Did Port Phillip Bay nearly dry up between ~2800 and 1000 cal. yr BP? Bay floor channelling evidence, seismic and core dating

G. R. HOLDGATE*, B. WAGSTAFF AND S. J. GALLAGHER

School of Earth Sciences, University of Melbourne, Parkville, Victoria, Australia, 3010.

Imagery of meandering river-like channel features up to 5 m deep and 100 m wide on the floor of Port Phillip Bay have been revealed by recent multibeam surveys. They are in water depths to ~22 m below the present bay water level. This young channelling overlies older infilled Pleistocene–early Holocene channels considered to be cut by the Yarra and Werribee rivers during the last glacial or previous low stand minima > 10 000 cal. yr BP and infilled during the Holocene transgression. Vibrocoring data indicate the young channels incise shelly mud. Twelve 14C shell dates in vibrocores from bay floor to 3.5 m are in two units—a lower unit range between 2880 cal. yr BP at 0.7 m to 9491 cal. yr BP at 3.5 m, and an upper unit ~0.5 to 0.7 m thick <869 cal. yr BP forming the present bay floor. Seismic and vibrocore evidence suggests the post-869 cal. yr BP upper unit also covers the base of the young channels. This evidence implies that Port Phillip dried out to ~22 m between ~2800 and ~1000 cal. yr BP at a time of stable present day sea-levels. The most likely cause is a sand blockage to the Port Phillip Bay channel entrances, coupled with high evaporation rates. Palynological and foraminiferal evidence suggests variable salinities occurred immediately prior to the sedimentary hiatus, with restoration of marine conditions after. The results have wide implications on Port Phillip’s water balance, salinity, pre-European climatic events and Aboriginal occupation.

KEY WORDS: Port Phillip, marine geology, channels, Quaternary, Holocene.

AIMS OF THIS STUDY

This study seeks to explain the occurrence of channel features on recently acquired multibeam surveys in Port Phillip Bay, Victoria, at water depths to ~22 m. Previously, Holdgate et al. (1981, 2001) described the distribution, age and morphology of the unconsolidated Port Phillip bay floor sediments, and Late Pleistocene channels identified seismically and dated largely by stratigraphic interpretation. At the time, channels on the bay floor had not been recognised, however depressions on some sub-bottom seismic profiles were interpreted to result from compaction (Holdgate et al. 2001). Previous Port Phillip radiocarbon (14C) dates of shells and carbonaceous material in bay floor cores (e.g. Bowler 1966; Holdgate et al. 1981) were single dates at a few locations. For this paper, 12 new 14C shell dates were obtained from five vibrocores. The palynology and foraminiferal paleoenvironments of two cores were also studied to investigate the paleoenvironmental change during this time.

(1) ‘Port Phillip was once dry land where kangaroos and emus were hunted. One day some small boys were throwing toy spears near some wooden troughs full of water when one spear upset a trough. This was a magic trough and held a lot of water, which came rolling down engulfing all the land and threatening to drown all the people. Bunjil felt sorry for them and placed a rock where Mornington now is, and told the water not to go any further. Then with two other rocks he made the heads, and told the water to run out between them and meet the ocean.’ (Presland 1998).

(2) ‘Murray, an aborigine, assured me that the passage up the bay, through which the ships came, is the Yarra river, and that the river once went out at the heads, but that the sea broke in, and that Hobsons Bay which was once a hunting ground, became what it is.’ (William Hull’s testimony to the Parliamentary Committee, 9 November 1858).

The implications of these stories are further elaborated on in Paradox 6 in the Discussion section.

ANECDO TAL EVIDENCE FROM ABORIGINE ORAL TRADITION

Several Aboriginal stories exist on how Port Phillip Bay formed that appear to corroborate a once dryer bay:

(1) ‘Port Phillip was once dry land where kangaroos and emus were hunted. One day some small boys were throwing toy spears near some wooden troughs full of water when one spear upset a trough. This was a magic trough and held a lot of water, which came rolling down engulfing all the land and threatening to drown all the people. Bunjil felt sorry for them and placed a rock where Mornington now is, and told the water not to go any further. Then with two other rocks he made the heads, and told the water to run out between them and meet the ocean.’ (Presland 1998).

(2) ‘Murray, an aborigine, assured me that the passage up the bay, through which the ships came, is the Yarra river, and that the river once went out at the heads, but that the sea broke in, and that Hobsons Bay which was once a hunting ground, became what it is.’ (William Hull’s testimony to the Parliamentary Committee, 9 November 1858).

The implications of these stories are further elaborated on in Paradox 6 in the Discussion section.

HYDRODYNAMIC SETTING

Port Phillip Bay on the southern coast of Victoria covers an area of 1930 km². Port Phillip is an almost land-locked body of water connecting in the south to the ocean...
through a series of naturally scoured tidal depressions known as the West Channel and South Channel that incise through the sand shoals of the Nepean Bay Bar (Keble 1946). The Nepean Bay Bar consists of a thin veneer of sand overlying Pleistocene aeolianites of the Bridgewater Formation, similar to the adjacent Nepean Peninsula (Figure 1).

Water depths in Port Phillip range from 0 to 24.0 m (with reference to the lowest astronomical tide) with the deepest waters towards the southern end. In the south, water depths rapidly shallow to <5.0 m over the Nepean Bay Bar. The Nepean Bay Bar is cut by South Channel and the Rip—the latter 3.2 km wide maintains oceanic exchange between Bass Strait and Port Phillip Bay where water depths can be >60 m.

Hydrodynamic models and bay water circulation are detailed in Walker (1997) and Walker & Sherwood (1997). They suggest a total water volume for Port Phillip Bay of 26 km³. The total freshwater input to Port Phillip measured in the 1980s was estimated at 1.4 km³/yr from rivers and creeks, and 1.3 km³/yr from rainfall. The total evaporation off Port Phillip is quoted to be 2.3 km³/yr (Walker & Sherwood 1997). As a result, the total freshwater input (2.7 km³/yr) exceeds evaporation by 0.4 km³/yr (i.e. 15%) (Walker 1997; Walker & Sherwood 1997). Any further reduction in input could see a net loss to bay water levels but for its ocean connection. Since the 1980s the input to Port Phillip has now changed due to 25% reduction in rainfall over the last 10 years. Therefore, now the river input is 1.05 km³/yr, rainfall input is 0.97 km³/yr, but evaporation remains at 2.3 km³/yr, i.e. 0.28 km³/yr more than water input.

The largest freshwater source to Port Phillip is the Yarra River with a 1980s mean flow average of 21 m³/s (Walker 1997). Port Phillip salinity increases southwards from 33S near the Yarra River mouth to 35S at the Rip. Particulates (total non-filterable residue) transported into Port Phillip, primarily from the Yarra River, are estimated by Harris et al. (1996) to be around 51 000...
Did Port Phillip Bay nearly dry up?

PREVIOUS WORK AND OBJECTIVES OF THIS STUDY

Bottom sediment distributions in Port Phillip have been published from grab samples, push cores and vibrocores (Beasley 1966, 1969, 1971; Link 1967; Buckley & Clark 1987; Seedsman & Marsden 1980; Holdgate et al. 1981, 2001; Greilach et al. 1996). The distribution of bay floor sediment is shown on Figure 1 (inset) adapted from Buckley & Clark (1987). From 1977 to 1982, the Geological Survey of Victoria (GSV) studies provided additional information from seismic profiles and related vibrocoring on the subsurface geology. Four seismic sequences were recognised from seismic character (Holdgate et al. 1981) and are illustrated as Supplementary Figure 1 in the Supplementary Paper. The top Sequence A is mostly Holocene marine mud, thickest in the infilled channels where vibrocores often did not penetrate through. The more seismically layered sequences B, C and D below, appear to be mostly fluvially derived sandy sediments of the last glaciation. A few vibrocores reached the top beds of Sequence B. Outside the channels most cores penetrated through Sequence A and went into stiff clays believed to be Fishermans Bend Silt of middle Pleistocene age (Holdgate et al. 1981, 2001; Neilson 1988).

