A SEISMIC REFRACTION STUDY OF THE CRUST AND UPPER MANTLE IN THE VICINITY OF BASS STRAIT*

By R. Underwood†

[*Manuscript received July* 7, 1969]

Summary

A reconnaissance seismic refraction study of the crust and upper mantle of Bass Strait and adjacent land was undertaken in 1966 under the sponsorship of the Geophysics Group of the Australian Institute of Physics. The shot locations and times, the station locations, distances, and first arrival travel times are presented. Analysis of these data is described; they indicate a P_n velocity below 8 km sec^{-1}. Time terms are less than expected and do not agree with previous work. Crustal thicknesses cannot be computed until studies of upper crustal structure are made. These, and several mantle refraction studies, are suggested for future work.

Introduction

Although direct knowledge of the solid earth extends only a few kilometres below the surface, seismic and other geophysical methods lead us to suppose that the top 30 or 40 km of continents are approximately horizontally layered with P wave velocities up to 6·5 or 7 km sec^{-1}. Below this is the Mohorovičić discontinuity (M) where the velocity jumps to about 8 km sec^{-1}. Under oceans, M is only about 10 km below the sea bed. To investigate the crust and upper mantle in south-eastern Australia, a seismic refraction experiment, the Bass Strait Upper Mantle Project (BUMP), was sponsored by the Geophysics Group of the Australian Institute of Physics.

In designing the experiment, we chose to cover a wide region rather than concentrate on a detailed study. Further more detailed work could then be tied to the framework of our observations. BUMP was linked to previous work (Doyle, Everingham, and Hogan 1959; Doyle, Underwood, and Polak 1966) by recording in the Snowy Mountains and south to the coast. Shots were fired in eastern Bass Strait, with further observations in Tasmania. A second line pivoting on Tasmanian stations with shots off King Island was also observed in western Victoria. This paper presents the data gathered from the experiment. The interpretation is provisional on further work.

* Prepared under the auspices of the Bass Strait Upper Mantle Project (BUMP) Committee of the Geophysics Group of the Australian Institute of Physics: C. Kerr Grant (convenor), R. Green, L. V. Hawkins, B. M. Hopkins, W. D. Parkinson, K. Richards, J. Spinks, R. Underwood, J. P. Webb; and co-opted participants J. R. Cleary, C. Dampney, D. Dyson, B. D. Johnson, D. J. Sutton, and Officers of the Bureau of Mineral Resources. This report was prepared by R. Underwood, in consultation with C. Kerr Grant and other members of the Committee.

† Department of Geophysics and Geochemistry, Australian National University, Canberra, A.C.T. 2600.

