EVIDENCE FOR ACTIVE TECTONICS ALONG THE AUSTRALIAN PASSIVE MARGIN: QUATERNARY MARINE TERRACES OF WARATAH BAY, VICTORIA

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INTRODUCTION

Located within the interior of the Australian-Indian Plate, the continental margin of Australia is generally described as a classic passive margin. However, along the southeastern coast, historical seismicity and a variety of anomalous geologic and geomorphic features indicate active crustal deformation (Abele, 1988; Jenkins, 1988; Ollier and Pain, 1994). At Waratah Bay, Victoria (Fig.1), a flight of marine terraces wraps around the rocky headland of Cape Liptrap and extends northeastward toward the Yanakie isthmus inland of Wilson's Promontory (see Fig. 1, Gardner, this volume). The purpose of this study is to map these terrace surfaces, establish age constraints, and identify any evidence of deformation. The results of this investigation provide new insights into the geomorphic and tectonic history of the southeastern Australian passive margin.

METHODS

The nature and extent of the Waratah Bay terrace sequence were determined through initial field reconnaissance and examination of aerial photographs. Field mapping and GPS surveying was then conducted along a series of transects across the terraces (Fig. 1) and the positions of terrace treads, risers, outer, and inner edges were recorded. The spatial coordinates of these features (location and elevation) were surveyed along each transect using a Trimble XRS-Pro GPS receiver and TSC1 data logger with real time differential correction yielding vertical accuracies of <1 m. The GPS elevation data from each transect were plotted onto an aerial photo of the Waratah Bay area (#3965-247, 1:26,000 scale). Guided by these elevation data and the stereoscopic analysis of aerial photos, the terrace treads were then mapped onto the air photo base (Fig. 1).

Three representative transects (WB 1, 7, and 10) were projected onto profile lines oriented perpendicular to the northeast trend of Cape Liptrap (Fig. 1). Elevation data from these transects were projected onto lines of azimuth 325° using the formula $[\cos(\theta)(\textit{northing})] + [\sin(\theta)(\textit{easting})]$, where θ is the projection

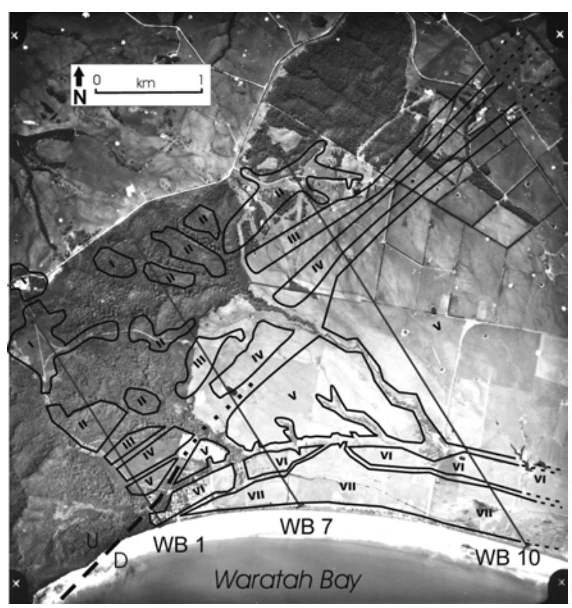

Figure 1: Marine terrace treads of Waratah Bay mapped on an aerial photo base. Gray lines mark locations of projected terrace profiles WB 1, 7, and 10 (Fig. 2).

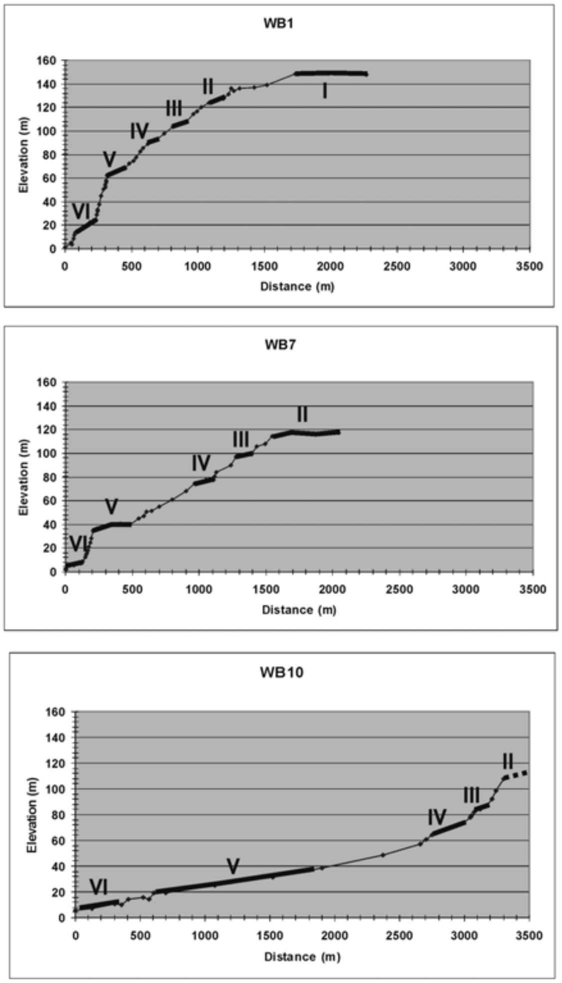

Figure 2: Projected terrace profiles WB 1, 7, and 10. See Fig. 1 for location.

