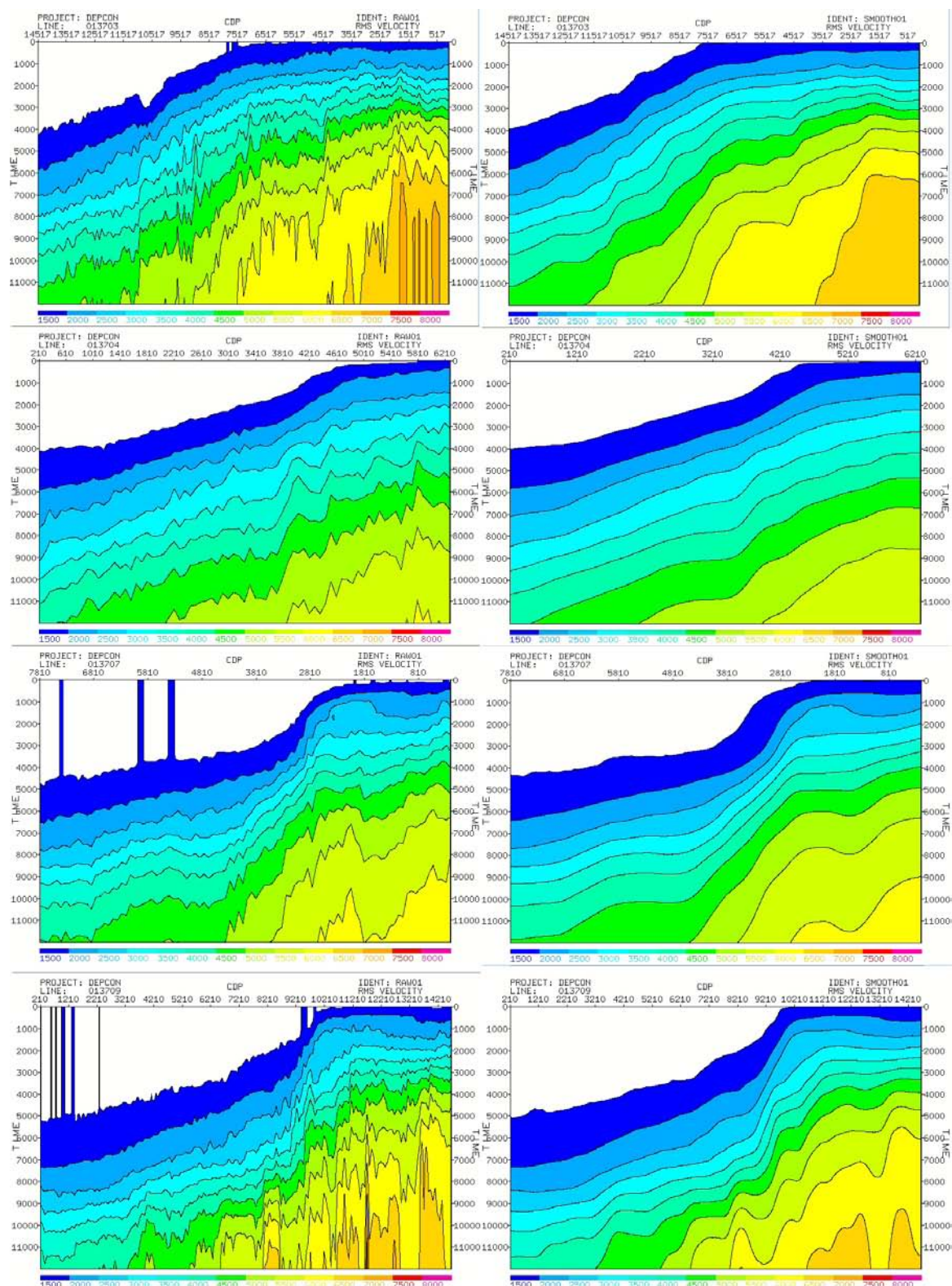
Figure 9. Stacking (rms) velocity profiles from lines 3, 4, 7 and 9 from survey 137 are shown as raw (left hand column) and smoothed (at right). Vertical axis is two-way travel time (msec); horizontal axis is CDP number; velocity colour assignment is given in the bar below each diagram The smoothed velocities were applied to the depth conversion process using the procedure and process described in Appendix 4.

Regardless of this, it may be necessary to produce interpretations in depth based on best available evidence. The next section discussed a simple transformation for doing this.

After converting the seismic traces from time scale to depth, three major crustal horizons were identified on the selected lines. Despite some ambiguity in identification, the misties are listed in Table 4 (in parentheses). As expected, uncertainty increases with depth, but the mistie is of the same order of magnitude as the confidence of the pick.

	137/03	137/04	137/07	137/09
water bottom	2.0 (+0.0)	1.8 (+0.0)	2.3 (+0.0)	2.2 (+0.1)
basement	8.0 (+0.3)	5.8 (+0.4)	8.2 (+0.2)	9.0 (–0.2)
Moho	18.0 (+1.2)	18.5 (+1.9)	17.4 (+0.4)	- (20.0)