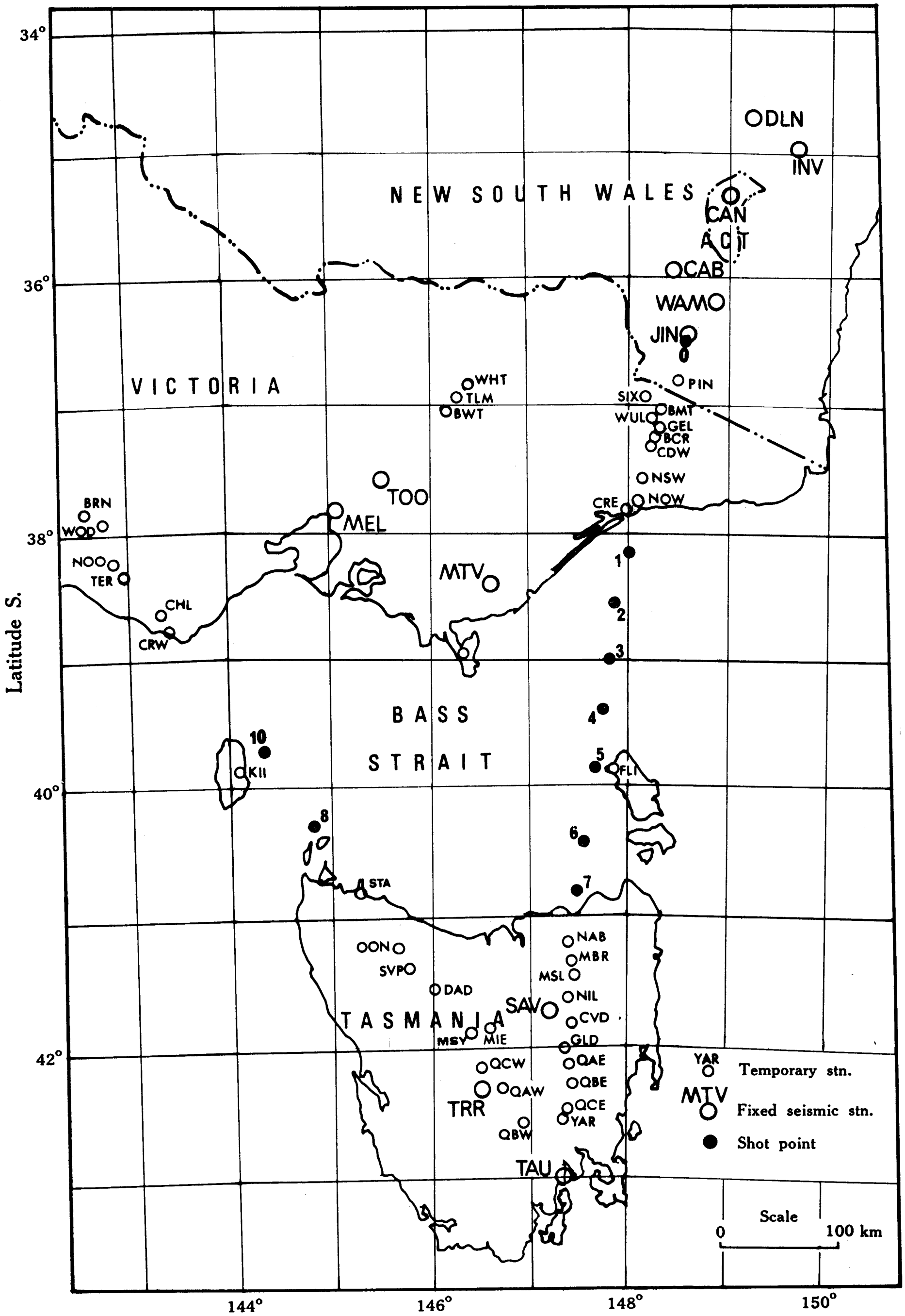

Fig. 1.—Locations of shots and stations.

The Experiment and its Results

Nine 1-ton bundles of obsolescent depth charges were fired on the sea bed at the locations plotted in Figure 1 and listed in Table 1. These sites were chosen for uniform coverage of two lines, but only part of the western line was shot. Locations by Hifix, horizontal sextant, and radar should be accurate to ±200 m (max), except shot 10 which may be up to 500 m in error. Errors in the origin times have been estimated; they are based on VNG radio time signals interpolated by marine chronometer.

Table 1

COMPUTED SHOT POSITIONS AND TIMES

Shot No.	Geographic Latitude S. ° ′ ″	Geographic Longitude E. ° ′ ″	Height above Mean Sea Level (m)	Location Fixing Method*	Date	Time h m s	Error (msec)	Remarks†
0	36 26 33·0	148 37 33·4	960	Ground survey	5.ii.66	17 15 00·3	100	
1	38 08 43	148 01 09	−52	Hifix	6.ii.66	18 14 55·25	16	(1)
2	38 32 58	147 54 14	−65	Hifix	7.ii.66	11 14 58·690	11	
3	38 59 46	147 49 37	−55	Hifix	7.ii.66	18 13 57·980	6	(2)
4	39 26 04	147 43 54	−50	H.S.A.	8.ii.66	06 14 58·275	6	(3)
5	39 52 33	147 37 21	−49	H.S.A.	8.ii.66	12 14 58·057	11	
6	40 23 46	147 31 35	−47	H.S.A.	8.ii.66	18 14 58·532	6	
7	40 48 32	147 27 00	−37	Gyro and radar	9.ii.66	06 14 58·331	6	
8	40 18 53	144 50 58	−37	H.S.A.	17.ii.66	09 14 56·432	11	(4)
9								(5)
10	39 43 50	144 18 20	−46	H.S.A.	17.ii.66	20 15 00·932	9	

* H.S.A., horizontal sextant angles.

† Remarks are: (1) Large error as VNG time signals hard to pick up above Hifix interference. (2) Shot fired 1 min early. (3) Double break instead of single break in tone indicating shot instant. (4) Precise time doubtful as ship recorded 110 msec pulses as against nominal 100 msec. (5) Shot 9 omitted as location too exposed to rough seas and also impossible to position accurately.

A quarry blast at Jindabyne was also used. The location is accurate, and the shot time is known to within 0·1 sec.

Fixed and portable seismographs recorded signals from the shots. Station details are given in Table 2; most locations were taken from available maps and some will not be accurate to better than a few hundred metres. Travel times of seismic signals are listed in Table 3 (upper values), each value being the first discernible arrival on the record. The accuracy of the observations depends on the signal to noise ratio at onset, on the clarity of radio time signals and count-down signals, and on instrument response and paper speed; and the quality of the value estimated by the observer is indicated in Table 3 by the number of decimal digits. Distances are also given in Table 3 (lower values). They have been computed by a geodetic programme and are as accurate as the site coordinates allow.

Discussion of Results

Table 3 lists only about 60% of the possible entries. Data are missing where some stations did not attempt recording of some shots or where instruments failed. Some blanks occur because 1-ton underwater shots seldom generate large enough

TABLE 2

BUMP STATION POSITIONS

A.N.U., Australian National University; B.M.R., Bureau of Mineral Resources; Vic. C.R.B., Victorian Country Roads Board