MATERIALS AND METHODS

Vibrocoring

Details given in Holdgate et al. (2001) and tabled as Supplementary Tables 1 and 2. The maximum core length obtained in Port Phillip was 4.2 m, although most cores finished in stiff clay (Fishermans Bend Silt) prior to this depth. The average core length recovered was 1.76 m with a range between 0.53 and 4.20 m. The locations of relevant core sites are shown on Figure 1.

Multibeam surveys

Three multibeam survey areas by the Port of Melbourne Corporation (PoMC) have been undertaken within Port Phillip Bay. These were undertaken using a SeaBat 8125 ultra-high resolution, focussed multibeam echo sounder system. Frequency used was 455 kHz with 240 focussed 0.5° beams, 2.5 cm near-field resolution and 6 mm depth resolution over a 120° swath. The purpose of the survey was to map the bay floor in detail in areas of deeper water for location of spoil dumps; their locations are shown on Figure 1.

The three survey areas are:

(1) North-central bay Dump Ground (DMG) areas 3, 4, 9, 10 and 11, comprising four approximate rectangular conjoint surveys southeast of the old Spoil Ground dumps, approximately 15 km west of Ricketts Point. These cover an area totalling around 4 km². Four seismic lines were run in the southern part of the DMG survey using an Innomar sediment echo sounder system (SES–2000 standard) at 8 kHz/2 pulses (250 µs).

(2) The central bay area PoMC Heavy Lift Site comprising a rectangular area measuring 1.3 km east-west and 1.1 km north-south, about 16 km east of Portarlington.

(3) The south-central bay Pinnace Channel Survey comprising an area measuring 1.6 km east-west to 2.4 km north-south, about 7 km NNW of Rosebud and 1 km north of the Nepean Bay Bar Middle Ground.

Seismic Surveys

Methods of seismic surveys are described in Holdgate et al. (1981, 2001). Thirty-six seismic runs totalling 656 km were made by the GSV between 1977 and 1982 (Figures 1). Seismic penetration to 50 ms two-way time (TWT) (about 37.0 m) below the sea bed was obtained in favourable sub-bottom conditions such as the soft mud that exists in the central basin. Resolution of single beds down to 1 ms (~0.7 m) or less is possible. Conversion of seismic TWT to depth appeared to approximate the signal velocity in water of 1.5 km/sec. This assumed depth was found to agree with the depths found in the cores.

Carbon-14 dating

Prior to this work, seven 14C dates, five of which were on carbonaceous material and two on bivalve shells, existed from the whole Port Phillip Bay area (Table 1). These had been analysed in the 1960s to 1970s (Holdgate et al. 1981). For this new work, 12 carbonate AMS 14C dates were obtained from whole shells recovered in six of the Port Phillip vibrocores (Figures 2, 3, Table 1). Dating was done by the Waikato Radiocarbon Dating laboratory. Most dates were obtained from single bivalve shells that appeared in-situ usually single valves encased by the bay floor muds. Carbonate preservation was excellent and enough material was recovered from a single bivalve shell for dating. Vibrocores 5C, 6BiII, 7C, 7D and Werribee Channel are in the Yarra, prior-Yarra or Werribee late Pleistocene channel systems (Holdgate et al. 1981) (Figure 2). Core 4B is on the western edge of the Yarra Channel and provides a date of a shell unit overlying a previously dated peat horizon. Vibrocores 5C and 6BiII are in a wider area of the Yarra channel. Vibrocore 7C is 250 m to the southwest of a young bay floor channel, and vibrocore 7D is 3.5 km east of the Yarra channel. Four dates were obtained from vibrocore 7D where the sedimentary record was interpreted from seismic to be well preserved.

The shells were acid etched to remove any post-depositional surface contamination and tested for recrystallisation using Feigl’s solution—a stain that can distinguish aragonite from calcite material. No recrystallisation was detected in any of the samples.
Figure 2 Logs for 5 Port Phillip vibrocores, showing main lithologies, $^{14}$C dates in cal. yr BP, percentages of sand, and relative abundance of foraminifera. Dotted lines indicate stratigraphic correlations. The upper line approximates to the bay floor hiatus between ~2800 and 1000 cal. yr BP.

Figure 3 $^{14}$C dates from the Holocene record in Port Phillip Bay cross-plotting time vs sample depth. The interpreted bay water levels approximate to the carbonaceous non-marine dates assumed to represent samples near to the shoreline at the time. Holocene sea-level curves for eastern Australia are shown for comparison are modified from Thom & Roy (1985), Sloss et al. (2007) and Lewis et al. (2008). The locations of all cores are shown on Figure 1.
Graphite targets were processed by the reduction of CO$_2$ with Zn in a reaction catalysed by iron powder at a temperature of 575°C. The resulting graphite was compressed into a target for measurement at the Keck Radiocarbon Laboratory University of California, Irvine. The marine reservoir correction for southeastern Australian marine waters was applied to the AMS 14C vine. The marine reservoir correction for southeastern Australia. Therefore, any correction would also be speculative, so any correction would be arbitrary. It is also likely that any reservoir correction applied will have changed over time providing correction differences between the 400 yr old sample and those that are 9000 yrs old. Therefore, any correction would also be speculative, so the dates are based on marine waters for southeast Australia.

The dates in Table 1 were corrected to the recalibration system given on the website <http://www.calpal-online.de/> . In most cases, this gives a slightly older date. This recorrected date is used throughout the ensuing text.

The full AMS results for 14C dates are presented in Supplementary Tables 3 and 4 of the Supplementary Carbon 14 Dating Results Section. A summary of the dates is presented in Table 1 above.

### Table 1 14C dates.

<table>
<thead>
<tr>
<th>Wk No.</th>
<th>Core</th>
<th>Depth (m)</th>
<th>Result yrs BP</th>
<th>Calpal correction (cal. yr BP)</th>
<th>Shell identification</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>25493</td>
<td>6Bii</td>
<td>1</td>
<td>4407 ± 36BP</td>
<td>4976 ± 67</td>
<td>Pectinidae sp.</td>
<td>See Fig. 1</td>
</tr>
<tr>
<td>25494</td>
<td>7D</td>
<td>1.5</td>
<td>6273 ± 36BP</td>
<td>7214 ± 34</td>
<td>Oyster</td>
<td>See Fig. 1</td>
</tr>
<tr>
<td>24835</td>
<td>4B</td>
<td>0.68</td>
<td>7071 ± 30BP</td>
<td>7900 ± 34</td>
<td>Cardiidae/Fulvia</td>
<td>See Fig. 1</td>
</tr>
<tr>
<td>24836</td>
<td>7D</td>
<td>0.1</td>
<td>423 ± 30BP</td>
<td>491 ± 20</td>
<td>Bivalve-species not identified</td>
<td>See Fig. 1</td>
</tr>
<tr>
<td>24837</td>
<td>7D</td>
<td>0.65</td>
<td>3466 ± 30BP</td>
<td>3987 ± 63</td>
<td>Pectinidae sp.</td>
<td>See Fig. 1</td>
</tr>
<tr>
<td>24838</td>
<td>WCh</td>
<td>0.5</td>
<td>6390 ± 30BP</td>
<td>7342 ± 57</td>
<td>Anadara trapezia</td>
<td>See Fig. 1</td>
</tr>
<tr>
<td>25387</td>
<td>5C</td>
<td>0.5</td>
<td>8307 ± 42BP</td>
<td>9338 ± 64</td>
<td>Veneridae sp.</td>
<td>See Fig. 1</td>
</tr>
<tr>
<td>25388</td>
<td>5C</td>
<td>3.5</td>
<td>8473 ± 55BP</td>
<td>9491 ± 32</td>
<td>Oyster</td>
<td>See Fig. 1</td>
</tr>
<tr>
<td>25389</td>
<td>6Bii</td>
<td>0.6</td>
<td>959 ± 31BP</td>
<td>869 ± 48</td>
<td>Pectinidae sp.</td>
<td>See Fig. 1</td>
</tr>
<tr>
<td>25390</td>
<td>6Bii</td>
<td>1.3</td>
<td>4933 ± 33BP</td>
<td>5664 ± 40</td>
<td>Bivalve-species not identified</td>
<td>See Fig. 1</td>
</tr>
<tr>
<td>25391</td>
<td>7D</td>
<td>3</td>
<td>8274 ± 44BP</td>
<td>9274 ± 100</td>
<td>Bivalve-species not identified</td>
<td>See Fig. 1</td>
</tr>
<tr>
<td>25783</td>
<td>6Bii</td>
<td>0.7</td>
<td>2770 ± 30BP</td>
<td>2860 ± 43</td>
<td>Bivalve-species not identified</td>
<td>See Fig. 1</td>
</tr>
<tr>
<td>25784</td>
<td>7C</td>
<td>0.6</td>
<td>3077 ± 30BP</td>
<td>3307 ± 39</td>
<td>Veneridae sp.</td>
<td>See Fig. 1</td>
</tr>
</tbody>
</table>