Table 4. Depth (km) to water bottom, basement and Moho along line 137/01. Misties are given in parentheses. For example, depth to basement on line 137/03 where line 137/01 intersects it is 8.0 + 0.3 (= 8.3) km. If no +/– sign is given inside the parentheses, then the number represents actual depth. A dash (-) indicates no pick can be made with confidence.
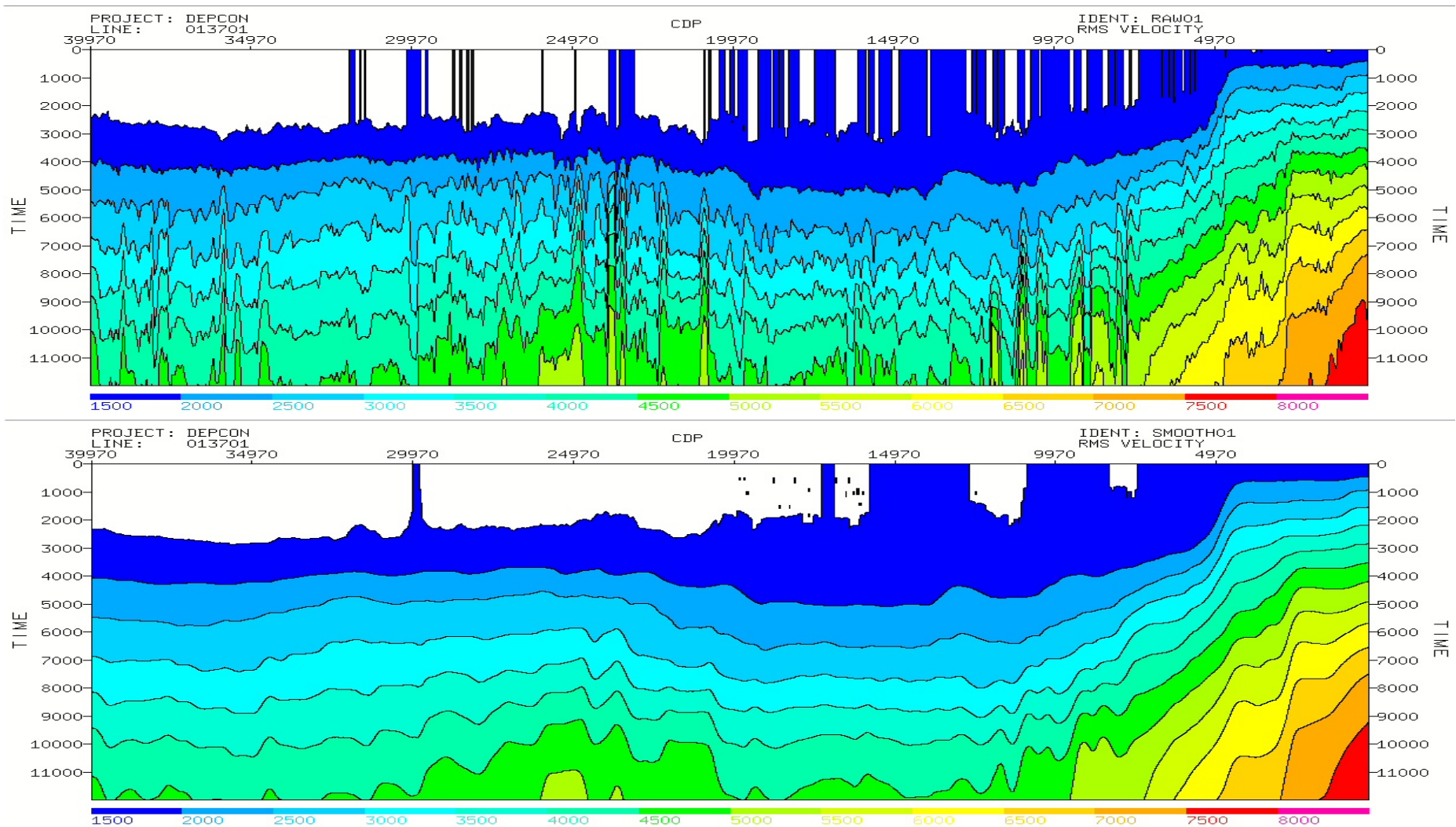
Figure 10. Stacking (rms) velocity profiles from line 137/01 shown as raw (upper) and smoothed (lower). Vertical axis is two-way travel time (msec); horizintal axis is CDP number; velocity colour assignment is given in the bar below each diagram. The smoothed velocities were applied to the depth conversion process using the procedure and process described in Appendix 4.
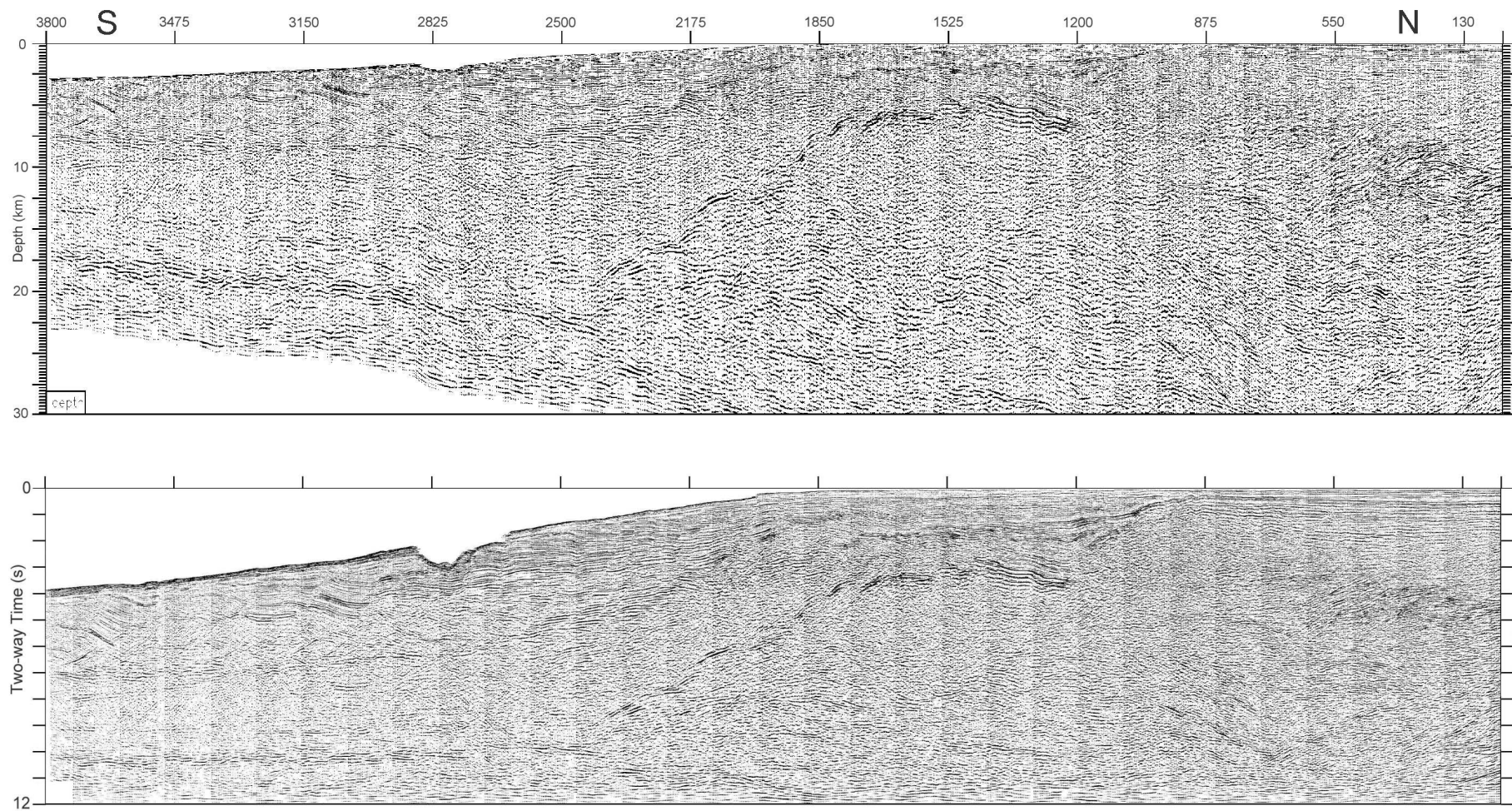
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Figure 11. Line 137/03 as conventional display with vertical axis in time (lower image) and depth (upper image). Basement and Moho reflections are prominent on this line. The horizontal scale is shotpoints and the section is approximately 190 km long.
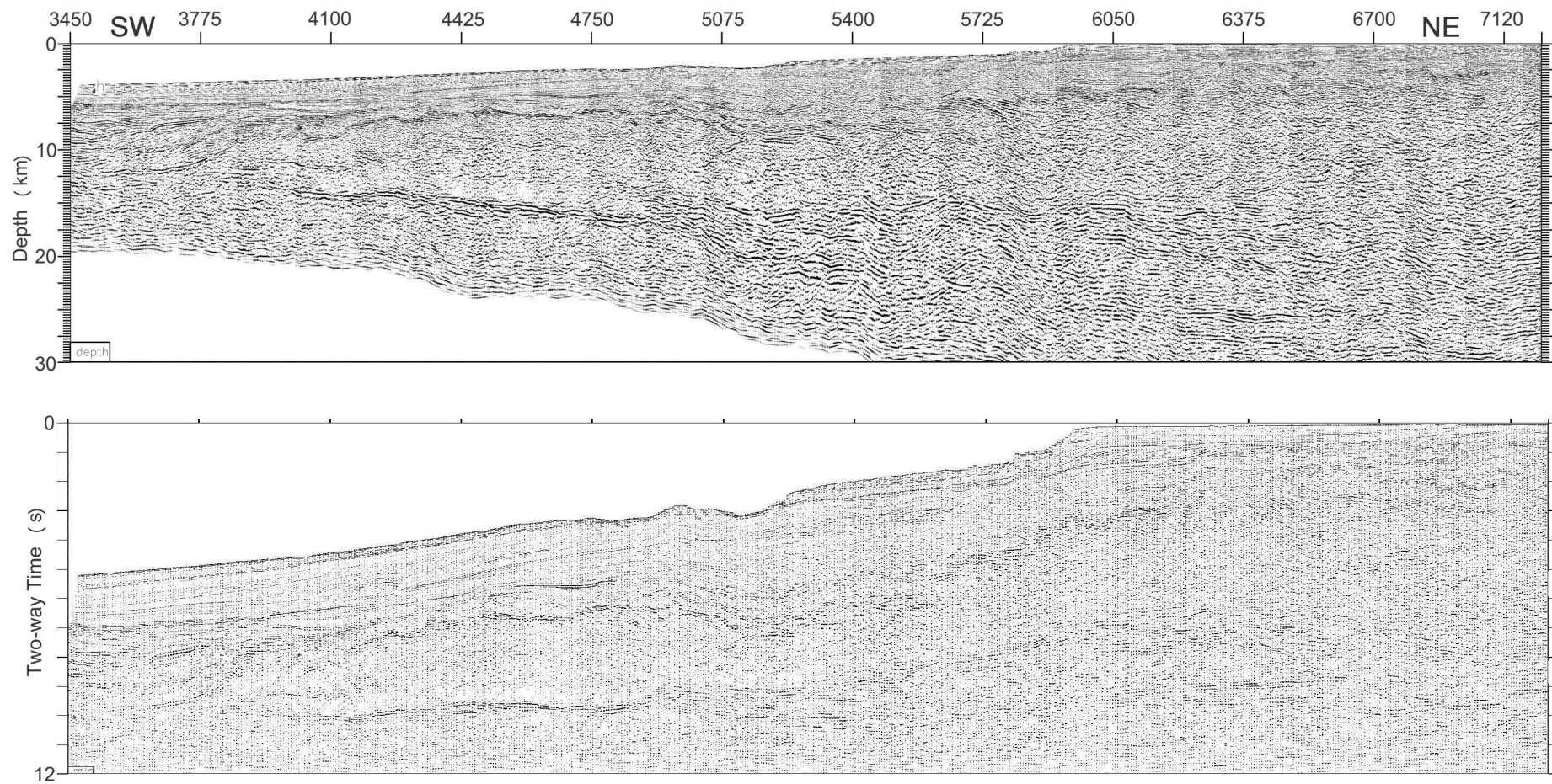
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Figure 12. Line 137/09 as conventional display with vertical axis in time (lower image) and depth (upper image). Basement and Moho reflections are prominent on this line. The horizontal scale is shotpoints and the section is approximately 190 km long.
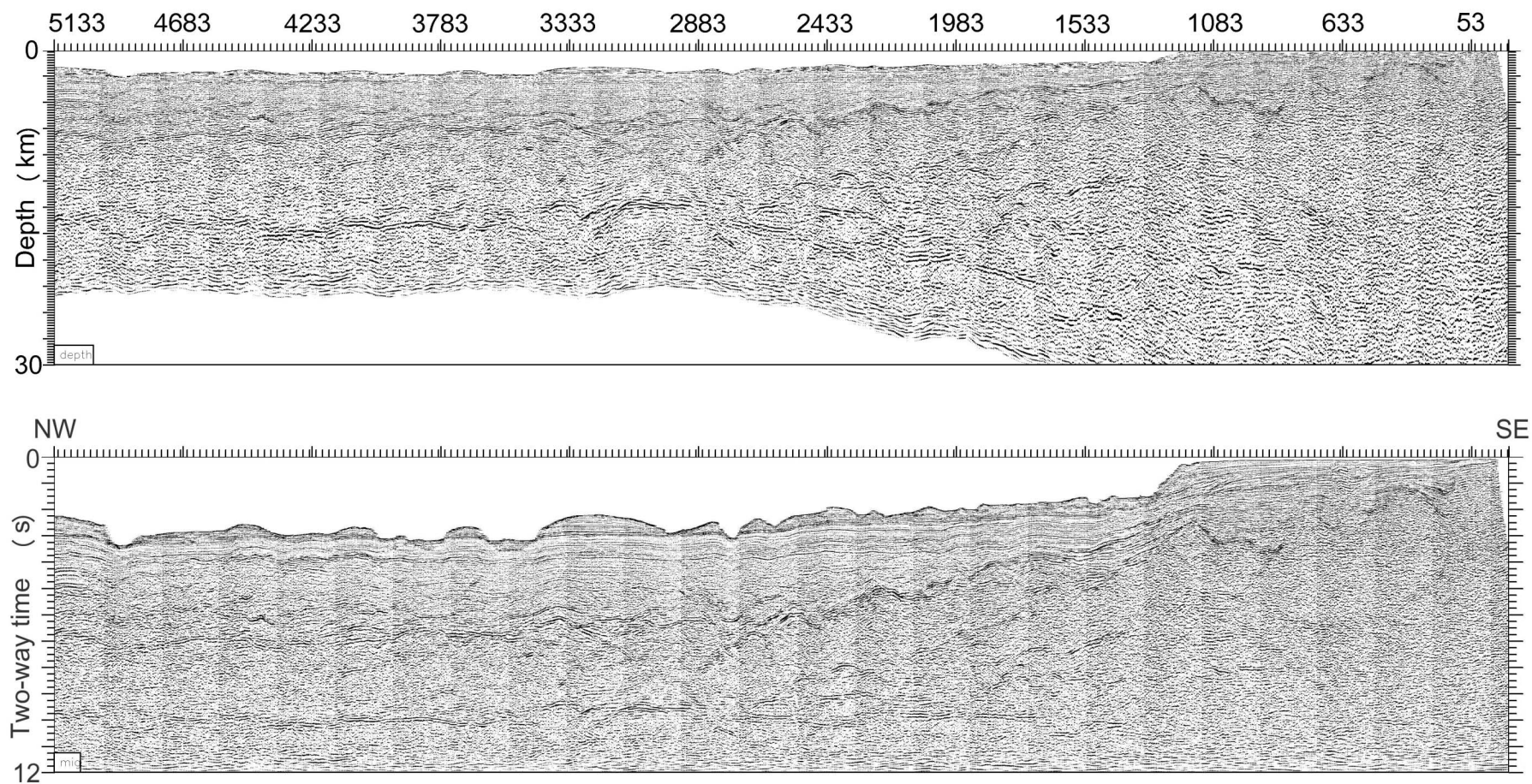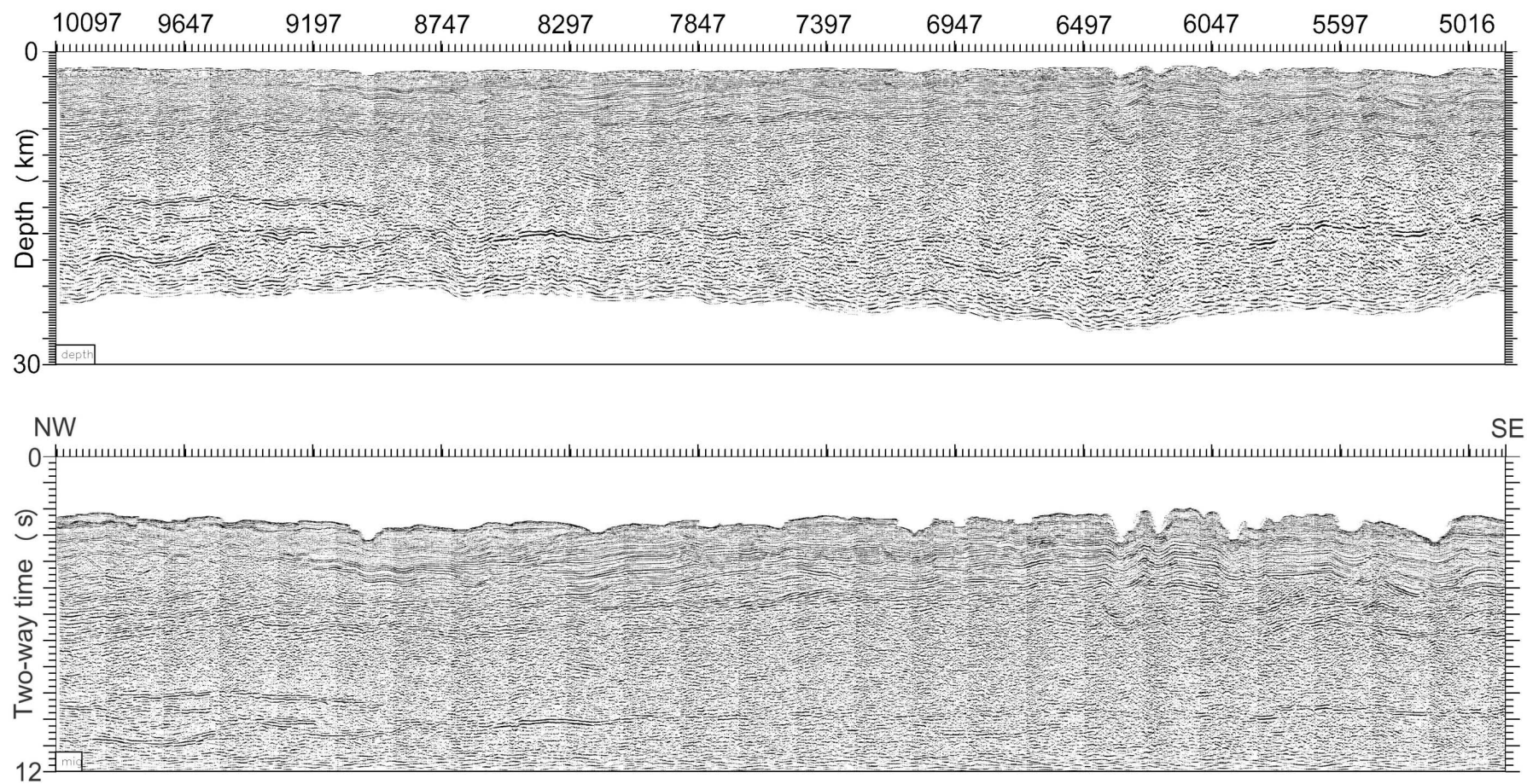
Figure 13. Line 137/01 (southeastern half) with vertical axis in time (lower image) and depth (upper image). Basement and Moho reflections are prominent on this line. The horizontal scale is shotpoints and the section is approximately 255 km long.