Name	Code	Geographic Latitude S. ° ′ ″	Geographic Longitude E. ° ′ ″	Elevation (m)	Operating Authority
Permanent Stations					
Werombi	WER	33 57 01	150 34 49	226	A.N.U.
Dalton	DLN	34 43 22	149 10 54	550	A.N.U.
Inveralochy	INV	34 57 54	149 40 01	640	A.N.U.
Canberra	CAN	35 19 15	148 59 55	700	A.N.U.
Cabramurra	CAB	35 55 36	148 26 35	1610	A.N.U.
Wambrook	WAM	36 11 34	148 53 00	1290	A.N.U.
Jindabyne	JIN	36 26 22	148 35 34	960	A.N.U.
Toolangi	TOO	37 34 17	145 29 26	604	B.M.R.
Melbourne	MEL	37 49 53	144 58 24	28	B.M.R.
Mt. Tassie	MTV	38 24 06	146 34 00	740	A.N.U.
Savannah	SAV	41 43 17·6	147 11 22·4	180	Univ. Tasmania
Tarraleah	TRR	42 18 16·3	146 27 03·5	579	Univ. Tasmania
Tas. Univ.	TAU	42 54 35·7	147 19 13·5	132	Univ. Tasmania
Temporary Stations of Eastern Line					
Pinch River	PIN	36 47 33·2	148 24 37	250	N.S.W. Mines Dept
Emu Plains, Black Mt.	SIX	36 56 30	148 13 03	1360	B.M.R.
Black Mt. Stn	BMT	37 01 06	148 15 54	900	B.M.R.
Wulgulmerang	WUL	37 05 40	148 15 20	940	Univ. Adelaide
Gelantipy	GEL	37 10 40	148 15 55	800	Univ. Adelaide
Butcher's Ridge	BCR	37 14 42	148 15 14	740	Univ. Adelaide
W. Tree	CDW	37 20 11	148 13 49·5	530	Comm. Dept Works
South Buchan	NSW	37 33 53·5	148 07 24·5	184	Univ. N.S.W.
Nowa Nowa	NOW	37 43 59	148 05 31	8	Univ. Sydney
Lakes Entrance	CRE	37 51 46	148 00 40	60	Vic. C.R.B.
Flinders Is.	FLI	39 53 45	147 47 50	30	Univ. Melbourne
Nabowla	NAB	41 10 33·5	147 22 22·7	105	B.M.R.
Mt. Barrow	MBR	41 21 09·2	147 22 38·4	460	B.M.R.
Musselboro	MSL	41 27 29	147 26 52·5	460	Univ. Tasmania
Nile	NIL	41 39 13	147 21 28	190	B.M.R.
Cleveland	CVD	41 47 51·5	147 25 40·5	210	B.M.R.
Goldsmith	GLD	42 00 13	147 19 33	400	Univ. Tasmania
Tunbridge	QAE	42 06 36	147 21 36	250	Univ. Queensland
Oatlands	QBE	42 18 12	147 24 18	420	Univ. Queensland
Tiberias	QCE	42 26 42	147 20 36	450	Univ. Queensland
Yarlington	YAR	42 32 41·6	147 18 46·7	400	Univ. Tasmania
Temporary Stations of Western Line					
Barrenook	BRN	37 51 07	142 33 26	210	Univ. Adelaide
Woorndoo	WOD	37 54 25	142 47 55	180	B.M.R.
Mt. Noorat	NOO	38 12 44	142 52 55	135	B.M.R.
Terang	TER	38 18 11	142 58 21	110	Comm. Dept Works
Chapple Vale	CVL	38 38 29	143 19 15	64	Univ. Melbourne
Rotten Point	CRW	38 46 46	143 24 40	110	Vic. C.R.B.
King Is.	KII	39 49 33	144 07 36	5	Univ. Melbourne

TABLE 2 (*Continued*)

Name	Code	Geographic Latitude S. ° ′ ″	Geographic Longitude E. ° ′ ″	Elevation (m)	Operating Authority
Stanley	STA	40 48 40·6	145 15 47·2	10	B.M.R.
Oonah	OON	41 11 44	145 39 14	397	B.M.R.
St. Valentine's Peak	SVP	41 22 07·1	145 45 11·2	1000	Univ. Tasmania
Daisy Dell	DAD	41 33 10·4	146 02 56	750	B.M.R.
Mersey Valley	MSY	41 40 57·1	146 12 51·9	440	B.M.R.
Miena	MIE	41 50 49·5	146 34 44·8	1200	Univ. Tasmania
Bronte Park	QCW	42 07 36	146 29 36	650	Univ. Queensland
Victoria Valley	QAW	42 17 24	146 42 36	650	Univ. Queensland
Pelham	QBW	42 33 18	146 56 42	650	Univ. Queensland
Yarlington	YAR	42 32 41·6	147 18 46·7	400	Univ. Tasmania
Other Temporary Stations					
Whitlands	WHT	36 49 55	146 21 05	640	A.N.U.
Tolmie	TLM	36 55 39	146 14 39	730	A.N.U.
Barwite	BWT	37 00 51	146 08 52	430	A.N.U.
Wilsons Promontory	WPR	38 56 54	146 18 39·7	20	B.M.R.

signals to be seen above the noise at distances in excess of 500 km. A further account of the logistics of the experiment has been presented by Kerr Grant (1967).

The pattern of observations was by no means ideal. No exact reversals, i.e. occasions on which recording and shooting points were interchanged, were observed. This is important because without reversal it is not possible to separate the effects of refractor velocity from the effects of dip on the interface. The quarry blast at Jindabyne was poorly recorded down the eastern line. Arrangements for a marine seismic recording boat to occupy some shooting points while others were fired could not be made. Both these valuable controls on the interpretation are therefore missing. There is much scope for further work to achieve the desired reversals.

Much extra information not presented in Table 3 is available on the seismograms, and detailed studies are at present being made.

ANALYSIS

The interpretation of the results involves velocity analysis followed by an examination of the "time terms" or "delays" for both shots and stations. At every stage, the interpretation is conditioned by gravity, magnetic, and drilling results, and by geological knowledge and judgment which is difficult to justify explicitly. An outline of the geology is given below. The interpretation presented here is a synthesis of unpublished work by Underwood (1967), Johnson (1969), and Kerr Grant *et al.* (1969).*

* The work by Kerr Grant *et al.*, entitled "The Bass Strait Upper Mantle Project. Data and first arrival interpretation", is available on application to the Editor-in-Chief, Editorial and Publications Section, CSIRO, 372 Albert Street, East Melbourne, Vic. 3002.