Previous 14C dates (corrected to Calpal System)

<table>
<thead>
<tr>
<th>ID No.</th>
<th>Sample source</th>
<th>Depth (m)</th>
<th>Result yrs BP</th>
<th>Calpal correction</th>
<th>Identification</th>
<th>Location</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>N155</td>
<td>Core</td>
<td>0.7</td>
<td>5900 ± 160</td>
<td>6863 ± 203</td>
<td>Anadara trapezia</td>
<td>5 km west of Ricketts Point</td>
<td>Bowler (1966)</td>
</tr>
<tr>
<td>SUE995</td>
<td>Core</td>
<td>1.2</td>
<td>5240 ± 135</td>
<td>6018 ± 162</td>
<td>Bivalve not identified</td>
<td>5 km WSW of Mt Martha Power Street</td>
<td>Holdgate et al. (1981)</td>
</tr>
<tr>
<td>GaK-1100</td>
<td>Excavation in Coode Island Silt</td>
<td>2.4</td>
<td>6010 ± 100</td>
<td>6873 ± 127</td>
<td>Eucalyptus wood</td>
<td>South Melbourne Power Street</td>
<td>Gill (1968b, 1971)</td>
</tr>
<tr>
<td>W-170</td>
<td>Excavation in Coode Island Silt</td>
<td>0.7</td>
<td>4820 ± 200</td>
<td>5539 ± 238</td>
<td>Eucalyptus wood</td>
<td>Maribyrnong River bank</td>
<td>Gill (1968b, 1971)</td>
</tr>
<tr>
<td>SUE992</td>
<td>Core</td>
<td>3.5</td>
<td>7010 ± 190</td>
<td>7854 ± 169</td>
<td>Carbonaceous silts</td>
<td>1 km east of Sorrento</td>
<td>Holdgate et al. (1981)</td>
</tr>
<tr>
<td>SUE993</td>
<td>Core</td>
<td>1</td>
<td>8110 ± 170</td>
<td>9019 ± 251</td>
<td>Carbonaceous sands</td>
<td>6 km NW of Dromana</td>
<td>Holdgate et al. (1981)</td>
</tr>
<tr>
<td>SUE1126</td>
<td>Core 4B</td>
<td>0.65</td>
<td>8290 ± 280</td>
<td>9193 ± 343</td>
<td>Peat</td>
<td>See Fig. 1</td>
<td>Holdgate et al. (1981)</td>
</tr>
</tbody>
</table>

Palynology

To aid in paleoenvironmental reconstructions of the Holocene Sequence A and upper part of Sequence B in Port Phillip Bay, 16 palynological samples were examined approximately every 0.5 m from cores 5C and 7D located within or near the main Yarra channels in middle of the bay. The methods for spore-pollen extraction, counting and identification are detailed in full in the Supplementary Paper.

Foraminifera

The foraminiferal record in core 7D was examined for paleoenvironment, salinity and paleodepth. The methods for foraminifera separation, counting and identification are detailed in full in the Supplementary Paper.

RESULTS

Vibrocoring and 14C dates

Logs of the vibrocores that were studied are shown in Figure 2. The upper section of each core is a medium- to fine-grained shelly mud. In cores closer to the River Yarra, more than 50% of the grains are coarser than...
65 μm and are classified as sandy mud (core 5C). All core and sample locations are shown on Figure 1. Core 4B outside the main channel comprises sand and shell beds overlying peat. In general, the cores become coarser-grained, sandy and contain less shell down section (e.g. core 7D), and they are also coarser close to the main channels (e.g. core 7C).

The twelve new AMS 14C dates on shells are detailed in Table 1. They indicate ages of the bay floor mud and sandy mud range from 491 ± 20 cal. yr BP to 9491 ± 32 cal. yr BP at around 3.5 m below the bay floor. The shells were identified by Sue Boyd (Museum of Victoria) and all are considered to be marine species (Sue Boyd pers comm. 2010). The seven previous dates in the Port Phillip Bay area are also shown in Table 1.

The older ages tend to be in the sandier lithologies that may be present near-surface dependent on erosion. For example, core 5C on the west side of the 2 km wide Yarra channel in the northern part of the bay ranged from 9338 to 491 cal. yr BP at 0.5 m to 9491 ± 32 cal. yr BP at around 3.5 m below the bay floor. The shells were identified by Sue Boyd (Museum of Victoria) and are all considered to be marine species (Sue Boyd pers comm. 2010). The seven previous dates in the Port Phillip Bay area are also shown in Table 1.

Averaged sedimentation rates based on the AMS 14C dates vary from 0.010 to 0.057 cm/year in the shelly mud to >1.746 cm/year in the sandy mud. Averaged sedimentation rates in Port Phillip are misleading, as they imply continuous deposition in channel fill sediments likely to be intermittent or prone to erosional hiatuses.

The Port Phillip Bay 14C dates are plotted for sample depth against time (Figure 3) and a boundary drawn between the carbonaceous sediment dates deposited at or above bay levels at the time (open circles) and shell dates deposited in situ in marine muds below bay levels at the time (closed circles). A line drawn between the carbonaceous and shell dates approximates to bay paleodepths through time. The previous 14C ages from carbonaceous woody material all come from core material below the marine sands or muds, or in outcrops in the Yarra delta. None of these older dated samples come from within the channels. Their locations are indicated as a plus sign (+) on Figure 1, and their details are given in Table 1.

From Figures 2 and 3, there is an ~2000 cal. yr BP gap in the dates in core 6Bii over 0.1 m between 2880 ± 43 cal. yr BP and 869 ± 48 cal. yr BP. In core 7D, there is a 3496 cal. yr BP gap over 0.7 m between 3887 ± 63 cal. yr BP and 491 ± 20 cal. yr BP. Absence of dates in these ranges may indicate these sediments were not sampled, or sediments for this age are condensed (<0.1 m in core 6Bii), or there is an erosional or depositional hiatus for this period in the sedimentary record in Port Phillip Bay.

Multibeam surveys

In all three multibeam surveys in Port Phillip Bay, there is evidence for channelling on the present bay floor:

(1) The Dump Ground multibeam survey shows a 0.5–1.0 km wide incision area wending a 2 to 5 m deep pathway southeast, with a narrower 100 m wide, sinuous paleochannel feature bifurcating away from the main channel in a more southerly direction (Figure 4). Two of the four PoMC Innomar seismic lines (1 and 4) show a distinct 100–200 m wide bay floor indention up to 2 m deep where they cross the meandering bay floor channelling. Line 2 did not cross the channel, line 3 appears to run alongside the channel. The seismic lines 1 and 4 show this youngest channelling overlies older channel fill at its deeper point, but does not mirror the same older channel meander pattern. This, together with the meander pattern and profiles, suggest a river-cut origin, discounting differential compaction as a sole cause for the bay floor indentations.