Figure 14. Line 137/01 (northwestern half) with vertical axis in time (lower image) and depth (upper image). Basement and Moho reflections are prominent on this line. The horizontal scale is shotpoints and the section is approximately 255 km long.

DEPTH-TIME FUNCTIONS

From analysis of stacking velocities, assuming shales and sands predominate in the sedimentary column, Table 2 (above) gives the best fit power trendlines for the depth vs time data in each of the provinces. The power function:

$$D = a.T^{b} \qquad\qquad \text{………}①$$

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

  D depth below sea floor (km)
  T two-way travel time 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 these 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 (Petkovic, 2004) the stacking velocity depths are reliable down to ~4 s twt depth below sea floor, but from there the error increases to about 15% [1] to a depth of 7 s TWT below sea floor. A similar situation is proposed here for the Otway Basin, where the stacking velocity depths are reliable down to ~1.5 s twt depth below sea floor, but from there the error increases to about 20% to a depth of 7 s TWT below sea floor. Below this there are no data to allow any sort of judgement to be made.

The following section develops a piecewise time-depth function which incorporates this observation for the Otway Basin and adjusts depths accordingly.

Modified time-depth function

To incorporate a correction 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. First, the following additional variables are required:

  t two-way travel time from sea level to a point in the sedimentary column (s)
  Z depth (km) from sea level, at time t
  d_w water depth (km), ie Z - D
  t_w two-way travel time (s) through water layer, t - T
  k scale factor which adjusts calculated depth to true depth

---

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

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

$$D = k.a.T^b$$

So,

$$Z = d_w + D$$
$$= d_w + k.a.T^b$$
$$= d_w + k.a.(t - t_w)^b$$
$$= d_w + k.a.(t - 4d_w/3)^b \qquad \ldots\ldots \text{③}$$

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

Equation 3 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'

In the comparison with velocities from wells and sonobuoys, it was noted that the depths from stacking velocities agree with the other velocity data sources 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,

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

Furthermore, we will use a linear interpolation between t_1 and t_2. This may be represented graphically:
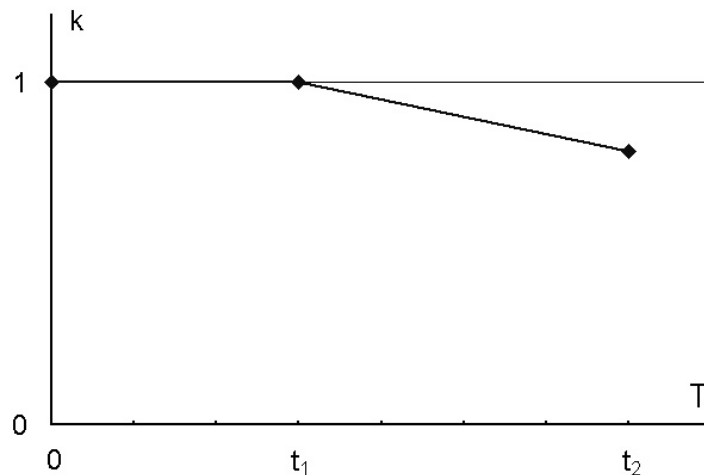
and finally, described as the following piecewise function:

$$k = 1 \qquad \qquad \text{for } T \leq t_1$$
$$k = 1 - E_{max} (T - t_1) / (t_2 - t_1) \qquad \text{for } t_1 < T \leq t_2$$
$$k = \varnothing \qquad \qquad \text{for } T > t_2$$

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 $T > t_2$ as there is insufficient information to suggest that it becomes smaller than that.

Example for Otway Basin

Say that the data suggest the following: $t_1 = 1.5$, $t_2 = 7$, $E_{max} = 20\%$, then

$k = 1$	for $T \leq 1.5$
$k = (58 - 2T) / 55$	for $1.5 < T \leq 7$
$k = \emptyset$	for $T > 7$

Or, expressed in terms of t,

$k = 1$	for $t \leq t_w + 1.5$
$k = (58 - 2t + 2t_w) / 55$	for $t_w + 1.5 < t \leq t_w + 7$
$k = \emptyset$	for $t > t_w + 7$

CONCLUSIONS

A stacking velocity database for the Otway Basin can be used for depth conversion of interpreted boundaries. Interval velocities derived from the stacking velocities are in agreement with seismic velocities from wells and sonobuoys to a depth of ~1.5 s two-way travel time below sea floor. Thereafter the depths from stacking velocities diverge to an overestimate of at least 20%.