Table 3

BUMP FIRST ARRIVALS

The top value of each pair represents the time in seconds, the bottom value the distance in kilometres

Stn	Shot Number 0	1	2	3	4	5	6	7	8	10	Stn
WER			75·7 564·91								
DLN	30·7 197·33				78·3 538·53	81·6 588·33					
INV	30·9 189·07	54·0 382·48	63·2 427·77								
CAN	21·6 128·92	50·0 325·41	54·1 371·32	60·1 420·93	66·2 470·11	71·9 519·93	79·5 578·00	90·7? 624·10			
WAM	6·2 36·08	36·8 229·88	41·8 275·56	47·1 324·81	53·7 373·81	59·6 423·51	66·7 481·42	73·9 527·42			
CAB	9·9 59·55	40·0 249·08	(46·1) 294·98	50·2 344·99	57·2 394·34	63·1 444·22	70·4 502·55			77·7 554·95	CAB
JIN	(0·5) 2·97	32·4 195·70	37·5 241·64	42·7 291·35	48·7 340·60	55·0 390·46	62·4 448·63	70·7 494·80			
PIN				37·75 249·90				65·84 453·58			
SIX	11·3 66·34	23·8 134·73									
BMT			29·56 172·89	33·4* 222·87	40·34* 272·23	47·04 322·11	53·79* 380·42		49·8 337·74		BRN
WUL			26·9 164·44		(39·7) 263·76	46·3 313·65	52·9† 371·96		46·5 320·78	32·5 240·02	WOD
GEL			26·4† 155·53	31·4† 205·46						35·2* 207·99	NOO
BCR				31·0 197·94	37·7 247·29	43·0 297·18					
CDW	(19·9) 105·31	17·20† 91·67	24·11 137·64	29·09 187·57	35·69 236·91	41·82 286·80	49·41* 345·09	54·91 391·35	41·93† 273·68	31·01† 193·07	TER
NSW		16·67 65·08	20·26† 110·98								
NOW		12·9 46·20			27·4 191·46	37 241·34	45·0 299·66	50·6 345·94	36·85 227·56	27·64 146·85	CVL
CRE		7·35 31·37	15·78 76·80							21·27 129·92	CRW
FLI							10·71† 60·16	18·66† 105·60	14·44† 82·15	4·04† 21·01	KII
NAB		48·52† 341·03			31·21 195·77		17·37† 87·57	7·64† 41·28	12·10† 65·33	25·25† 146·07	STA
MBR							18·90 106·96	10·80 60·69	21·20 119·10	32·30 199·85	OON
MSL			47·44 325·30	40·40 275·28	34·03 226·00				24·30 139·67	34·14 220·42	SVP
NIL			56·20 347·81	43·20 297·78	37·00 248·46		24·00 140·38	16·50 94·14	27·50 170·63		DAD
SAV			64·3 357·45		39·70‡ 258·09	31·9 208·20	25·0 149·90	17·7 103·69	39·0 251·29		SAV
CVD					38·90 263·69	32·70 214·06	25·20 155·88	19·00 109·83	30·80 190·43	41·20 271·14	MSY
GLD				47·86 336·69	41·71 287·38	35·30 237·65	28·25 179·35	22·38 133·13	35·49 223·79		MIE
QAE		58·11? 443·79	57·19 398·06	50·60 348·03	43·46 298·77	37·15 249·10	29·98 190·86	24·66 144·70	36·97 243·91	47·43 324·67	QCW

TABLE 3 (*Continued*)

Stn	Shot Number 0	1	2	3	4	5	6	7	8	10	Stn
QBE		64·30 464·65	59·40 418·99		45·99 319·78	39·87 270·21	32·68? 212·06	27·56 166·02	41·02 269·07	50·81 349·82	QAW
QCE		67·30 480·88	62·46 435·18	55·25 385·16	48·54 335·92	41·96 286·28	34·73 228·07	29·52 181·93	45·08 304·26	55·31? 385·02	QBW
TRR			71·3 434·80		48·7 336·51	41·4 287·12	34·5 230·27		42·0 258·49	49·0 339·15	TRR
YAR		68·49 492·20	62·75 446·49	55·86 396·47	49·58 347·22	43·14 297·56	36·01 239·15	30·86 193·15	47·70 322·08	58·82 402·61	YAR
TAU						48·9 337·92	48·5 279·73	39·7 233·61			TAU
									57·7 408·15		WHT
									56·1 395·11		TLM
										(48·0) 339·23	BWT
TOO	(49·7) 305·88	36·4 231·46	37·1 238·00	38·9 258·45	42·1 284·58	46·3 315·92	52·1 359·78	56·2 397·27	45·0 309·58	38·2 258·41	TOO
MTV		22·8 130·25	21·4 117·84	22·1 127·96	25·7 152·82	30·5 187·39	38·8 236·35	48·4 277·82	42·6 258·86	38·2 242·67	MTV
WPR				22·42† 131·52	23·7 134·39			50·1† 229·08	31·2† 196·45	30·8† 191·64	WPR

* Time from WWV or WWV(H). † Time from broadcast shot instant. ‡ Late arrival.

(i) *Geology*

The basement is metamorphosed sediments, mainly siltstones, quartzites, slates, and shales, deposited in north–south trending troughs of the Tasman Geosyncline up until Devonian time, when there was extensive granite emplacement. In the Mesozoic, the north–south pattern broke down and the Gippsland, Bass, and Otway basins were initiated by half-graben style faulting on east–west lines (Weeks and Hopkins 1967). Sedimentation commenced about the uppermost Jurassic, followed by a thick pile of greywacke deposited by rivers vigorously eroding the highland to the north in Lower Cretaceous time. The basins sank below the sea in Upper Cretaceous, especially the Gippsland Basin where there is a thick section of sand–shale–coal–siltstone facies, probably also derived from the north. Deposition extended into Eocene time. Widespread transgression followed in the Upper Eocene and continued to the Pliocene, the sediments being mainly calcareous.

The shot environments were:

Shot 1. North flank of the Gippsland Basin. There is 2 km of marine calcareous sediment over 0·6 km of sand–shale facies over probably a palaeozoic basement.