(2) The central bay Heavy-Lift multibeam survey shows a 100 m wide meandering channel incised into the bay floor area 3 to 5 m deep, wending a highly sinuous pathway south (Figure 5). The river origin for this incision is confirmed by the river-characteristic deeper incision on outer bends, and a progradational profile on the inner channel bends. The seismic line Run 20 crosses the main channel twice. Although the seismic quality is poor due to rough water at the time of the seismic survey, the bay floor Holocene depressions are obvious, and can be seen to overlie earlier Pleistocene channels and infilling sediments (Figure 5).

(3) The south bay Pinnace Channel multibeam survey shows a sinuous 7 m deep incision on the bay floor immediately to the north of the Nepean Bay Bar (Figure 6). The channel sinuosity appears less than in the other two surveys, but is deeper. It also lacks the more classic river-like deeper incision on the outer bends, and shows deepest incision in the centre of the channel. These differences may indicate an incision origin other than by river erosion (see Discussion). The sub-bottom seismic line part of Run 11 shown on Figure 6 (inset) crosses the main Pinnace channel at right angles.

Seismic surveys, 14C dates & channeling age

In many instances, where the 1977–1982 sub-bottom seismic profiles crossed the infilled Pleistocene Yarra Channel, depressions are present on the bay floor, with up to 2 to 3 m of relief and about 100 m wide (e.g. Figures 4–10). In the more northern bay areas, the infilled channels underlie broader and deeper bay floor depressions as shown on Figures 1 and 7. The channel from the Werribee River consistently shows this feature along most of its length. Holdgate et al. (2001) suggested some combination of differential compaction and incomplete infill was the most likely explanation for these bay floor depressions.

The three PoMC multibeam surveys provide the first detailed impressions of the bay floor. These images were not available from previous soundings surveys. The 100 m wide meandering channels coincide with bay floor depressions in profile on the seismic lines (Figures 9, 10). In the northern part of the bay, the Dump Ground
multibeam survey (Figure 4) shows a wider 500 m central depression with a pronounced sinuous course from which emanates a small meandering channel to the south.

Seismic (Core) Line 5 passes through the core locations for 5B and 5C, and crosses this wider depression about 7 km north of the Dump Ground multibeam survey (Figure 7). The Sequence B infill of the late-Pleistocene channel has been partly eroded by a later channelling event, now buried by the youngest marine mud. This latest channelling also cut its deepest against a steeper western wall of probable mid-Pleistocene stiff clays of the Fishermans Bend Silt. The late-Pleistocene Sequence B onlaps against the steeper western side, so that vibrocore 5B intersects >9338 cal. yr BP Sequence B fluvial muddy sands underlying 0.5 m of marine mud. Vibrocore 5B outside the late-Pleistocene channel intersected 0.65 m of marine sandy mud overlying 0.12 m of hard non-marine clay of the mid-Pleistocene Fishermans Bend Silt (Figure 7). Therefore, cores 5B and 5C (Figure 7) located on the far western edge of the Yarra channel at one of its widest points, intersect pre-9338 cal. yr BP of mostly non-shelly sandy mud below 0.5 to 0.65 m of undated slightly shelly sandy mud. In view of the other core dates, this result indicates a substantial time gap between >9338 cal. yr BP and the shelly mud above at possibly <1000 cal. yr BP. The time gap may be a result of river erosion that removed the intervening 8300 yrs period between 9338 and ~1000 cal. yr BP.

Seismic Core Line 6B-6Bii passes over the core sites of 6B and 6Bii, and is located 1 km north of the Dump

Figure 4 Dump Ground multibeam survey area in the north–central area of Port Phillip Bay. The locations of PoMC Innomar seismic lines 1 to 4 are indicated on the multibeam survey and shown above. Lighter colours near the channel base are thought to indicate harder or coarser material. The locations of bay floor channels are indicated with blue arrows. Inset shows location of this multibeam survey relative to the Late Pleistocene channels and vibrocore locations. The location of the seismic lines and multibeam survey is also shown on Figure 1.
Ground multibeam survey (Figure 8). The line shows the main late-Pleistocene Yarra Channel with higher ground on the eastern and western sides. Core 6B bottomed in mid-Pleistocene Fishermans Bend Silt at 0.75 m below 0.55 m of shelly quartz sand. Core 6Bii drilled within Sequence-A channel infill was still in shelly marine mud at 2.5 m. The laminated seismic reflectors over the upper ~0.7 m correlate to finer grained grey shelly silty muds of ~869 cal. yr BP. The lower 1.8 m is more muddy Sequence-A sediments that exhibit a blank reflector appearance dated between 2880 and >5664 cal. yr BP. A dating hiatus occurs over 0.1 m of ~2000 yrs between the two units—the dashed line in Figure 8.

Seismic Core Line 7 passes over the core sites of 7C and 7D (Figure 9). The line is located 4 km north of the Heavy Lift multibeam survey area. The better quality of Seismic line Run 15 about 4.7 km north of the Heavy Lift multibeam survey area, is shown on Figure 10 with the core logs extrapolated onto the line. On Seismic Core Line 7, core 7C is located 200 m west of several young Holocene surface channels (Figure 9). The upper 0.5 m of shelly mud is a laminated reflective seismic sequence that continues east into the base of the young channels (see also Figure 10). The lower 0.7 m is shelly sandy mud dated by 14C just below the laminated reflectors at 3307 cal. yr BP. The results indicate the young channel floor is covered by about 0.7 m of sediment younger than 3307 cal. yr BP.

Core 7D (Figures 9, 10) is located above an inter-channel high between the late-Pleistocene Yarra and proto-Yarra Channel system (Holdgate et al. 1981, 2001). The upper 0.6 m is correlated to a laminated reflective seismic interval—the same shelly mud interval at core 7C that also veneers the floor of the bay floor channels shown in Figures 9 and 10. A 14C date of 491 cal. yr BP was obtained near the top of this interval. The rest of core 7D mostly comprises a non-laminated reflective seismic interval of shelly muds, near the top at 0.65 m which was 14C dated as 3987 cal. yr BP. They grade into sandy mud below 2.3 m and muddy sand below 3.4 m. The lowest shells in the core 7D at 3.0 m were dated by 14C at 9274 cal. yr BP. The cored non-marine sequence below 3.4 m is correlated to the strong seismic reflectors of Sequence-B—interpreted to be part of a series of fluvial sediments deposited during the last-glaciation/earliest Holocene. The oldest palynology sample in core 7D at 3.7 m contains a glacial plant assemblage dominated by Asteraceae (see palynology results).

When all the bay floor depressions are located onto the seismic run map (Figure 11) an apparent bay floor channel system trends south down the bay, broadest in the north, narrowing at around the ~20 m depth contour into a 100 m wide meandering channel that...
can be followed as far as Run 20. The channelling shown on Figure 11 is generalised between seismic lines, and the multibeam surveys illustrate more complex meander morphologies.

The bay floor channelling becomes faint or disappears on seismic lines towards the south of the bay, at around the 722 m water depth. This occurs south of a line running approximately between Point Richards and Mornington where water depths exceed 22 m. This correlates to the deepest part of the bay, immediately north of the Nepean Bay Bar. At the southeastern end of this area is a prominent bay floor depression imaged by the Pinnace Multibeam survey and traversed on Run 11 (Figure 6). This channel appears to trend northwards from the Nepean Bay Bar, and by this pattern and different morphology, suggests it may be a tidal scour, in contrast to the rest of the channels in the bay that can be tracked back to the Yarra and Werribee Rivers.

**Palynology**

Palynological studies on core 7D from central Port Phillip Bay show what appears to be a relatively continuous record dating from about ~10,000 cal. yr BP to the present (Figure 12). The full palynological records for cores 7D and 5C are provided in the Palynology Supplementary Records. A summary of results for core 7D is as follows.

The oldest sample at 3.7 m (49274 ± 100 yrs cal BP) has evidence of the vegetation overlying glacial sediments. The dominant taxon is Asteraceae Tubuliflorae (long spine type) and lesser dominants are Casuarinaceae, Chenopodiceae and Poaceae. Also present in this sample in very low amounts is Asteraceae Tubuliflorae (short spine type), a taxon whose generic affinity is uncertain, but which is generally present in glacial periods and virtually absent in the Holocene (Wagstaff et al. 2001).