ACKNOWLEDGEMENTS

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APPENDIX 1 - SONIC LOGS FOR SELECTED OFFSHORE OTWAY BASIN WELLS

Sonic logs from selected onshore Otway Basin wells to which seismic lines were tied. Left hand column is plots of velocity vs depth showing both raw (grey dots) and despiked data (using 241 point median filter, ie window length of about 4 cm). Vertical axis is sonic velocity (km/s) computed from interval travel times and horizontal axis is depth below sea level (km).
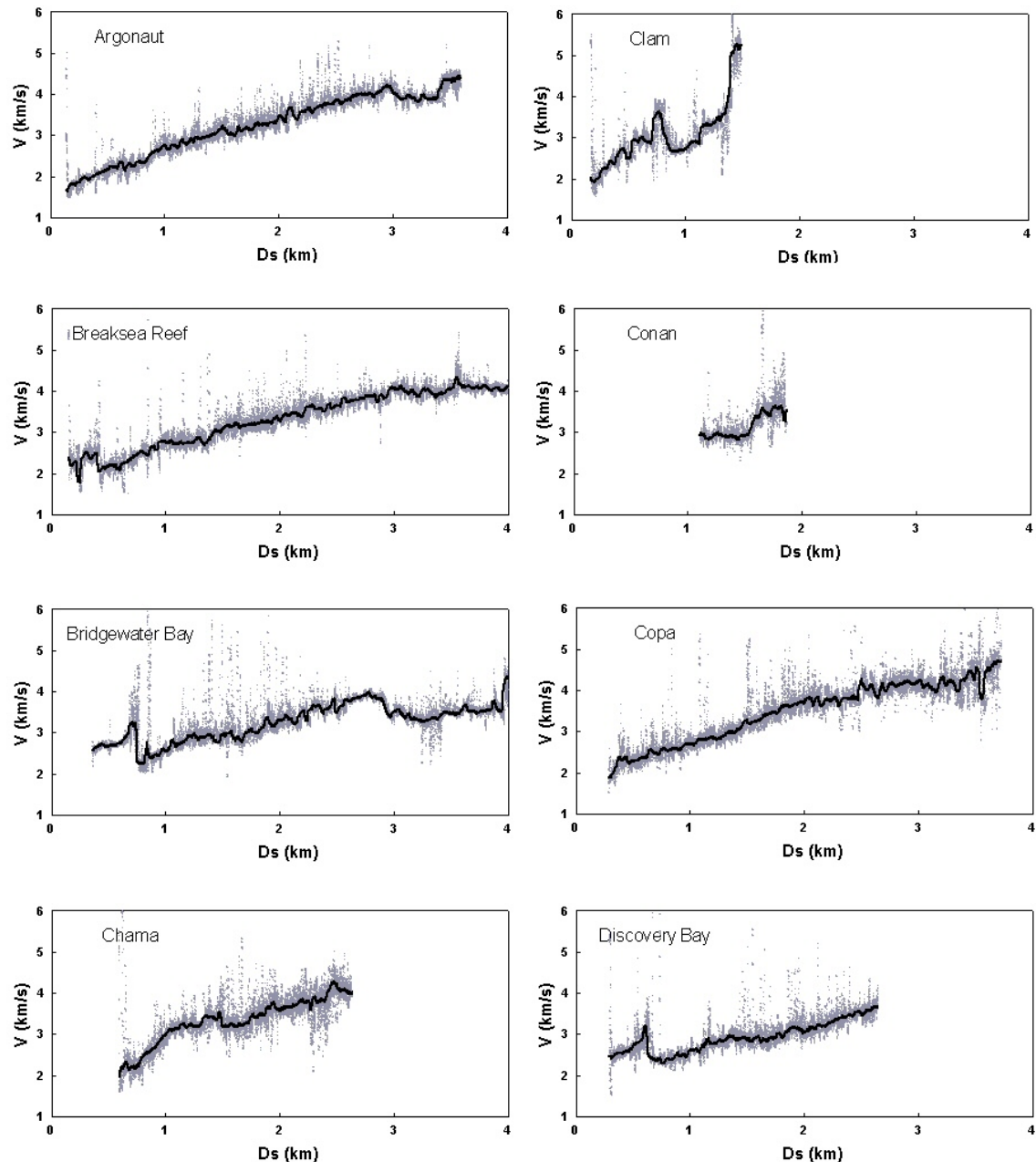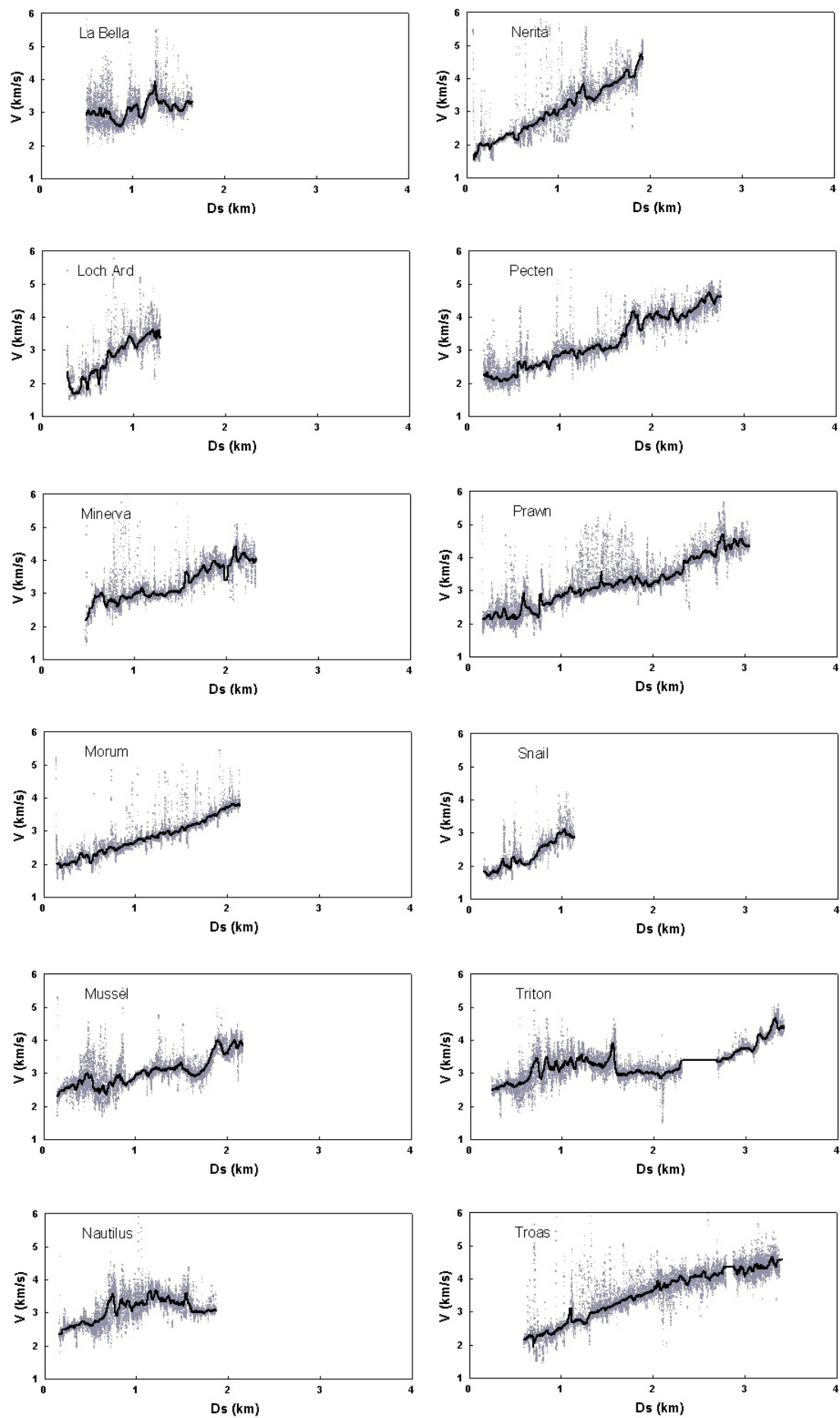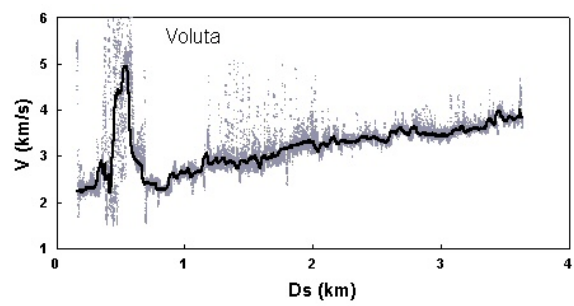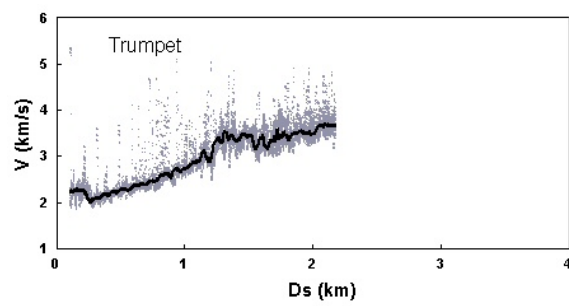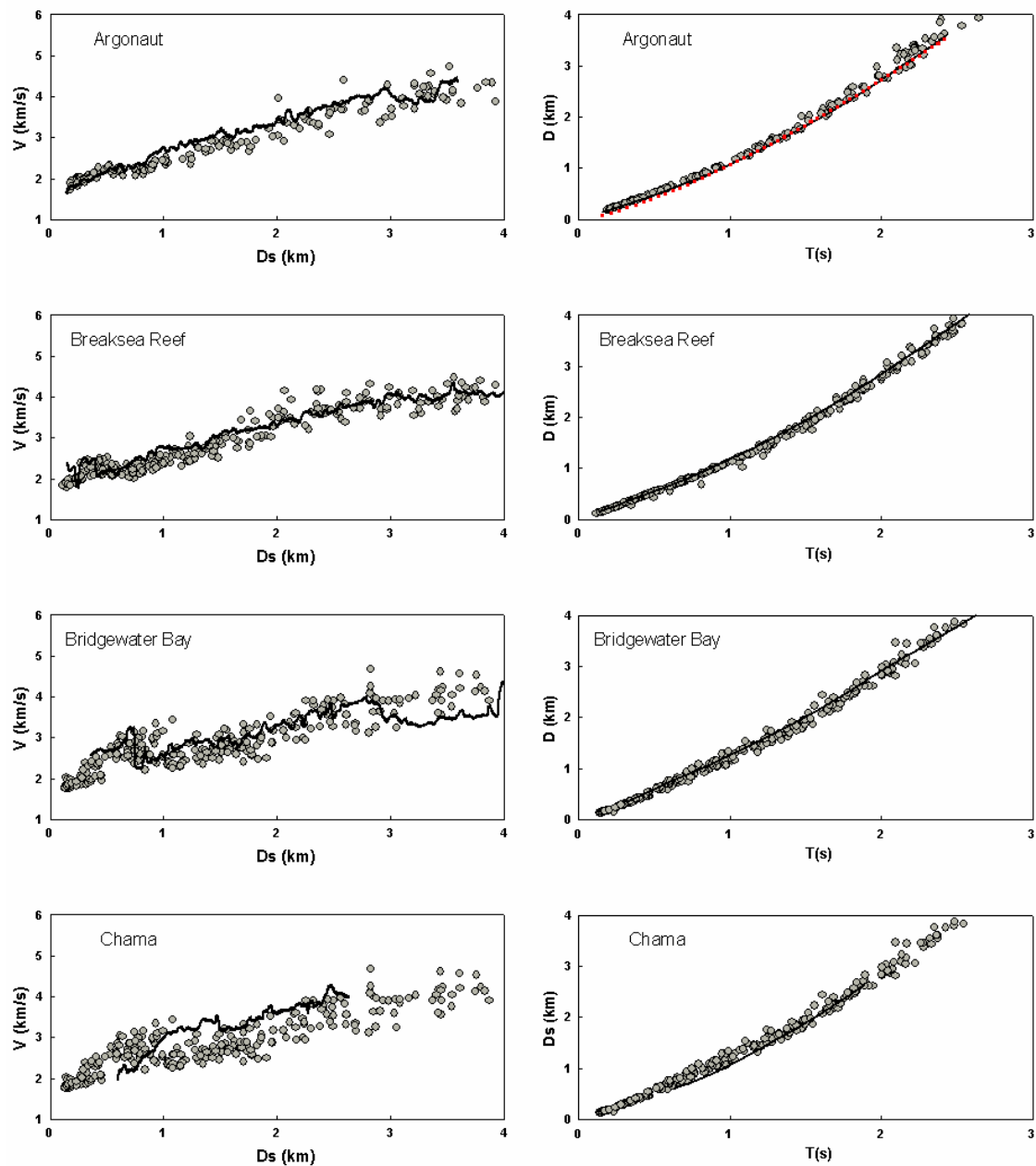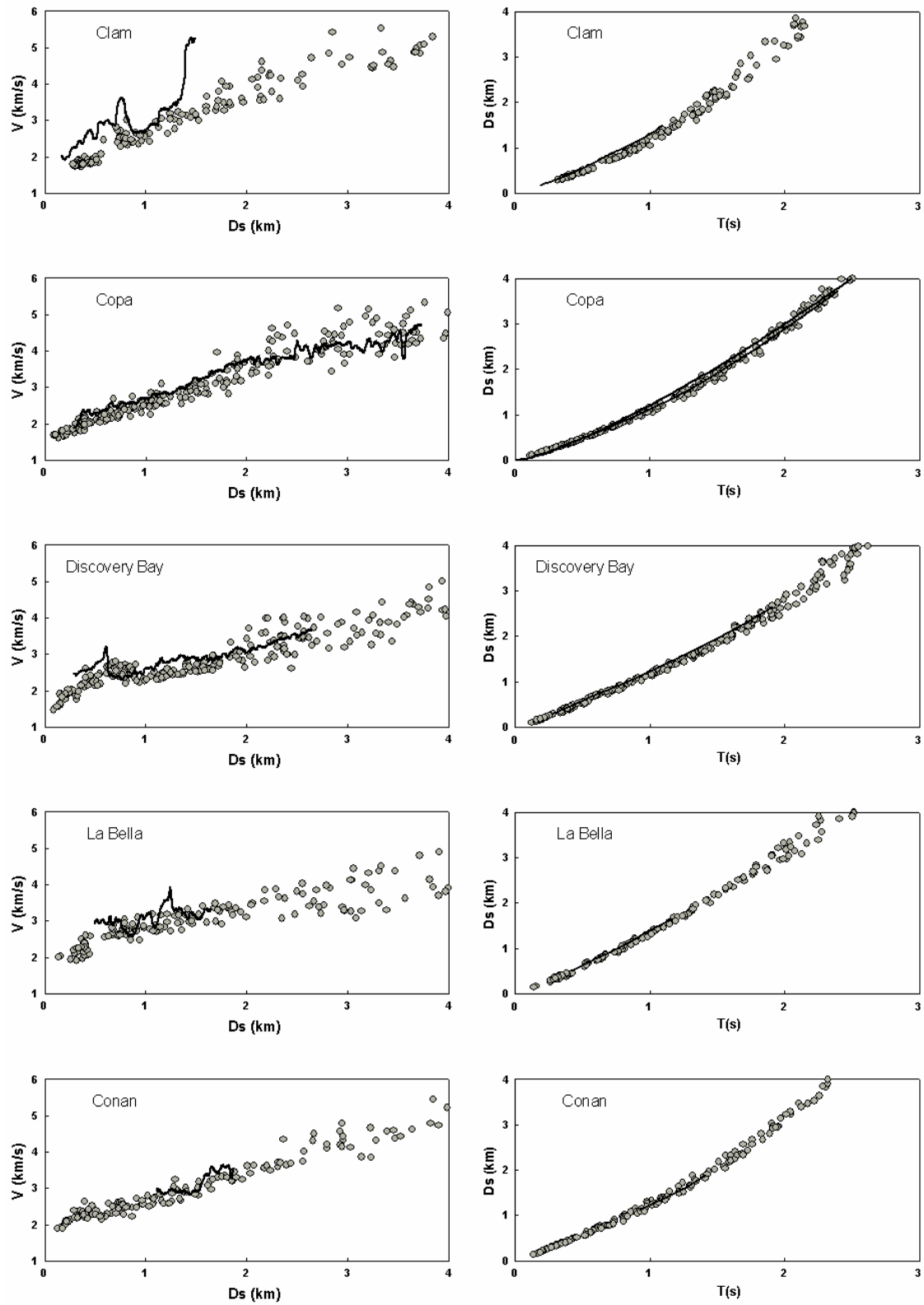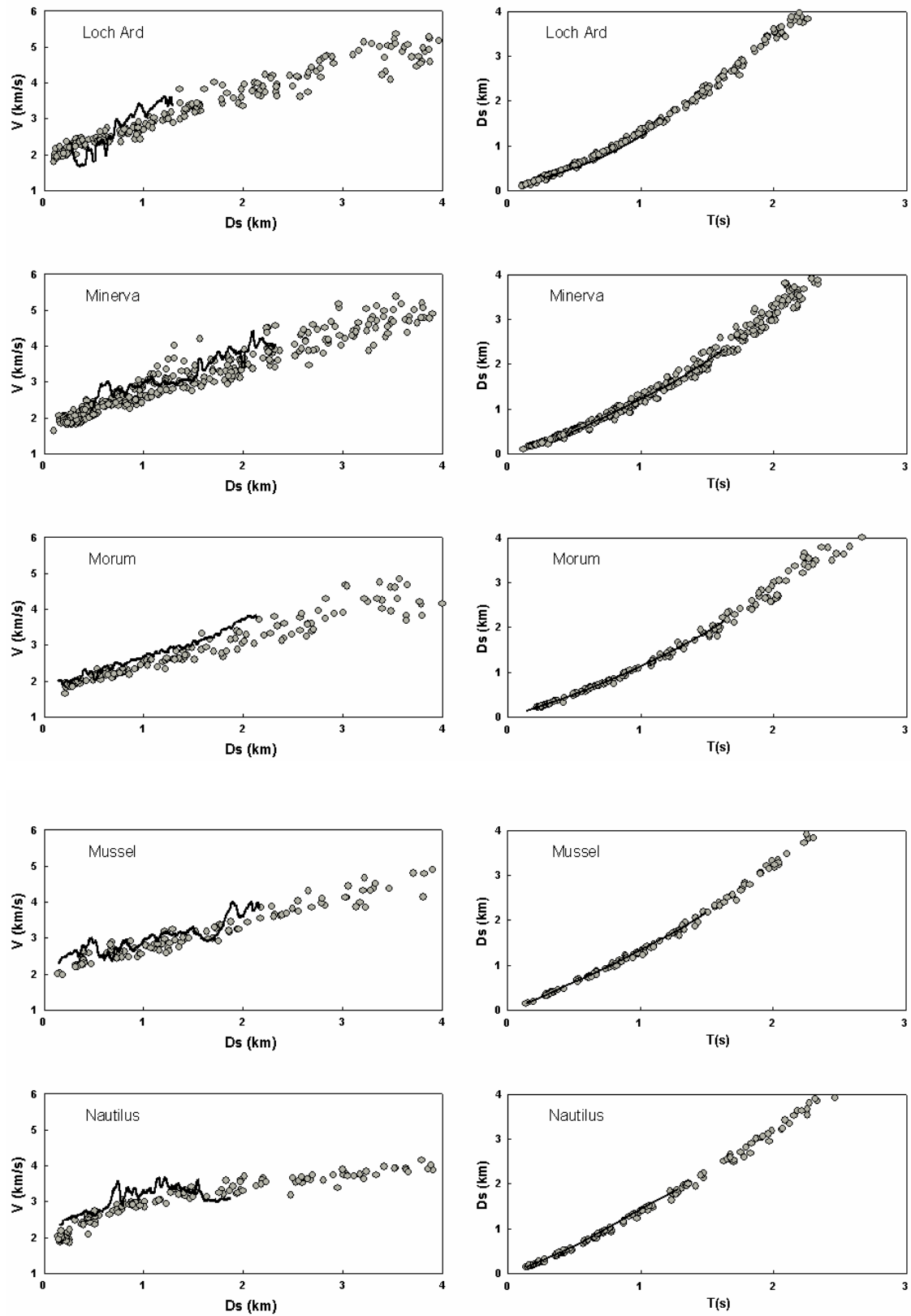
APPENDIX 2 - DEPTH, TIME AND VELOCITY FOR SELECTED OFFSHORE OTWAY BASIN WELLS