Shot 2. Central Gippsland Basin. There is more than 2 km of marine calcareous sediment over 1·5 km of sand–shale over the basement. Magnetometer estimates of the depth to the basement are $>$ 5 km in the trough axis near this shot.

Shot 3. The basement, probably granitic, is estimated at 0·75 km under primary marine calcareous sediments. The main controlling fault of the Gippsland Basin (normal, north side down) extends east–west from the coast to the Continental slope between 2 and 3.

Shots 4, 5, 6, and 7. The basement depth increases from about 0·3 to 0·75 km along this part of the line, which skirts the south-eastern rim of the Bass Basin.

Shots 8 and 10. There is an estimated 0·6 km of sediments on the western flank of the Bass Basin over a basement which is presumably Cambrian to pre-Cambrian metamorphics and volcanics.

TABLE 4

ANALYSIS OF ARRIVALS BY LINEAR REGRESSION

Arrival*	Intercept (sec)	Std Error (sec)	Velocity (km sec^{-1})	95% Confidence Limits Upper	Lower	Degrees of Freedom
$0P_1$ N.	0·04	0·09	5·98	6·18	5·80	2
$0P_1$ S.	−0·28	0·89	5·42	(36·0)	(2·9)	1
$1P_1$ N.	−0·13	0·78	3·81	5·44	2·94	2
$2P_1$ S.	−0·11	0·70	6·12	7·37	5·24	1
$5P_1$ S.	0	—	5·96	—	—	0
$6P_1$ S.	−0·74	0·83	5·75	6·20	5·35	4
$7P_1$ S.	1·05	0·18	6·21	6·34	6·09	7
$8P_1$ N.	0·38	0·63	6·09	(9·4)	(4·5)	1
$10P_1$ N.	0·04	1·29	5·64	(8·27)	(4·28)	2
$2P_2$ N.	5·07	0·34	7·19	7·63	6·80	2
$8P_2$ S.	3·56	0·03	6·76	6·85	6·68	1
$10P_2$ N.?	−1·20	3·60	5·83	—	(2·3)	1
$1P_n$ N.	4·55	0·36	7·12	7·36	6·89	4
$1P_n$ S.	3·61	1·76	7·60	8·72	6·74	2
$2P_n$ N.	5·23	0·59	7·49	7·81	7·19	5
$2P_n$ S.	5·39	2·41	7·72	9·04	6·74	3
$3P_n$ N.	4·07	0·34	7·52	7·69	7·36	8
$3P_n$ S.	4·01	1·88	7·59	8·58	6·80	4
$4P_n$ N.	4·20	0·91	7·56	7·99	7·18	4
$4P_n$ S.	6·69	1·07	8·11	8·73	7·58	8
$5P_n$ N.	5·18	0·67	7·75	7·99	7·53	8
$5P_n$ S.	4·46	0·54	7·64	7·94	7·37	6
$6P_n$ N.	4·31	0·78	7·69	7·96	7·44	5
$6P_n$ S.	5·78	0·44	7·93	8·32	7·58	6
$7P_n$ N.	3·64	3·69	7·44	(9·24)	(6·22)	3
$7P_n$ S.	6·37	0·41	7·89	8·58	7·30	2
$8P_n$ N.	10·98	2·38	8·85	(12·8)	(6·8)	2
$8P_n$ E.	6·32	0·45	7·97	8·35	7·63	2
$8P_n$ S.	6·01	0·63	7·75	8·14	7·40	7
$10P_n$ N.	8·53	—	9·80	—	—	0
$10P_n$ E.	5·72	1·48	7·78	8·72	7·03	3
$10P_n$ S.	6·48	0·69	7·87	8·21	7·55	7
CAN P_n S.	5·44	3·83	7·62	8·02	6·59	5
JIN P_n S.	6·80	1·56	7·96	8·74	7·31	5
BMT P_n S.	7·72	1·66	8·28	9·78	7·18	3
CDW P_n S.	6·12	0·44	8·01	8·30	7·74	5
QAE P_n N.	7·64	1·87	8·37	9·61	7·42	5
QCE P_n N.	5·49	0·68	7·74	8·06	7·45	5
YAR P_n N.	5·78	0·53	7·88	8·12	7·65	5

* The arrivals are designated: station code or shot point number, phase of arrival, and direction of arrival.

Velocities in these sediments range from as low as 2 km sec^{-1} in the top of the soft calcareous rocks to greater than 4 km sec^{-1} in the compacted sand-shale sequence, and in the greywacke.