The sample at 3.0 m (14C date of 9274 ± 100 cal. yr BP) shows a very dramatic change in the regional and local vegetation at the site. Diversity increased and an influx of pollen types attributable to Bursaria, Callitris, Coprosma, Eucalyptus, Gyrostemonaceae, Myoporaceae and myrtaceous shrubs are recorded. Casuarinaceae dominated the regional vegetation while Asteraceae Tubuliflorae (long spine type) is reduced. Chenopodiceae plays a predominant role in the local (and probably regional) vegetation and Poaceae values are at around 20%. This sample has the highest values of Isoetes. The spores are consistent with those produced by the quillwort Isoetes drummondii, a species that is recorded as growing in temporary fresh-shallow water or mud (Duncan & Isaac 1994) indicating a flooding of freshwater into Port Phillip Bay. The species continues to be recorded in the overlying samples, but never again at such high abundances. This species is no longer recorded as growing anywhere within the vicinity of Port Phillip Bay or within the catchment of the Yarra River (Duncan & Isaac 1994). Macphail & Casey (2005) found an analogous situation pre-European occupation in the Parramatta area near Sydney and suggested that grazing and cultivation were responsible for local extinction of Isoetes in the area.

**Figure 7** Seismic Core Line 5 opposite Point Cook. Location of vibrocores 5B and 5C shown on the line and their logs illustrated. Lithology symbols as for Figure 2. Location of cores shown on Figure 1. Sequence A is mostly Holocene marine mud; Sequence B is layered mostly early Holocene non-marine sandy sediments (Holdgate et al. 1981). Fishermans Bend Silt is mid-Pleistocene in age (Neilson 1988).
Seismic Core Line 6 opposite Werribee River. Location of vibrocores 6B and 6Bii shown on the line and their logs illustrated. Lithology symbols as for Figure 2. Location of cores shown on Figure 1. Sequence A is mostly Holocene marine mud; Sequence B is layered mostly late Pleistocene-early Holocene non-marine sandy sediments (Holdgate et al. 1981). Fishermans Bend Silt is mid-Pleistocene in age (Neilson 1988).

Figure 9 Two sections of Seismic Core Line 7 opposite Carrum. Location of vibrocores 7C and 7D shown on the lines and their logs illustrated. Lithology symbols as for Figure 2. Location of cores shown on Figure 1. Sequence A is mostly Holocene marine mud; Sequence B is layered mostly late Pleistocene-early Holocene non-marine sandy sediments (Holdgate et al. 1981).
Dinoflagellates occur at very low numbers in this and the overlying sample in core 7D but are high enough (43% of the total palynological assemblage) in the sample at 2.3 m to suggest the Bay had become open marine by this time (estimated at *8200 BP; Figure 2).

![Diagram](image)

**Figure 10** Part of seismic Run 15 opposite Carrum (see Figure 1). The young Holocene channelling indents the bay floor at the deepest point on the line. Location of cores 7A to 7D projected NW 0.7 km. Detail of the upper part of the seismic line over the bay floor channel shows a layered section of marine mud reflectors also occurs within the young channel base, and a dating hiatus in core 7D corresponds to the base of this layered section. The full log for 7D is shown on Figures 2 and 9. Cores 7A and 7B bottomed in mid-Pleistocene Fishermans Bend Silt at 0.89 and 0.20 m respectively. Lithology symbols as for Figure 2. For the location of line and vibrocores, see Figure 1.

![Map](image)

**Figure 11** Location map of seismic runs showing positions of the late Holocene bay floor depressions linked between runs. These overlie last glacial infilled low stand channels. The bay floor depressions disappear in the area contained within the heavy dotted line to the south where water depths are >22 m or deeper.

today. Dinoflagellates occur at very low numbers in this and the overlying sample in core 7D but are high enough (43% of the total palynological assemblage) in
Figure 12 Ratio diagram of main palynomorph groups for vibrocore 7D (central bay), also shows $^14$C dates. For location of core 7D see Figure 1. For a full list of species see Supplementary Figure 3.

The next sample in core 7D occurs at 1.4 m just above the $^14$C date of 7217 $\pm$ 34 cal. yr BP. Dryland taxa such as Callitris, Eucalyptus and myrtaceous shrubs are at their greatest abundance in the sample as are dinoflagellates. This increase in tree species in this sample is consistent with the increase in rainfall and slightly warmer conditions that is recorded in numerous other Victorian pollen records at that time (Dodson 2001). In the overlying samples (0.9 m and 0.7 m—the later dated 0.05 m above by $^14$C at 3987 $\pm$ 63 cal. yr BP) Callitris, Eucalyptus and myrtaceous shrubs and dinoflagellates, steadily decline to low abundance towards the youngest sample dated by $^14$C at 491 $\pm$ 20 cal. yr BP. This decline in tree species reflects the later Holocene drying that has been dated as commencing ~3000 cal. yr BP (Bowler 1981; Ahmad 1996) and finished ~1300 cal. yr BP (Ahmad 1996). Pteridium is also most abundant value in the sample dated by $^14$C at 7217 $\pm$ 34 cal. yr BP maintaining values of approximately 40% until the youngest sample where they decline to low (glacial-like) levels. Pteridium tends to colonise disturbed areas with fires stimulating its growth (Duncan & Isaac 1994). It appears that the marine catchment is better able to record this occurrence compared with the Holocene swamp vegetation records in the area surrounding the Bay (Aitken & Kershaw 1996; Jenkins & Kershaw 1997).

The dinoflagellate record in core 7D provides evidence of the amount of marine influence in the bay (see Figure 12 and Supplementary Figure 3). In addition, a notable occurrence within the dinoflagellate flora is the presence of Tuberculodinium vancampanoe in all the samples from 7214 $\pm$ 34 cal. yr BP and younger. McMinn (1990) recorded this tropical to sub-tropical species in low numbers in the sediments of the present-day Port Phillip Bay and in his sites along the east Australian coast. The presence of T. vancampanoe in low abundances in the Bay suggests not only that it can tolerate the temperature regime but also indicates an open-marine connection to allow this species to be swept in via the currents. However, the disappearance from the bay of the species Operculodinium israelianum after 3987 $\pm$ 63 cal. yr BP implies a different scenario. McMinn (1990) does not record this species in the present-day assemblages further south than Port Hacking (except for one occurrence in the Gippsland Lakes). O. israelianum is recognised as being typically a warm water species inhabiting temperate/subtropical to tropical waters of normal salinity. It is restricted to fully open-marine sites and can thrive in coastal sites, inshore bights and the open ocean (Marret & Zonneveld 2003). It can dominate high-salinity environments such as shallow lagoons and is most abundant in association with higher salinity environments up to 36.8S (Marret & Zonneveld 2003). Its disappearance from the Bay sometime after 3987 $\pm$ 63 cal. yr BP and its absence in the only overlying sample at 491 $\pm$ 20 cal. yr BP, and in the present-day sediments (McMinn 1990), implies (bearing in mind the lack of samples between these dates) either: (1) a dramatic cooling of the Bay, for which there is no evidence in the vegetation or (2) a longstanding relict population that was pushed to extinction due to a change in salinity (blocking of the bay) prior to the deposition of the youngest sample at 491 $\pm$ 20 cal. yr BP. The vegetation in the youngest sample at 491 $\pm$ 20 cal. yr BP in core 7D is not significantly different from the preceding samples; however it does exhibit an increase in diversity with a number of taxa making a first appearance in the record. These include Apiaceae, Malvaceae, Urtica and the fern species of Asplenium and Ceratopteris. The vegetation at this time is consistent in a broad sense with the historical records of vegetation around the Bay and the riparian vegetation of the Yarra and Maribyrnong rivers (Beardsell & Beardsell 1999).