Left hand column are plots of velocity-depth, while the right hand column gives the corresponding plot of depth-time (units are kilometre and second). The black line represents the relationship derived from the despiked sonic logs. The grey dots are from proximal (within 10 km) stacking velocity functions.
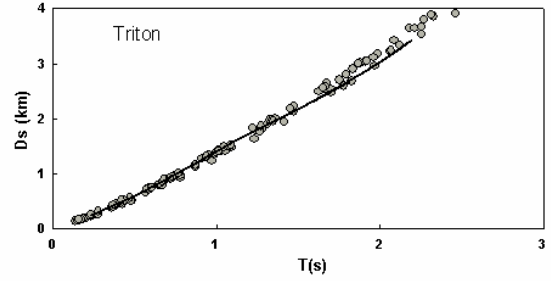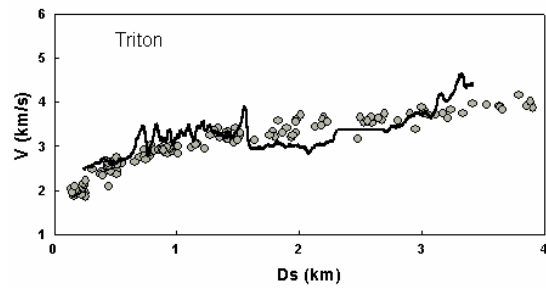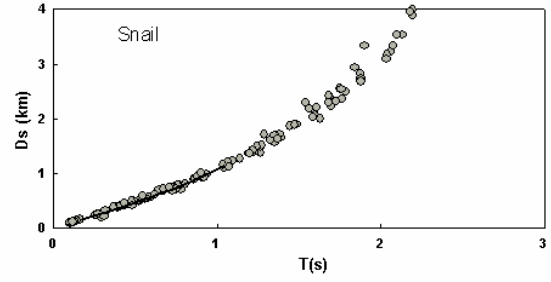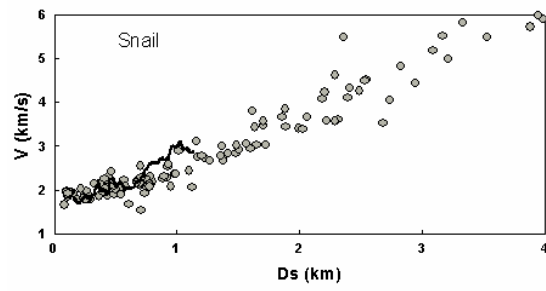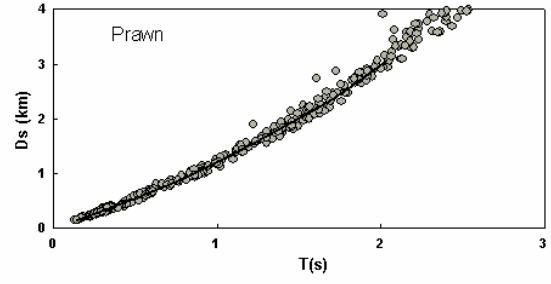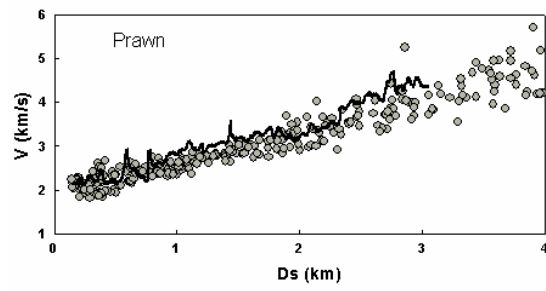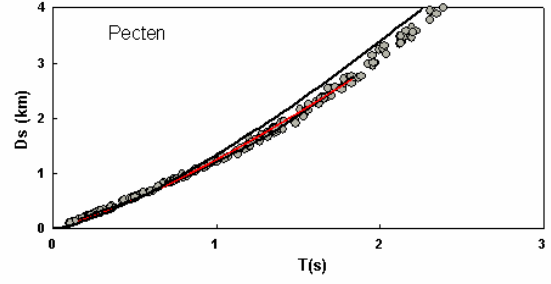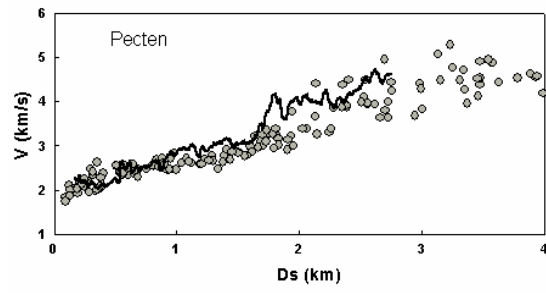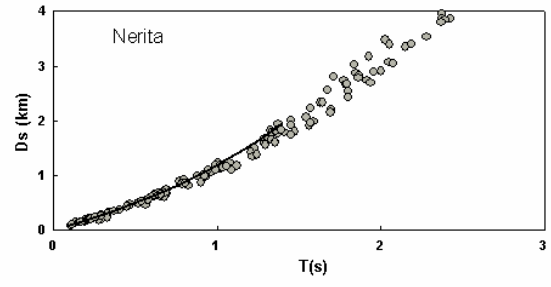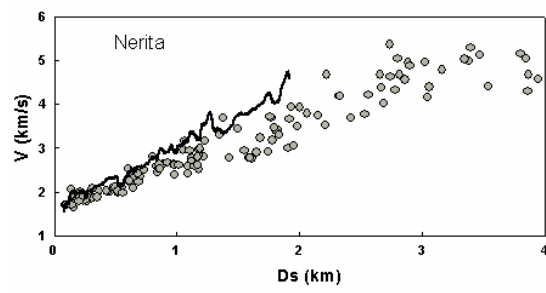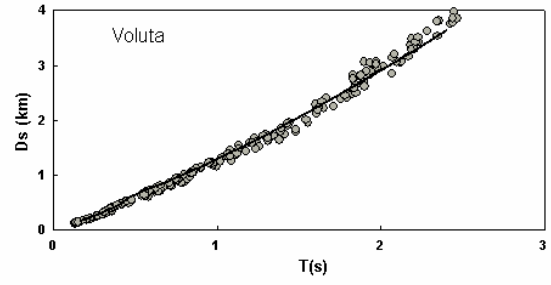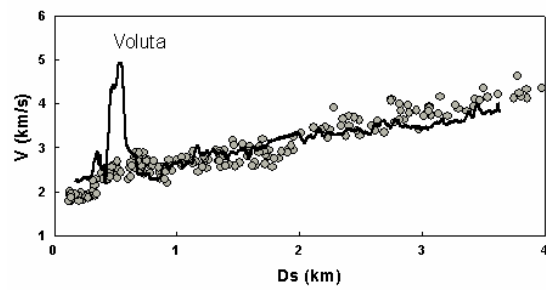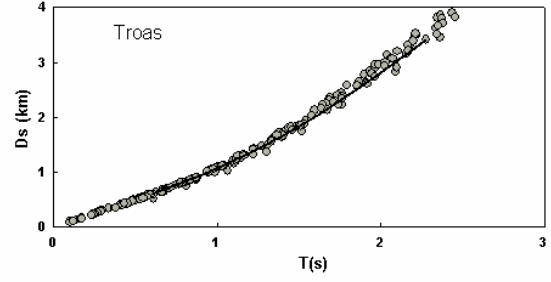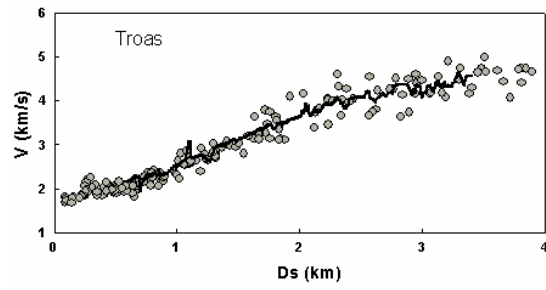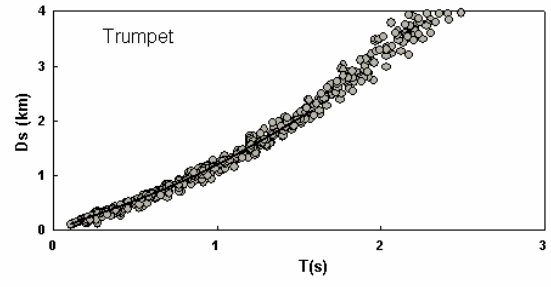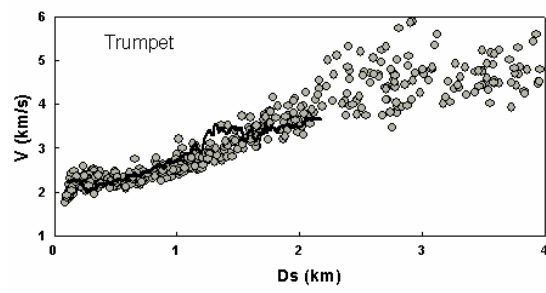
APPENDIX 3 - DEPTH, TIME AND VELOCITY FOR SELECTED ONSHORE OTWAY BASIN WELLS