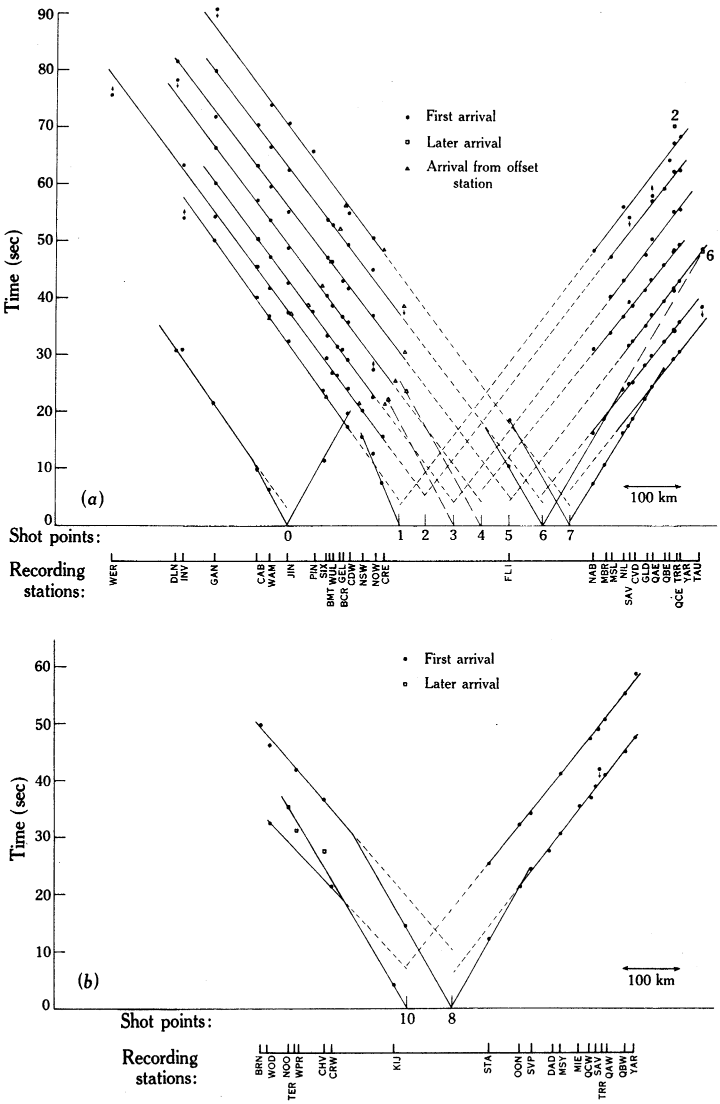

Fig. 2.—Observed travel times for (*a*) the eastern line and (*b*) the western line. Shot to station distances are shown, although the shots have been projected onto the section lines.

Shot 0. Jindabyne Quarry in (Devonian) granite of the Tasman Geosyncline. The P_n velocity is 6·0–6·1 km sec^{-1} and this is probably typical of the whole of the basement rocks. Previous work indicates an intermediate layer, velocity 6·5 km sec^{-1} at a depth of 20 km, with M at 40 km. The P_n velocity under this is 8·1 km sec^{-1} (Doyle, Underwood, and Polak 1966).

(ii) *Velocity Analysis*

The results of a linear regression analysis on the data are given in Table 4, while all the first arrival times are plotted in Figure 2 against distance from the shots. For the eastern line they are also assembled with respect to a common origin in Figure 3. Nearly all the arrivals are mantle refractions. The apparent velocities north and south are indistinguishable in Figure 3 at 7·84 km sec^{-1}. This low value is matched by low intercept times. The arrivals at mainland stations are more scattered than the Tasmanian arrivals. First arrivals at short distances do not define a crustal velocity with any certainty, and more observations are needed. In Tasmania there is a clear indication from three or four first arrivals of an intermediate (P_2) velocity layer. The mainland P_2 is based on paths mainly under the Gippsland Basin, and its reality cannot be confirmed by this work.

The western line readings are not plotted. They confirm the P_n apparent velocity of 7·84 km sec^{-1}.

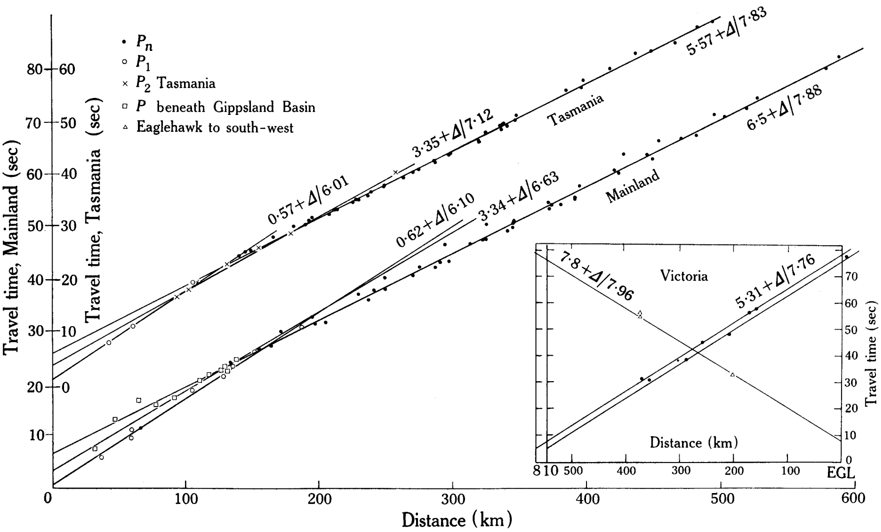

Fig. 3.—Eastern line travel times reduced to common origins for north-shooting and south-shooting observations. The inset shows the reversal mentioned in the text. All the equations were derived by least squares.

The inset in Figure 3 combines readings which approximately reverse observations of Doyle, Everingham, and Hogan (1959). This allows a direct solution. Assuming a single layer crust, M dips 1° north-east, the true velocity is 7·86 km sec^{-1}, and the depth to M is 37 km under the Snowy Mountains and 25 km under shots 8 and 10. Assuming an intermediate layer would result in depths 3–4 km greater than these. This reversing solution may be misleading (see Subsection (v) below).

Because there is otherwise a lack of reversals in the pattern of the data, nothing more can be done with simple velocity analysis.

(iii) *Time Term Analysis*

It is usual to assume that the travel time T_{ij} of P_n can be separated into time terms a for the shot i and station j and a term in the distance Δ and velocity V,

$$T_{ij} = a_i + a_j + \Delta_{ij}/V \ .$$

If there are enough observations, the set of these equations can be solved by least squares for the time terms and the velocity. The implicit assumptions are that the refractor has a constant velocity and that its top surface is not too irregular, and especially not too irregular under any of the sites. Since the a_i and a_j are linearly dependent, an additional constraint must be applied. In BUMP this is provided by identifying the time terms of shot 0 and the Jindabyne station. However, for an unbiased estimate of velocity, the systematic error due to dip of the refractor must be randomized by exact or approximate reversals, and here the BUMP data are deficient.