Foraminiferal record

The foraminiferal record at the site of vibrocore 7D in Port Phillip Bay (Figure 2) included the following results from oldest to youngest:

1. The oldest samples from 3.7 to 2.3 m contain no foraminiferal assemblages and this is taken to indicate Port Phillip Bay was either dry, occupied by freshwater or their calcareous shells were dissolved. The presence of the fern Isoetes drummondii, and the alga Botryococcus brownii would support a freshwater bay.

2. The first estuarine-marine signal occurs at 2.1 m (extrapolated to around 8200 cal. yr BP from Figure 2 when rare species of Ammonia beccarrii, Elphidium spp., Bulimina marginata and Lagena spp. first appear.
(3) The marine signature at 1.5 m ($^{14}$C dated at 7214 ± 34 cal. yr BP) becomes stronger with increasing numbers of the taxa above, in particular *Bulimina elongata* indicates open marine conditions.

(4) Between ~7000 and 4500 cal. yr BP (1.4 m and 0.9 m respectively) the foraminifera counts include rare planktonic species (mainly *Globigerina* spp.) together with similar benthonic with the addition of *Discorbis dimidiatu*—indicating an open deeper water marine bay (shelfal <50 m).

(5) Foraminifera numbers begin to decline towards the 0.65 m sample $^{14}$C dated at 3987 ± 63 cal. yr BP where *A. beccarrii* and rare agglutinates make up a sparse estuarine assemblage.

(6) Agglutinate species increase at 0.1 m (near surface sample) $^{14}$C dated at 491 ± 20 cal. yr BP, with the reappearance of species of *Elphidium* spp. and *A. beccarrii*.

The presence of planktonic foraminifera between ~7000 and 4500 cal. yr BP is interpreted to indicate a slight increase in oceanicity in this estuarine environment, and bay levels would have equilibrated to sea-level at the time. Generally, over this time interval, the sea-level was thought to be up to 2.0 m above present levels (Sloss et al. 2007; Lewis et al. 2008) and so it is likely parts of the Yarra delta may have become inundated, providing for a drowning of the Yarra River up to 10 km inland, as interpreted from wood in shellbeds at Flemington dated by Gill (1968a) at 5539 ± 238 cal. yr BP. The sparse foraminiferal sample at 0.65 m suggests a fall in bay levels at this time (3987 ± 63 cal. yr BP), with low sample numbers until <1000 cal. yr BP when they become more open marine again. A similar pattern was found in core 6BII (Figure 2) where small numbers of foraminifera first appear at 2.5 m, increase through 1.9 and 1.5 m (older than 5664 ± 40 cal. yr BP), decline at 1.0 m (4976 ± 67 cal. yr BP), increase slightly at 2880 ± 43 cal. yr BP, but after 869 ± 39 cal. yr BP increase further in samples at 0.4 and 0.05 m.

**DISCUSSION**

Today Port Phillip Bay covers an area of 1930 km$^2$ but has a shallow water depth (maximum 24 m). In the south, it connects to the open ocean through narrow channels across the Nepean Bay Bar, but most of the bay floor is a large central muddy basin. Three new PoMC multi-beam surveys of the deeper bay floor have revealed high-sinuosity, 100 m wide river-channel-like features that have cut up to 5 m into muds at present water depths between −24 and −18 m. At shallower depths to the north, the width and degree of incision is larger and spatially related to the Yarra and Werribee Rivers. Where sub-bottom seismic lines cross these channels, there appears <0.5 m of marine mud infill. However, $^{14}$C dated shells in vibrocores indicate the bay floor sediment comprise over 4.0 m of <491 to >9274 cal. yr BP Holocene marine to non-marine mud. However, there is a gap in dates at around the 0.5 m level between >2880 cal. yr BP and <869 cal. yr BP in chronological order from bottom to top (Figure 3). Using seismic profiling between the bay floor channels and dated vibrocore, the gap is interpreted to correspond to a period of relatively recent channelling. Since ~1000 cal. yr BP, 0.5 m of shelly marine mud has been deposited over the central basin, and this post 1000 cal. yr BP mud is interpreted to cover the base of the channels. Therefore, it is possible channelling occurred sometime between 2800 and 1000 cal. yr BP and the central basin down to −22 m may have been sub-aerially exposed during the late Holocene, at a time when sea-level outside the bay stabilised to around present levels. Since >20.0 m of subsidence in the last ~1100 years is unlikely, the bay water may alternatively have become separated from the ocean over this period. This may have happened if the shallow Nepean Bay Bar channels filled with sand thus blocking oceanic exchange. The abundance of freshwater algae such as *Botryococcus* spp. in core samples between ~2974 and 7217 cal. yr BP indicates early Holocene freshwater lakes existed in the bay when global Holocene sea-level curves would indicate the bay should have been flooded (e.g. Sloss et al. 2007; Lewis et al. 2008; Figure 3). Therefore, it is possible the Nepean Bay Bar channels may have been initially blocked, delaying marine transgression into the bay by around 1000 years. Based on foraminiferal data in core, these channels eventually opened and full estuarine to marine conditions extended throughout the bay between about 7000 to 4500 cal. yr BP. Near the middle of this period (~5500 cal. yr BP) bay levels are interpreted to peak, +1.0 to +2.0 m above present ocean level, as they inundated the swamplands of the Yarra Delta (Gill 1968a, Presland 1998). However, after 4500 cal. yr BP, and in particular between ~2800 and ~1000 cal. yr BP, the Nepean Bay Bar channels may have once again blocked turning the bay into a lake falling to −22 m. The lake, if originally filled with saline marine water, may have become hypersaline associated with an upward decrease in foraminiferal abundance.

**Paradox 1: how could Port Phillip Bay have become blocked?**

The apparent intermittent history of different salinities and water levels between Port Phillip and the outside ocean would not be hydrostatically sustainable (without marine breakthrough) for any length of time if not for the thick sequence of underlying Pleistocene Bridgewater Formation aeolianite limestone underlying the Nepean Bay Bar sands (Keble 1968). Indeed, an outcrop of this unit occurs on, and probably underlies at shallow depth the whole of Mud Islands (Keble 1946). Borehole data on the Nepean Peninsula suggest the Bridgewater Formation aeolianite extends to ~67.0 m below present sea-level (Mallett & Holdgate 1985), and so this unit forms a thick underpinning stable ‘bedrock’ divide between the Nepean Bay Bar–Nepean Peninsula and the open ocean. A number of shallow vibrocores have been recorded to intersect Bridgewater Formation (Keble 1946; Figure 13; see also Supplementary data on bores over the Nepean Bay Bar). The depths to Bridgewater Formation and other later Pleistocene units beneath the Nepean Bay Bar are shown from vibrocore data on Figure 13 relative to present sea-levels. The Bridgewater Formation age is wide ranging, but the
outcropping beds on Nepean Peninsula were dated by thermoluminescence methods between 118.0 and 47.1 ka (Zhou et al. 1994).

Today, tidally scoured channels allow oceanic water exchange between the ocean and Port Phillip Bay. Some, like South Channel, exist as former river-cut-channels incised through to the upper aeolianite beds or late Pleistocene ligneous clays at times of lower Pleistocene sea-levels. Some tidal channels have been accentuated by later tidal scouring (Holdgate et al. 1981, 2001; Figure 13). Other northeast-orientated shallower channels across the Nepean Bay Bar represent more recent tidal-scour features cutting partly through Holocene shelly sands.

From PoMC vibrocore data (Figure 13; see also Supplementary data) the present-day tidal delta channel morphology is a result of incision by tidal currents into Holocene shelly sands, sometimes through to a late Pleistocene non-marine surface (Figure 13). Using the PoMC core data, the top late Pleistocene surface can be variously identified as a hard-ground, cemented limestone, ligneous silt and clay, stiff clay, sandy clay or sand, all lacking shell material. Ligneous silts below shelly sands are dated in two cores north of Sorrento and Dromana as 7854 ± 169 cal. yr BP and 9019 ± 343 cal. yr BP respectively (see Figure 1, Table 1). The average thickness in over 36 vibrocores for overlying shelly sand is about 15.0 m, but can range from 4.5 to 17.5 m below the Nepean Bay Bar (see Supplementary data on bores over the Nepean Bay Bar). In the South Channel, shelly sand thicknesses above non-marine ligneous clays are usually less than 5.0 m because of recent tidal scour and dredging activities by PoMC. In the historical past, shipping channels such as South Channel were prone to infilling by sand (particularly at its eastern end) probably because the late Pleistocene surface appears to shallow in this area to less than 14.5 m below present bay levels. Early bathymetry maps based on leadline and other soundings indicated there was less than 11 m of water at this point in the early to mid 19th century (e.g. Flinders 1814; Cox 1864).