Sonic logs from selected onshore Otway Basin wells are presented here. Left hand column is plots of velocity vs depth showing both raw and despiked data (using 241 point median filter, ie window length of about 4 cm). Right hand column gives the corresponding plot of depth-time from the despiked data. Units are kilometre and second.
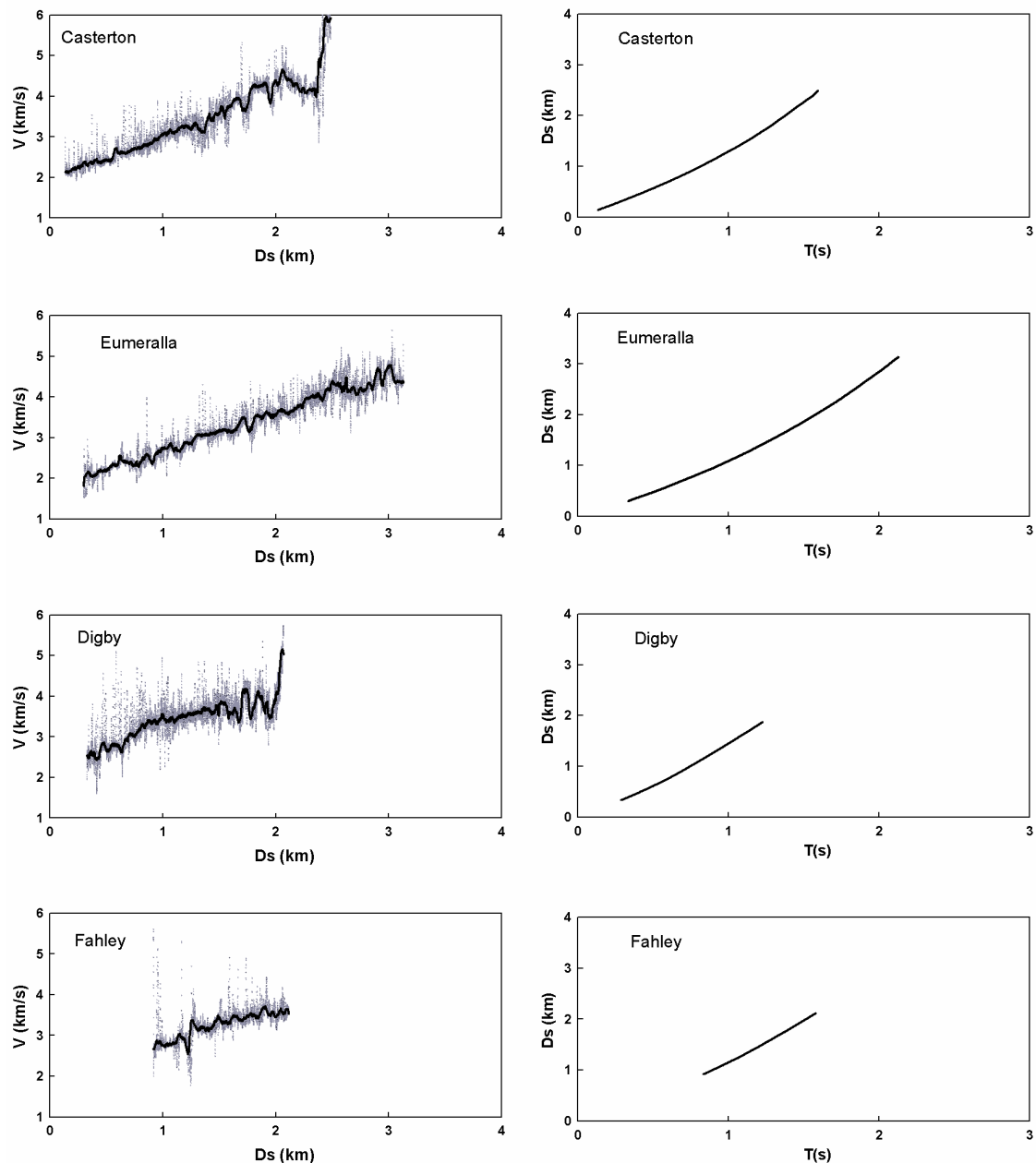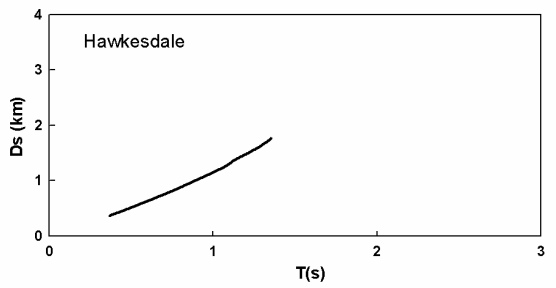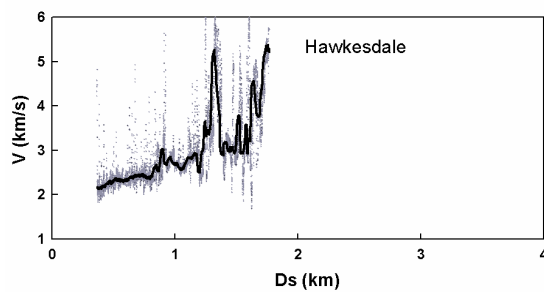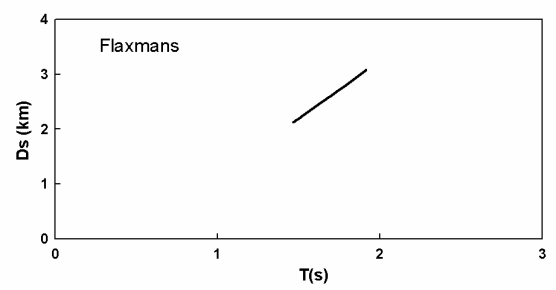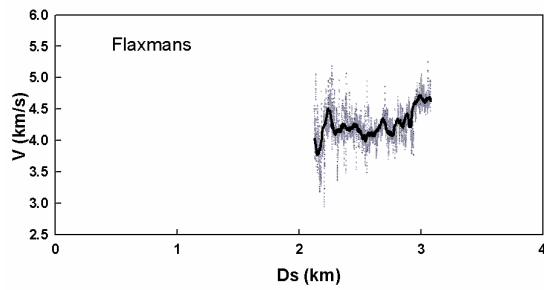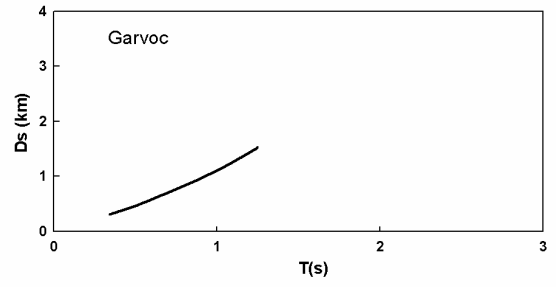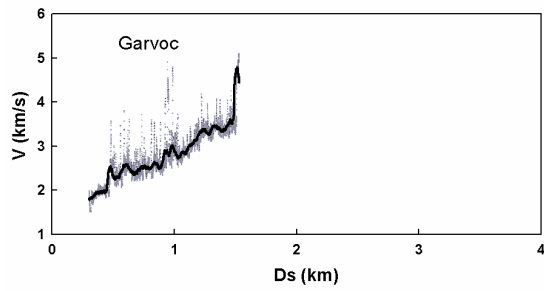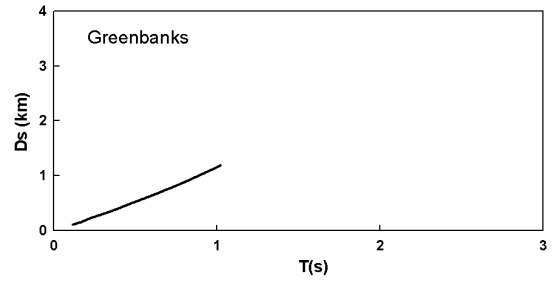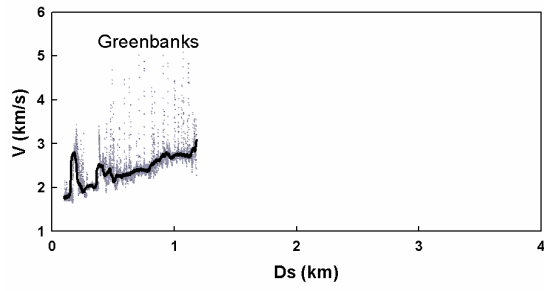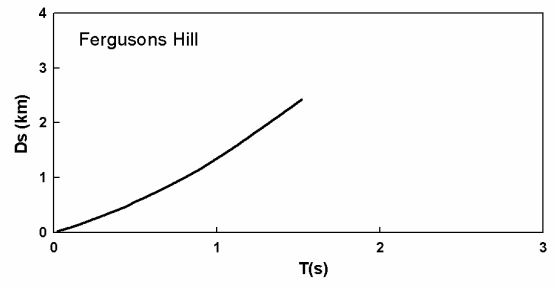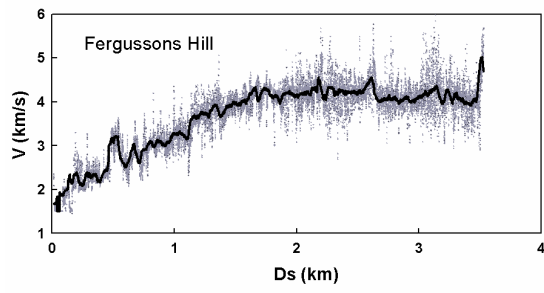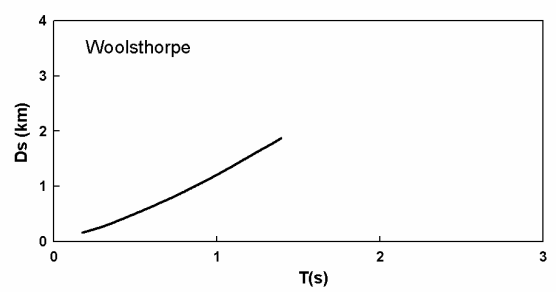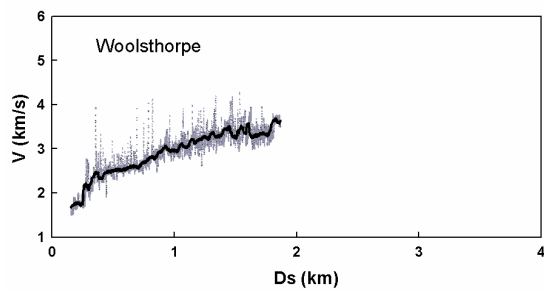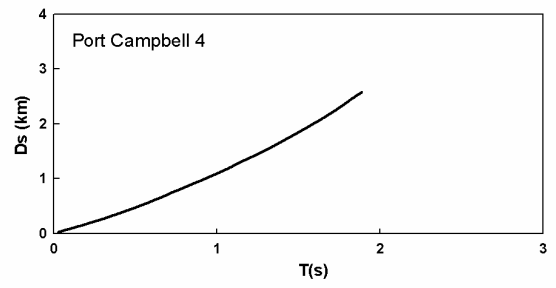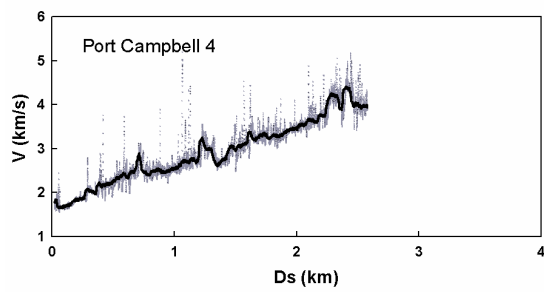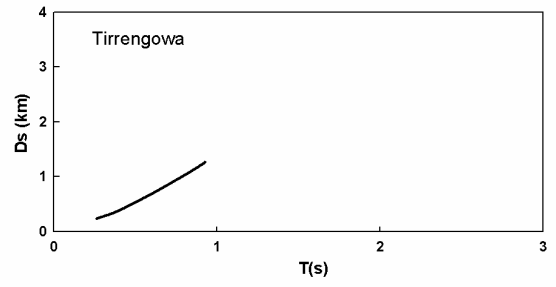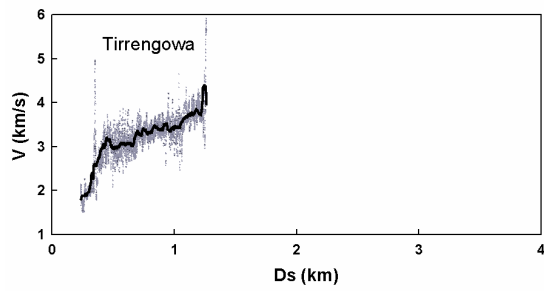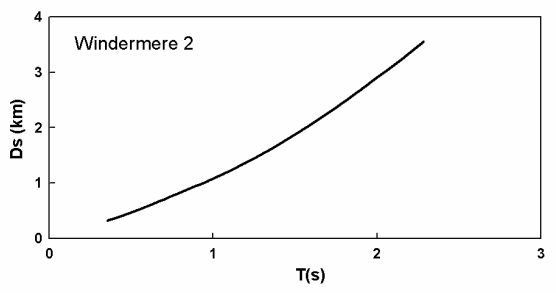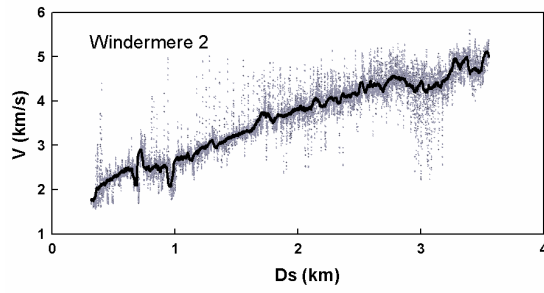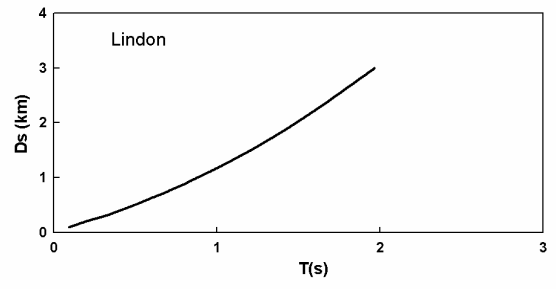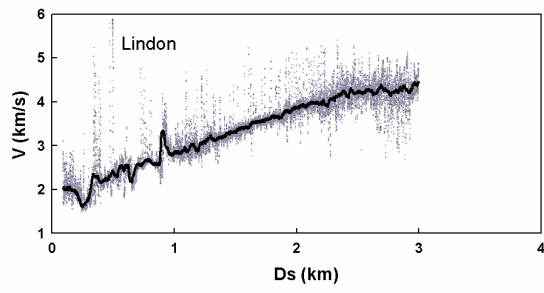
APPENDIX 4 - PROCESSING DETAILS

This appendix records the major components of the processing carried out in this study. For each panel the left hand column records the name of the program used, which may be a commercial software package such as Cogniseis' 'Disco' or in-house developed software written in Perl or Fortran. The right-hand part of each panel records the processes carried out (rectacles) and the files created (lozenges). SSSS denotes survey number and LLLL denotes line number.