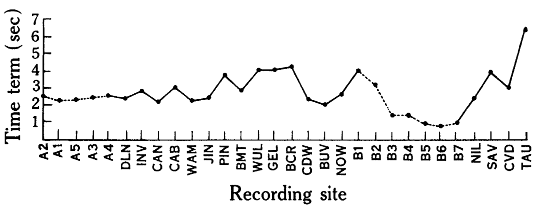

Fig. 4.—Example of a time-term solution incorporating selected data from Doyle, Underwood, and Polak (1966). The recording sites are drawn in order but at constant spacing. The velocity derived in this solution is $7 \cdot 54$ km sec^{-1} (see text).

However, one such solution is presented in Figure 4. It combines the eastern line data with previous work by Doyle, Underwood, and Polak (1966). All such solutions have similar features, namely, the low time term ($\sim 2 \cdot 5$ sec) at Jindabyne, discussed further below, the relatively high time terms about shot 1, the relatively low time terms flanking this as far north as Butcher's Ridge and south in Bass Strait, and the poor control on velocity. The particular velocity value plotted is much too low, because of an arbitrary programme provision to reject residuals beyond two (normal) standard deviations. The residuals are skewed late, so some reliable early readings were rejected in the solution.

The trend in the time terms is, however, sufficiently interesting to encourage a more detailed analysis.

(iv) *Delay Time Analysis*

Regional variations in refractor velocity can be allowed for, using the least squares lines of Table 4 as a guide. The intercept times can be analysed into delays under shots and stations. Relief under sites is allowed for semi-graphically by plotting the delays at the offset refraction points. The delay times determined are listed in Table 5, and shown in Figure 5. This represents the most consistent interpretation of all BUMP first arrivals. It shows rather more detail than the previous methods, at the expense of wider confidence bands.

(v) *Discussion of Analysis*

The results of the analysis may be summarized as follows.

(1) The mantle velocity, from each of the analyses above, is substantially lower than the velocities derived by Doyle, Underwood, and Polak (1966) for south-eastern Australia. This may not be too significant when we consider the uncertainties in the

TABLE 5

DELAY TIMES

Eastern Line			Western Line and Central Stations			Shot Points		
Stn	Delay Time (sec)	Est. Error (sec)	Stn	Delay Time (sec)	Est. Error (sec)	No. and Direction	Delay Time (sec)	Est. Error (sec)
DLN	2·91	—	BRN	5·23	—	1N	4·48	0·38
INV	3·83	—	WOD	3·96	—	2N	3·71	0·43
CAN	2·58	0·43	NOO	—	—	3N	2·41	0·38
CAB	3·35	0·15	TER	4·98	—	4N	2·67	0·22
WAM	2·56	0·38	CHV	5·54	—	5N	2·52	0·34
JIN	2·29	0·23	CRW	2·81?	—	6N	2·39	0·24
PIN	3·02	—				7N	2·61	0·45
SIX	1·75?	—						
BMT	2·75	0·49	STA	3·41				
WUL	2·89	0·54	OON	3·60	—	1S	2·54	0·43
GEL	2·50	0·05?	SVP	2·75	—	2S	3·04	0·21
BCR	2·83	0·48	DAD	1·93?	—	3S	2·68	0·40
CDW	2·48	0·21	SAV	3·14	—	4S	2·48	0·26
NSW	3·70	—	MSY	3·05	—	5S	2·47	0·15
NOW	3·84	0·35	MIE	3·13	—	6S	2·76	0·19
			QCW	2·80	—	7S	3·37	0·27
			QBW	2·72	—			
			TRR	2·52	—			
			YAR	2·80	—			
NAB	3·37	0·53	QAW	2·93	—	8SE	3·8	—
MBR	2·47	—				10SE	3·2	—
MSL	2·73	0·16						
NIL	2·89	0·41	WHT	2·52	—			
SAV	2·99	0·18	TLM	2·58	—			
CLV	2·75	0·19	BWT	1·91	—	8NE	3·1	—
GLD	2·47	0·23				10NE	2·8	—
QAE	3·05	0·30						
QBE	2·87	0·26						
QCE	3·10	0·24	TOO	2·45	0·15			
TRR	2·52	0·43	MTV	3·35	0·29			
YAR	2·79	0·18	WPR	3·42	0·35			
TAU	3·31	—						

BUMP experiment and the geographic separation of the two study areas. However, north of the Snowy Mountains the BUMP observations contradict the 1959 Eaglehawk result of Doyle, Everingham, and Hogan on which previous analyses were based.

(2) The time term at Jindabyne is about 2·3 sec. This value is fixed by the identification of station and shot 0 time terms, irrespective of the velocities. Even with the addition of the data from the 1959 and 1965 experiments, the time term is still near 2·5 sec. However, the interpretation of the previous data implied a time term of about 4·0 sec for Jindabyne.

(3) The section from shots 8 and 10 to the Snowy Mountains in Figure 5 dips generally south-west, which is just the opposite to the solution in the velocity analysis. This is another aspect of the contradiction between BUMP results and the earlier work.

A new assessment of all the refraction work in south-east Australia will be necessary to resolve these discrepancies. In particular, new and detailed travel time studies from Snowy Mountains explosions are required.