The PoMC continues to dredge this area to remove sand, and seismic profiling along South Channel shows
easterly-directed sand-wave forms on the channel floor (Holdgate 2002). Figure 13 shows the shallow nature of the Nepean Bay Bar and possible constriction areas at the eastern end of the South Channel. Drilling data from Keble (1968) (inset on Figure 13) shows 2.0 to 10.0 m-thick unconsolidated sand that overlies aeolianite (Bridge-water Formation) across the sand banks area of the Nepean Bay Bar. Blockages in the South Channel, together with a buildup of sand above sea-level across the top of the Nepean Bay Bar (i.e. expansions to the existing Mud Islands), would potentially isolate Port Phillip Bay from the ocean.

**Paradox 2: where did the sand derive from, and in what quantities?**

At the time of the 1990s Environmental Studies on Port Phillip Bay, no estimates were available for sand input into Port Phillip (Walker & Sherwood 1997). However, since then, estimates of sand input entering Port Phillip Bay have been made to support the PoMC Channel Deepening Project (SES 2008). This report states about 200 000 m³/year of sand enters the bay from Bass Strait. This sand quantity was reached from a number of calculations (David Provis pers. comm.) that includes: 1) 82 000 m³/yr of sand has to be pumped from the Queenscliff area to maintain the status quo there. 2) 400 000 m³/yr of sand travels along the Bass Strait coast from the southwest towards Point Lonsdale, of which half goes offshore with the ebb and flood currents coming out of the bay, and is deposited in sea floor sand bars south of Port Phillip heads, or travels further east along the Nepean Peninsula coast. 3) The other 200 000 m³/yr of sand enters Port Phillip passing Point Lonsdale; 80 000 m³/yr enters Lonsdale Bay and accumulates at Queenscliff, and about 120 000 m³/yr continues across the shallows and shoals towards Popes Eye, South Channel and Symonds Channel, some of which eventually exits the bay past Point Nepean (SES 2006; David Provis pers. comm.).

In order to block the entrances to Port Phillip Bay additional sand would need to build up over the Nepean Bay Bar and also partly infill South Channel. This amount can be calculated as an area-volume sand calculation contained within the dashed lines on Figure 13 so as to raise the Nepean Bay Bar above present sea-level. The volume of sand to do this is calculated around 230 mil. m³, or around 35% more than the existing Holocene sand accumulation in the same area across the Nepean Bay Bar, if it is assumed from bore data (Figure 13) that the average depth to the top of the late Pleistocene non-marine surface is 15.0 m. A second area-volume calculation indicates an additional 45 mil. m³ of sand is required to completely block South Channel in the area indicated on Figure 13. This covers the shallowest water depth for the east end of South Channel, where bore data indicates the late-Pleistocene surface is at its shallowest point beneath South Channel. Therefore, the total quantity of sand required to block Port Phillip Bay from Bass Strait could be about 280 mil. m³, and this could accumulate within 1400 years assuming a similar rate of input (with no losses) to the present day 200 000 m³/yr sand input.

If the hypothesised sand cover across the Nepean Bay Bar were to comprise a more linear beach and dune expansion across the existing Mud Islands and present day <1.0 m deep sand shoals, then the sand quantities required to raise the Nepean Bay Bar above sea-level would be considerably less than 230 mil. m³. In support of this, there has been an approximate 40% area reduction to the total size of Mud Islands over the last 174 years (as shown inset on Figure 13) extrapolating from the first maps of the islands in 1836 to today, using the series of maps of Mud Islands over this time period (DCNR 1995). This size reduction may reflect a continuation to the dismantling of a once shallower Nepean Bay Bar since ~1000 cal. yr BP (see Figure 13 inset). This would also infer that the tidal scour into Holocene shelly sands within Coles, West, Loelia, Symonds and Pinnacle channels largely commenced only since the post 1000 cal. yr BP period, after marine waters appeared again into Port Phillip Bay. The present dredging program by PoMC seems to be required to maintain a status quo situation with regard to sand buildup in the more restricted channel areas.

**Paradox 3: why would sand buildup occur between 2800 and 1000 cal. yr BP**

The ¹⁴C dates in vibrocores 6Bii and 7D suggest an ~1800 year gap (2800 to 1000 cal. yr BP) during which the bay may have been isolated from Bass Strait (Figure 3). The palynology record in core 7D also suggests this may have been a period of climatic drying and sustained droughts e.g. Callitris, Eucalyptus and myrtaceous shrubs and dinoflagellates, steadily decline after 3967 ± 63 cal. yr BP (Figure 12). Further evidence for drying climates in the period ~3000 to 1000 cal. yr BP has been suggested in other parts of southeastern Australia (e.g. Bowler 1981; Luly 1993; Sluiter & Parsons 1995; Dodson 2001). The reason why sand would build up over this particular period remains conjectural, but possible amelioration of winter storms during drought years could allow sand to accumulate at a faster rate.

Young tectonic uplift in this area is also possible resulting in sand buildup and an overall shallowing of environments. Two lines of evidence support a relatively recent emergence of shorelines coupled to tectonic uplift in the southern Port Phillip Bay area:

1) Raised Holocene beach deposits, up to 1.0 m above high tide levels occur along the bay side coasts of Nepean Peninsula and Mount Martha (Hills 1940; Jutson 1940; Keble 1946). In some cases the beach deposits have been tilted, suggesting differential fault movements such as the major Selwyn Fault east of Rosebud.

2) Australian tidal records over the last 25 years indicate gauges at Point Lonsdale and Stony Point (Westernport) record relative sea-level fall (H-Y Park et al. 2010 in press). In contrast over 30 other tide gauges around Australia (including two at Williamstown and Geelong in Port Phillip Bay) indicate a linear trend for annual mean sea-level rise averaging about 0.8 mm/year (H-Y Park et al. in press). This evidence could be interpreted to indicate the area between Point Lonsdale and Stony Point (i.e. Nepean Peninsula) is rising at a faster rate than the ~0.3 mm/year sea-level rise seen
elsewhere. This 25 years record of sea-level rise could suggest isostatic rebound of the coastal areas (e.g. Lambeck & Chappell 2001) can be enhanced in the local area, such as between Point Lonsdale and Stony Point (Nepean Peninsula).

**Paradox 4: where was the marine breakthrough at ~ 1000 cal. yr BP?**

If the results of the PoMC Pinnace Channel multibeam survey are positioned on the bathymetric map (Figure 13), it appears the imaged bay floor channel emanates from a narrow northeast trending channel across the Nepean Bay Bar. This connects to a wider and deeper part of South Channel known as the Schnapper Deep. The continuity of these deeper channel areas could suggest any sand blockage in South Channel would occur at the narrowest point of the South Channel to the east of this position, where the late Pleistocene surface shallows up to ~14.5 m below present sea-level. Therefore, the Pinnace Channel multibeam survey (Figure 6) has imaged an erosion channel that may have been created when the sea broke through the Nepean Bay Bar and headed north into Port Phillip Bay. The $^{14}$C dates and biostratigraphy results in vibrocores 6BiI and 7D suggest this might have occurred shortly before 880 $^{+49}_{-48}$ cal. yr BP when bay water level may have been 22 m lower than present-day sea-level. Deep scouring during the breakthrough would explain how this erosional feature formed. Cross-sectional profile symmetry to the Pinnace Channel multibeam survey contrasts with fluvial-derived asymmetric profiles of channels in the other multibeam surveys (where the deeper cut is on the outer bends). If the area of bay floor below ~22 m represents the final Port Phillip lake area prior to marine flooding, then the likely scenario would be for the Pinnace Channel breakthrough point to scour a path across the Nepean Bay Bar towards this Port Phillip lake area (Figure 11).