- Panel 1 -
Standardise stacking velocity file format

Reformat to Disco 'define' format; change line names to adopted convention; add position data

- Panel 2 -
Smooth Stacking Velocities

Smooth the velocities in time, resample smoothed velocities in depth
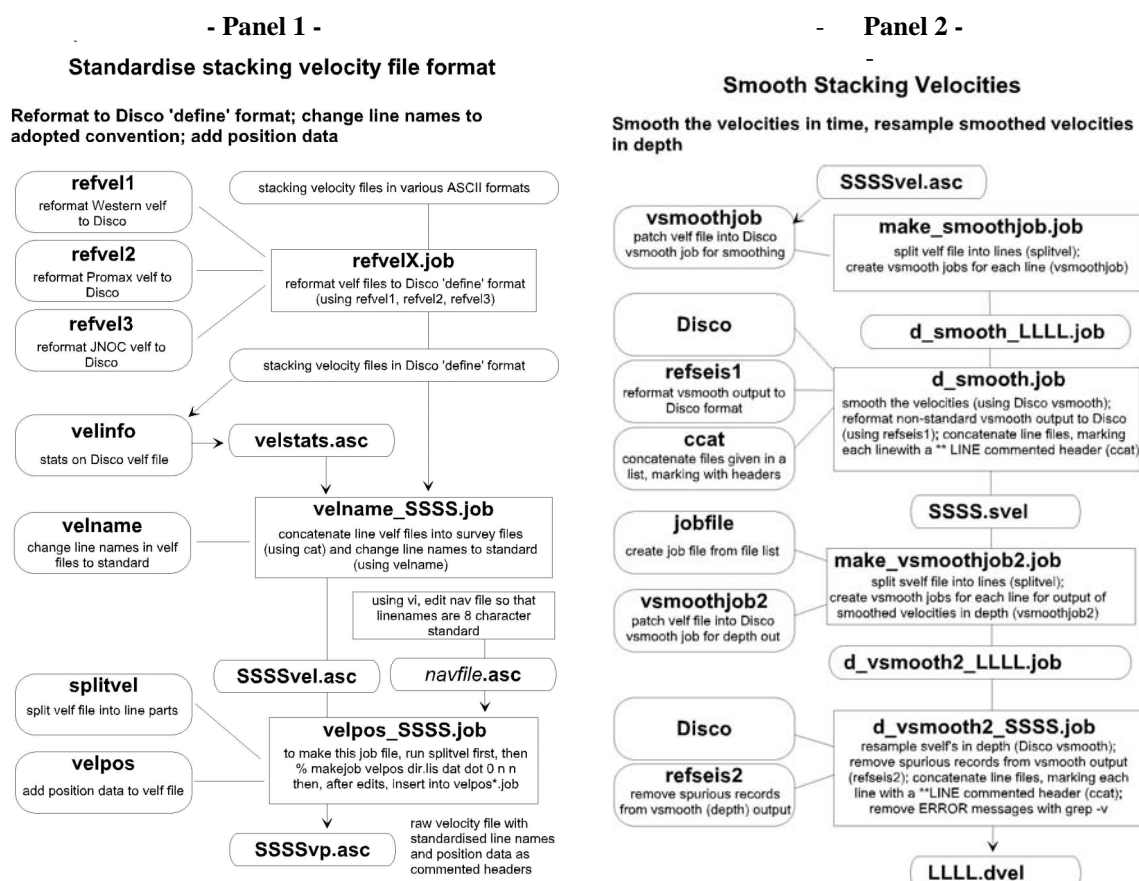
This panel describes the process for standardising the velocity files which were originally submitted to Geoscience Australia in various formats. The internal format used for processing is a Cogniseis 'Disco' compatible ASCII format known as 'handvel' or 'define'. Although 'Western' format is more widely used by industry, Disco's format is used by Geoscience Australia for convenience. Various scripts are maintained to allow conversion between any of the common formats.

The remainder of this module extracts statistical metadata from the velocity files, standardises line-names to an eight character field, and inserts positions from the navigation files as GDA94 (= WGS84) geodetic coordinates.

The stacking velocities are smoothed prior to application to depth conversion of the seismic reflection records. The first part of the sequence produces a smoothed velocity file in Disco's 'handvel' or 'define' format (*.svel).

The Disco module used to perform the smoothing was purpose-built by Bob Harms of Geoscience Australia. A combination of median filtering to remove spikes and averaging to smooth was applied. (See program description of 'VSMOOTH' and a typical job below).

The second part resamples the smoothed velocities in depth in preparation for entering into a Disco database.

- Panel 3 -
Depth Conversion

Add velocities into Disco database for viewing and then crate velocity model for depth conversion

Disco —— **geometry.job** — creates space in Disco database for velocities

SSSS.svel — HANDVEL format

vi — include velfs in job file

define.job — add velfs to Disco database for viewing

Focus — view velocities

LLLL.dvel

velmodjob.pl

make_velmodjob.job — patches the LLLL.dvel file into a Disco 'velmod' job

Disco

velmod_LLLL.job — enters velocity model into Disco database

ssssLLLL.sgy

Disco

depcon_LLLL.job

ssssLLLL_depth.sgy

Due to quirks of Disco, the velocities are added in two ways in order to perform the depth conversion of the seismic reflection data.

The first part of this panel shows data entered into a Disco database from the ASCII 'handvel' format file to allow viewing and qc via Focus, the graphical front-end of Disco.

The second part of this panel shows the depth-sampled stacking velocity files (also ASCII) entered into a Disco database and depth conversion carried out.

- Panel 4 -
Well data & proximal stacking velocities

a) Extract proximal stacking velocities and compute depths

stackvel.lis — path to *vp.asc files

proxivel.pl — locate proximal velfs given radius, posn and name

proxivel_wells.job
proxivel_sonos.job — radius: 10km for wells, 20 km for sonos

*name*_prox.asc

deptime.pl — compute depths

deptime_wells.job
deptime_sonos.job — compute depths for proximal velfs

*name*_tzv.asc
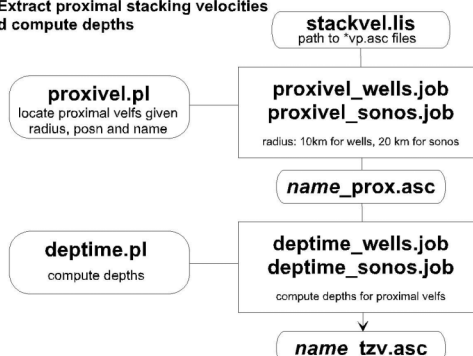
b) Extract and clean up sonic logs

well log 'las' file

wellog.pl

wellog.job — extract DV in metric units

well log D,V

edits — apply edits to remove erroneous values

edited well log

spiker.f

spiker.job — despike velocities

well log D,V
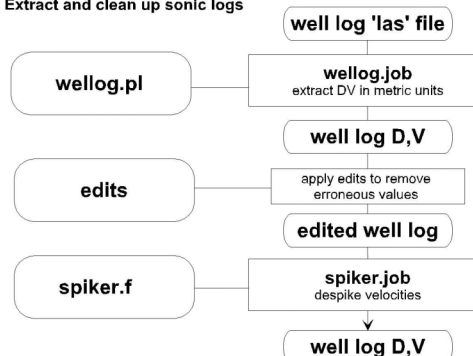
Part a) of this panel records the process of extracting stacking velocities which are proximal to particular locations, say wells or sonobuoys. The output of the process is a file of time, depth and velocity triplets.

Part b) records the process of converting the sonic logs to standardised format, then computing depth - velocity pairs.

The output of the two processes is then used in data analysis packages, in this case CurveExpert 1.3 (Hyams, 1997) and SigmaPlot 8.0 (SPSS Inc, 2003), to perform statistical regression and determine best-fit time-depth functions.

VSMOOTH

VSMOOTH is a DISCO module for smoothing of velocities, usually prior to
time migration. This automatic velocity smoothing can be easier than
doing manual velocity pick editing. The advantage of using a smoothed
velocity field for migration is that interval velocites are more likely
to be reasonable in a smoothed velocity field, and sharp lateral
velocity variations are minimised.

VSMOOTH inputs the unsmoothed HANDVEL picks and outputs the same HANDVEL
picks with smoothing applied. These output HANDVEL velocities can then be
used as input for the DISCO DEFINE module to define a smoothed velocity
function. This smoothed velocity field can then be used for migration
or can be plotted using "vutl".

VSMOOTH has several ways of velocity smoothing: "smashing", "smoothing",
"median", "trimmed mean", and "minimum".
Smashing involves addition of adjacent velocities to form an output
velocity. "Smoothing" involves a weighted-mix smoothing of adjacent
velocities, similar to a running-mix on seismic trace data. In a normal
run of VSMOOTH, all of these processes can be done, but they are always done
in a specific order. All operations are done using linearly
interpolated velocities from the adjacent functions.

The order of operations is:
  1. smashing
  2. median
  3. trimmed-mean
  4. minimim-ising
  5. smoothing

VSMOOTH is an EDIT-phase only module; it does not process seismic traces.

As well as smoothing velocities, VSMOOTH also has some obscure velocity
manipulation methods, that are run independantly of the smoothing:
  1. WBMULT, for water bottom multiple attenuation.
  2. WBINT, for interpolation of velocities according to water depth,
              and/or according to lateral distance.
  3. DEPTH, for converting RMS velocities to depth values, that can be
              input into the VELMOD and DEPCON modules for depth
conversion,
              or that can be input into the VELMOD module and this model
              used for a depth migration.