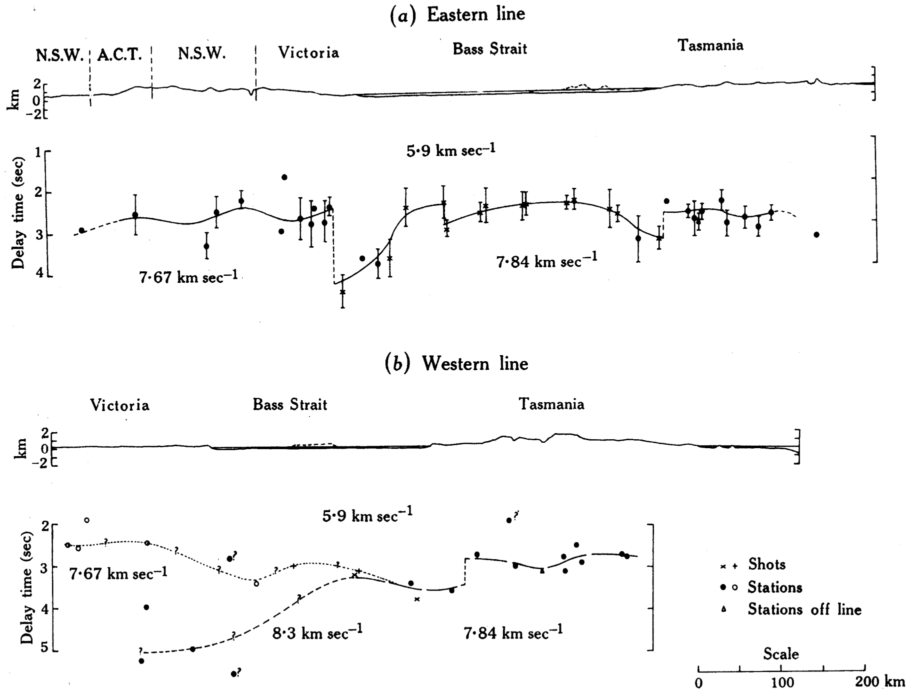

Fig. 5.—Topography and delay time sections for the eastern and western lines. The points are plotted at their offset positions, projected onto the section lines. The curves through the points are for clarity only; in particular, the "steps" do not necessarily imply faults.

(4) In this paper, we do not attempt to convert from time terms to crustal thickness. This step must await more complete studies of the velocity structure of superficial layers. For example, the basement under shots 1 and 2 will have a velocity greater than 6 km sec^{-1}, but the sediments of the Gippsland Basin probably do not average more than 4 km sec^{-1}. They could introduce up to 0·5 sec delay in times at 1N, 2N, 1S, and 2S (Table 5) and rather less at Nowa Nowa (NOW) and South Buchan (NSW) stations. The "step" in Figure 5 at the Victorian coast would

then be substantially reduced, and the step at the southern edge of the Gippsland Basin eliminated. Some delay in the south of the Bass Basin may also have to be allowed for.

(5) The time section for the western line is less reliable than for the eastern line. There is no inconsistency between Tasmanian stations of the two lines, but the observations in the Western District of Victoria are few and scattered and subject to the accumulated errors of the whole analysis.

Conclusions

The study of Bass Strait crust and upper mantle structure has been initiated by the BUMP experiment. The link which has been made with previous work indicates that a re-examination of all the south-eastern Australian refraction work should be commenced.

A number of studies can in the future be linked to the framework of the observations established by BUMP:

(1) The most pressing need is for a shot in the Snowy Mountains to be recorded in detail by lines to the north, south-west, and south, in order to resolve the discrepancy between BUMP times and earlier work.

(2) Control over BUMP results can be much improved by using marine seismic recording gear at some shot points while reshooting others. A suitable pair for east line control would be 1 and 7.

(3) Another experiment which avoids marine recording would be to record at the Flinders Island station while reshooting 10 and similarly reshooting 5 while recording at KII (on King Island). This would give a nearly exact reversal across the centre of Bass Strait.

(4) Studies of upper crustal velocities should be made. The information gathered by oil exploration work should be gathered as it becomes available.

In all cases, it will be more profitable to re-occupy BUMP sites than to establish new ones. Modern equipment with arrays of geophones and magnetic recording will probably be required to improve the signal to noise ratio and to determine accurate apparent velocities.

Acknowledgments

The project was supported by grants from the Nuffield Foundation, Hematite Explorations Pty Ltd, Esso Exploration Australia, Inc., and the Shell Company of Australia Ltd. The Committee is also grateful to the following organizations for permitting their personnel to participate and for providing equipment and facilities for them to do so:

> The Bureau of Mineral Resources, Geology and Geophysics; the Commonwealth Department of Works; the New South Wales and Queensland Mines Departments; the Country Roads Board of Victoria; the Australian National University; and the Universities of Adelaide, Melbourne, New South Wales, Queensland, Sydney, and Tasmania. Various items of equipment were generously loaned by The Bureau of Mineral Resources, Geology and Geophysics; the Carnegie Institution of Washington, Department of Terrestrial Magnetism;

the Department of Public Works, Western Australia; the Department of Lands, Queensland; the Geological Survey of Queensland; the Geological Survey of Tasmania; Austral Geoprospectors Ltd; Geophysical Associates Pty Ltd; Dresser S.I.E. Inc.; Seismic Supply Co.; and N.A.M.C.O. Ltd.

The cooperation of the Royal Australian Navy, and particularly of the Captain of HMAS *Kimbla*, Lt Cdr P. Cummins, and his officers and crew; of the Snowy Mountains Hydro-Electric Authority; and of Mr. J. Scott of Station 2XL, Cooma, is also gratefully acknowledged.

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