**Paradox 5: what happens to Port Phillip if the entrance blocks?**

Fluctuating bay-levels will change Port Phillip's water balance and salinity. If the Nepean Bay Bar extends above sea-level and the South Channel blocks then the bay is isolated from oceanic sea-levels. If this blockage occurs during an extensive period of drought, Port Phillip would become an evaporative lake since there is a high evaporation rate over the whole bay area (1980 figures quote ~2.3 km$^3$/yr; Walker 1997; Walker & Sherwood 1997) compared with a comparatively low river/rain input (1980 figures quote 2.7 km$^3$/yr; Walker 1997; Walker & Sherwood 1997). A 15% reduction in freshwater input would see evaporation and input equilibrate. Further reduction in freshwater input could see a net loss of bay water levels, and the Yarra and Werribee rivers would meander across a progressively exposed muddy lake floor. Water inputs in 2008 were 25% lower than in 1980 as a result of 10 years of drought.

An evaporating lake in Port Phillip would result in the following:

(1) As the bay level fell, the Yarra and Werribee Rivers followed the retreating lake.

(2) Newly exposed bay floor became a non-depositional surface because all fluvial sediments were trapped within the river channels and lake.

(3) The lake receded to the south further from river sources.

(4) Sinuosity of the rivers increased because their gradient lessened.

(5) The northern part of the bay, including Hobsons Bay south to around the Spoil Ground Dumps, became exposed sub-aerially for longer periods, and the rivers cut wider channels in this area (Figure 14A, 14B).

(6) These channels were similar to the bay floor configuration out to about ~20 m as shown in Figures 11 and 14A.

(7) The high sinuosity 100 m wide channels in the middle of the bay indicate a relatively short-duration final evaporating lake phase that immediately preceded marine break-through near Pinnace Channel at around 1000 cal. yr BP (Figure 14B).

(8) The disappearance of bay floor depressions on the more southerly seismic lines indicates the final lake phase formed in this area at ~22 m (Figure 14B) and became the main repository for river sediment during the hiatus period.

The Port Phillip lake waters should logically become increasingly saline as they lowered, but this would also depend on their salinity prior to marine blockage. Evidence for freshwater algae begins at 9274 $^{+100}$ cal. yr BP but the appearance of *Tuberculodinium vancaam-poe* (a subtropical species) and open marine planktonic foraminifera (e.g. *Globigerina* spp.) after ~7500 cal. yr BP indicates normal marine salinities were present up until the bay blocked. Evidence for hypersalinity in cores such as layers of gypsum has not been detected, possibly due to subsequent dissolution by the current marine bay waters. However, the sparse foraminifera in the 7D core sample at 0.65 m dated at 3987 $^{+63}$ cal. yr BP may indicate a trend towards hypersalinity.

Any still-stands in lake retreat could produce lake shoreline features such as bay floor steps or buried shorelines. A continuous belt of coarse sand bars on the eastern coast of Port Phillip Bay occurs offshore from Brighton to Mornington at between 7 and 11 m water depths. The zone ranges between 500 m and 2 km offshore with a width between 1.0 and 5.0 km (Buckley & Clark 1987; Holdgate et al. 2001). The sand bars comprise very coarse sand (1.0 to 2.0 mm) with a local Tertiary provenance, contain minor shell material, occur in beds up to 4.0 m thick, and overlie shelly muddy sand or stiff clay. The sandbars occur below normal wave base. They remain undated. By their coarse size it has been suggested they were formed as lag sand bars deposited along a shoreline during rising Holocene sea-levels (Buckley & Clark 1987; Holdgate et al. 2001). However, two $^{14}$C shell dates on shelly mudds 0.5 km west of the sand bars gave 6863 $^{+203}$ cal. yr BP for ~14.3 m off Sandringham (Bowler 1986) and 6018 $^{+162}$ cal. yr BP for ~17 m water depth (Holdgate et al. 1981, 2001). Both dates indicate these offshore sand bars are likely to be younger than ~6000 cal. yr BP. Because Port Phillip Bay water levels probably
equalised with modern ocean levels by \( \sim 7500 \) cal. yr BP then a shoreline origin for sandbars at \( -7 \) to \( -11 \) m water levels is untenable. Alternatively the sandbars could be much younger than \( 6000 \) cal. yr BP, considering their stratigraphic position, and could represent beach ridges formed along a lake shoreline during a period of falling lake levels post-2800 cal. yr BP, now drowned in-place after bay levels rose post-1000 cal. yr BP.

**Paradox 6: effects of a drying bay and a flooding bay on Aboriginal occupation?**

The several Aboriginal stories that exist on how Port Phillip Bay formed (see Anecdotal Evidence from Aboriginal Oral Traditions at beginning of paper) (Presland 1998; William Hull's testimony to the parliamentary committee 9 November 1858) refer to a dryer bay with...
little water, followed by a flood event that filled the bay to its present level. Convention has assumed this oral tradition refer to the last glacial bay approximately 10,000 cal. yr BP, i.e., the most recent time the bay could logically be dry based on known sea-levels. This date, therefore, assumes considerable longevity to the oral tradition. However, if the bay was dry as recently as ~1000 cal. yr BP, then the oral tradition of a dry bay followed by a flood would more likely be remembered.

Further justification for oral tradition of a (comparatively) recent drier bay comes from the defining of aborigine clan boundaries around the bay. These boundaries, recorded by Thomas (one of the Aborigine Protectorates), came about from discussions with local Aborigines during early European settlement of the Melbourne area in the 1830s (Presland 1998). The map of clan boundaries shown on Figure 14B indicates the Bun Wurrung clan of Mornington–Westernport also saw as theirs a narrow strip around the shoreline of the bay as far west as the Werribee River mouth (Clark 1990). This crescent-shaped boundary extension is more easily explained if the tribal boundaries were based on a once near-dry bay. Hence, the Bun Wurrung would consider the dry bay floor as part of their tribal land, and therefore could be contiguous across the bay to the Werribee River mouth. The location of a final ~22 m lake and Werribee River (Figure 14B) would also explain why the Bun Wurrung might claim the bay floor as far south as Lake Phillip, and why the Wada Wurrung clan of the Geelong area would have claimed the southwestern side of Lake Phillip as part of their Bellarine-Geelong area. This idea has been further explored by Fels (in press).

If bay levels fall, aborigine occupation sites around the present shoreline would be abandoned in favour of sites nearer the lake shoreline. Therefore, present shoreline occupation sites should also show a gap in their dates between 2800 and 1000 cal. yr BP. Unfortunately, no detailed dating of midden sites is available around the dates between 2800 and 1000 cal. yr BP. Unfortunately, no detailed dating of midden sites is available around the dates between 2800 and 1000 cal. yr BP. Unfortunately, no detailed dating of midden sites is available around the dates between 2800 and 1000 cal. yr BP. Unfortunately, no detailed dating of midden sites is available around the dates between 2800 and 1000 cal. yr BP.; then the oral tradition of a dry bay followed by a flood would more likely be remembered.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the Port of Melbourne Authority Channel Deepening Branch in particular Paul Downie and Liz Condills for access and use of their multibeam and seismic surveys in Port Phillip Bay. We thank David Provis of Cardno-Coastal Ocean Water & Environment for advice on sand movements into Port Phillip Bay. We also acknowledge the Geological Survey Victoria (GSV) for supplying digital copies of the Port Phillip seismic surveys and access to sample cores at the core library at Werribee. The bay floor sediment-distribution map was kindly provided by R. W. Buckley. The 14C dated shells were kindly identified by Sue Boyd at Museum of Victoria. We also thank Andrew Heap and a second anonymous reviewer for their helpful comments and suggestions.

REFERENCES

Ahmad R. 1996. Late Holocene major Australian arid period revealed by direct sedimentological evidence from lakes in the Coorong region of South Australia. Geology 24, 619–622.