PARAMETER SUMMARY:


```
*CALL  VSMOOTH        NSMOOTH        NSMASH NMIN   NMEDIAN        NTRIM  NTRIM2
WEIGHTS
WEIGHT WEIGHT WEIGHT WEIGHT WEIGHT WEIGHT WEIGHT WEIGHT
HANDVEL        PKEY
TIME   VEL    TIME   VEL    TIME   VEL    TIME   VEL
TIMPERC
TIME   PERCENT
TMEAN  NTMEAN NTMEAN2        TMEAN  MODE
WBMULT NWB    NPICK
WBINT  NPICK  FCDPOUT        ICDPOUT        LCDPOUT        DELTAZ
CDPWD  CDP    WD
OUTPUT INCR
DEPTH  DPTHINC        DPTHEND        DEPTHL DELTMAX        DELRATE
```

PARAMETER DETAILS:

```
NSMOOTH = the number of adjacent velocity functions to mix together.  This
          must be an odd number.  If NSMOOTH=1, then no smoothing will be
done.
          Smoothing involves a weighted summing of adjacent velocity
locations.
          Lower limit: 0
          Upper limit: 101
          Default: 5
NSMASH  = the number of adjacent velocity functions to smash together.  This
          must be an odd number.  If NSMASH=1, then no smashing will be
done.
          Smashing involves simple adding (or stacking) with normalisation
of
          adjacent velocities.
          Lower limit: 0
          Upper limit: 101
          Default: 5
NMIN    = the number of adjacent velocity functions to look for the minimum.
          If this number is greater than zero, then minimum-ising is done.
          The program will look at the adjacent NMIN locations, and take the
          minimum velocity as the velocity at the central location.  This
means
          that the bumps in the velocity field are smoothed out by reduction
          of velocity, and by reducing the velocity highs, not just an
averaging
          process as used in smashing and smoothing.  This filters out
spurious
          high-velocity picks.  For minimising, at NMIN should be at least
2.
          If NMIN is set to a negative value, then the MAXIMUM velocity will
be
          used instead of the minimum velocity; this means that localised
          velocity minima will be eliminated.  For maximising, NMIN should
be
          set to -2 or lower.
          Lower limit: -101
          Upper limit: 101
          Default: 0
NMEDIAN = the number of adjacent velocity functions to median filter.
          Lower limit: 0
          Upper limit: 101
          Default: 0
NTRIM   = the number of adjacent velocity functions on which to do a
          trimmed-mean filter.
          Lower limit: 0
          Upper limit: 101
          Default: 0
NTRIM2  = the number of adjacent velocity functions within "NTRIM" to
          average.  The lower and top NTRIM-NTRIM2 velocities are thrown
          away before the average is taken.
          Lower limit: 0
          Upper limit: NTRIM
          Default: 0
```

WEIGHTS list

```
WEIGHTS = a list of weights to use for mixing; there must be NSMOOTH
          WEIGHTS supplied to the program.
          Default: If NSMOOTH=3, a 1-2-1  mix is done.
                   If NSMOOTH=5, a 1-2-3-2-1 mix is done.
                   If NSMOOTH=7, a 1-2-3-4-3-2-1 mix is done.
                   If NSMOOTH=9, a 1-2-3-4-5-4-3-2-1 mix is done.
                       etc.
          WEIGHT = weight to apply to the velocities during mixing.  The
                   sum of the WEIGHTs supplied to the program will be
                   normalised to 1.0.
```

HANDV EL list

```
HANDVEL     PKEY
TIME   VEL    TIME   VEL   TIME   VEL    TIME    VEL
        = a list of TIME,VELOCITY pairs to smooth.  The output smoothed
          velocities will be at the same time as the input velocities.
          For the purposes of simplicity, the program assumes that the input
          velocities are in order; ie. the PKEY values are assumed to be
          equally spaced and increasing or decreasing in value.  If this is
          not the case, the output velocities may not be correct.  If the
          spacing is somewhat irregular, then this may not matter, but
          out-of-order PKEY values will probably result in a very strange
          velocity field.
```

```
TIMPERC list
------------
TIMPERC
TIME   PERCENT
        = a list of time, percent pairs (one pair per input line) to
        vary the velocity field by.  Linear interpolation and flat
extrapolation
        is used to obtain percentage values for time between those
specified.
        This can be easier than using the standard DISCO "vutl" module.
        e.g.
        TIMPERC
        0     85
        will scale all of the velocities by 85 percent.
        e.g.
        TIMPERC
        2000 94
        4000 90
        6000 85
        will time-vary the scaling of velocities.  From 0 to 2000 mills the
        velocities will be 94% of input velocities.  From 6000 (to infinity)
        the velocities will be scaled by 85%.  Between 2000 and 4000 the
        scaling will vary from 94% to 90%.  Between 4000 and 600ms the
scaling
        will vary from 90% to 85%.
```

TMEAN LIST

This list is intended for temporal smoothing of velocities. The temporal
smoothing is done by a trimmed-mean algorithm. If temporal smoothing is
not required, do not supply this list.

```
TMEAN  NTMEAN NTMEAN2       TMEAN  MODE
        NTMEAN  = integer = The number of points in the trimmed mean window.
                            The larger this value, the more smoothing will
be
                            done.
        NTMEAN2 = integer = The number of points in the centre of the
                            trimmed mean window to actually use.  This
                            should be equal to or smaller than "NTMEAN".
                            The larger this value, the more statistically
                            reliable/stable the results will be.
        TMEAN = real = The time increment between velocity samples in the
                       trim-mean window.  The larger this value, the more
                       smoothing will be done.
        MODE = character*8 = 'NORMAL' or 'INCREASE'
                       'NORMAL' = just do a trim-mean.
                       'INCREASE' = do a trim-mean, then do a check on the
                            velocities to make sure they increase.  If
                            velocities do not increase, they are forced to
                            increase.
e.g.
TMEAN 5    3      100.0  INCREASE
        does a trim-mean based on velocity values every 100ms.  The velocity
```

values at five points, -200ms, -100ms, 0ms, +100ms, +200ms relative to
the time-value in question are sorted, and the central three values are
averaged to form the output value.

.

WBMULT LIST

This list is intended for water-bottom multiple attenuation. The TIMPERC
list should also be supplied if the WBMULT list is supplied. Multiple
attenuation is done by flattening multiples.

NWB = integer = The water-bottom multiple number to suppress. Normally
                this should be 2. The first order multiple is 2. The
                second order multiple is 3. If 0 is supplied, then all
                peg-legs will be suppressed.

NPICK = integer = The velocity pair in the HANDVEL list for the water-bottom
                primary. This is normally the first T,V pair (1) or the
                second TV pair (2) in the HANDVEL list.

WBINT LIST

This list is intended for interpolation of sparsely spaced velocity analyses
according to water depth. The idea is to:
   1. input HANDVEL cards with sparsely spaced velocity picks.
   2. input CDP, water depth pairs along the line.
   3. Output a series of closely spaced HANDVEL picks, according to
        some pre-determined CDP increment.
Thus, the three lists you must input are:
   1. HANDVEL cards
   2. WBINT list
   3. CDPWD list
The "FCDPOUT", "ICDPOUT" and "LCDPOUT" parameters determine the HANDVEL
locations to output (The OUTPUT list is ignored for WBINT processing).
Interpolation is done in the following manner:
   1. The two enclosing input locations

NPICK = integer = The velocity pair in the HANDVEL list for the water-bottom
                primary. This is normally the first T,V pair (1) or the
                second TV pair (2) in the HANDVEL list.
FCDPOUT = integer = first CDP to output.
                Minimum: 1
                Maximum: 200000
                Default: no default
ICDPOUT = integer = CDP increment to output.
                Minimum: 1
                Maximum: 200000
                Default: no default
LCDPOUT = integer = last CDP to output.
                Minimum: FCDPOUT
                Maximum: 200000
                Default: no default
DELTAZ = real = the water-depth difference between input locations that is
                significant. If the water depth difference between
                INPUT HANDVEL locations is:
                a) more than DELTAZ, then interpolation will be based
                   on the water depth.
                b) less than DELTAZ, then interpolation will be based
                   on distance from the surrounding input locations,
                   not water depth. This is the preferred option when
                   there is a flat water bottom.
                This parameter is important when the water bottom
                topography is locally flat, or nearly flat, so that
                sudden jumps in velocity (causing a stepped velocity field)
                do not occur. DELTAZ should be chosen carefully. If your
                your water depths do not have a large range, a small DELTAZ

is required, but this has the disadvantage of increasing the
likelihood of steps. If your water depths vary a lot in a
deep-water regional survey, then DELTAZ should be set to
between 20 and 100 metres. A value of zero will almost
certainly produce steps in the velocity field.
Minimum: 0
Maximum: 200
Default: no default

CDPWD list

This is used only with the WBINT list. Each card consists of:
CDPWD cdp   wd
where "cdp" is the CDP number, and "wd" is the water depth at that CDP.
This card is repeated along the line, and defines the water depth profile.
Linear interpolation and extrapolation between input points is used to
calculate water depths for CDPs not supplied.

OUTPUT list

This list affects the way that HANDVEL cards are output.

INCR = integer = increment between output HANDVEL locations, compared to
                input HANDVEL locations. If INCR is 1, then there will be
                the same number of output HANDVEL locations as input
HANDVEL
                locations. If INCR is 2, then every second input HANDVEL
                location will be output; so that there will only be half
                as many output HANDVEL locations as input. If INCR
                is 10, only every tenth location will be output.
                Minimum: 1
                Maximum: 1000
                Default: 1

DEPTH list

This list indicates that the user wants to output depth values from the
input HANDVEL cards. The output is horizontal depth horizons, using
the format required by the VELMOD module. The user has a choice of
the way in which the horizontal layers are spaced. The user must make sure
that the number of layers output is fewer than the maximum allowed by
the VELMOD module (currently 1000 horizons). The "DEPTH" option can easily
produce very large ".o" files; up to several megabytes if IVIS (ie. closely
spaced) velocities are input: this in turn can take up large amounts of
disk space when creating the VELMOD model.

DEPTHL = character*8 = the mode of depth layering.
                "LINEAR" = layers are all the same thickness.
                "NONLIN" = layers are thin at shallow depths, and
                           gradually thicken at depth.
                Default: NONLIN
DPTHINC = real = If DEPTHL=LINEAR, the thickness of each layer, in metres;
                the number of layers is DPTHEND/DPTHINC+1
                If DEPTHL=NONLIN, the thickness of the shallowest layer, in
                metres; the number of layers is most easily determined
                at run-time.
                Default: 20 metres
DPTHEND = real = The deepest layer, in metres.
                Default: 40000 metres
DELTMAX = real = If DEPTHL=NONLIN, the thickest layer allowable, in metres.
                Default: 500 metres.
DELRATE = real = If DEPTHL=NONLIN, the thickness change between successive
                layers, in metres. If layer N is X metres thick,
                the layer N+1 will be X+DELRATE thick, unless this
                exceeds DELTMAX.
                Default: 2.5 metres

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Typical Parameters for VSMOOTH

```
*job   depcon      s?????      ppetkovivsmooth for depth conversion
**
*alt   vsmooth     ~msexton/local_progs/dcilcl12/vsmooth
**
*call dumin
**
**     Typical smoothing parameters:
**          Smooth across 5 velocity analyses using weights supplied.
**          A 9/5 spatial median filter
**          A 5/3 temporal median filter, using velocities every 100
ms
**          Velocities forced to increase with time
**          Velocities are changed according to time/percentage
values
**
*call    vsmooth 5¹        0²        0³        0⁴        9⁵        5⁶
tmean⁷  5⁸        3⁹        100.0¹⁰   increase¹¹
weights 1       2       5       2       1
timperc¹²
0       100
16000   100
**
**     Insert the appropriate stacking velocity function here,
**     save file with appropriate name and run job
**
**
*end
```

Typical Parameters for VSMOOTH

```
*job   depcon      s?????      ppetkovivsmooth for depth conversion
**
*alt   vsmooth     ~msexton/local_progs/dcilcl12/vsmooth
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**     Typical smoothing parameters:
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**          A 5/3 temporal median filter, using velocities every 100
ms
**          Velocities forced to increase with time
**          Velocities are changed according to time/percentage
values
**
```

*call   vsmooth 5[1]   0[2]   0[3]   0[4]   9[5]   5[6]
tmean[7] 5[8]   3[9]   100.0[10]   increase[11]
weights 1   2   5   2   1
timperc[12]
0   100
16000   100

```
**
**     Insert the appropriate stacking velocity function here,
**     save file with appropriate name and run job
**
**
*end
```

---

[1] number of adjacent velocity functions to mix together (weighted summing)

[2] number of adjacent velocity functions to smash together (simple adding with normalisation)

[3] number of adjacent velocity functions to look for the minimum (filters out spurious high-velocity picks)

[4] number of adjacent velocity functions to median filter

[5] number of adjacent velocity functions on which to do a trimmed-mean filter

[6] number of adjacent velocity functions (after discarding highest and lowest) to average

[7] for temporal smoothing

[8] number of points in the trimmed mean window

[9] number of points in the centre of the trimmed mean window to actually use

[10] time increment between velocity samples in trim-mean window

[11] INCREASE=force velocities to increase; NORMAL=just do trim mean

[12] list of time, percent pairs to vary the velocity field by (100%=no change)