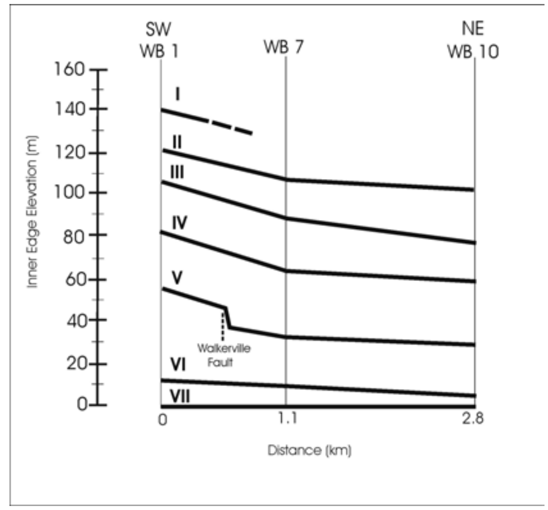

Figure 3: Terrace inner edge elevations plotted in a line perpendicular to profiles WB 1, 7 and 10.

azimuth and *northing* and *easting* are GPS coordinates. Topographic profiles of the terrace sequence were then plotted along these three projection lines (Fig. 2).

Terrace deposits were examined and described in the field at several locations. These observations provided a guide for estimating the thickness of terrace deposits throughout the study area. Inner edge elevations for the terraces were estimated using back edge elevations from the GPS profiles and assuming a 10 m ($\pm$5 m) thick terrace deposit.

Inner edge elevations along each transect were plotted along a SW-NE trending line perpendicular to the projected transects (Fig. 3). This plot reveals elevation changes across the field area which may indicate deformation of terrace surfaces (tilt or offset).

Terrace ages and uplift rates (Table 1) were estimated by correlation with late Cenozoic sea level high stands (Bull, 1985; Lajoie, 1986; Anderson et al., 1999). Inner edge elevations were plotted in conjunction with paleo-sea level curves (Fig. 4) for the late Tertiary and Quaternary (Chapell and Shackleton, 1986; Darter, 2000). Assuming a constant uplift rate, terrace inner edges were linked to sea level high stands using a straight line where *slope = uplift rate*. Multiple scenarios were examined in order to determine a best-fit correlation.

RESULTS

Seven relatively continuous marine terraces (I-VII) were identified in the study area (Fig. 1). Tread elevations range from near sea level for Terrace VII to >140m for Terrace I (Fig. 2). While terraces I-V occur as typical wavecut surfaces mantled by terrace deposits, terrace VI consists of a series of lobate depositional fans centered around the mouths of streams incised into the upper terraces.

The coastline of the study area (Fig. 1) curves toward the east from the northeast trend of high topography along Cape Liptrap to an east-west trend along low-relief topography of Waratah Bay. Risers to the lower terraces (V-VI) are sub-parallel to the modern shoreline, whereas those of the upper terraces (I-IV) extend inland along the linear northeast trend of the Cape Liptrap Peninsula. The width of Terrace V, therefore, increases significantly toward the east and its tread corresponds with the lowland surface of the

Yanakie isthmus east of the study area (see Fig. 1, Gardner, this volume).

Terrace deposits consist of well sorted, fine-grained silicic beach and dune sands interbedded locally with silts and clays. Terraces I-IV are mantled with dune deposits that occur in distinct linear ridges. Based on observations in both this and adjacent study areas, deposit thicknesses range from approximately 5 to 15 m. Soils formed on Terrace V approach 5 m in thickness and resemble spodosols, with a distinct light gray leached horizon.

The projected terrace profiles (WB 1, 7, and 10) show a significant decrease in tread elevation, toward the east (Figs. 2 and 3) indicating a systematic tilt away from Cape Liptrap. In addition, terrace V shows an anomalously high elevation along transect WB 1 (Fig. 3) when compared with WB 7 and 10, indicating localized deformation in the southwest portion of the field area.

A best fit correlation between terraces and the paleo-sea level curve (Fig.4) resulted in estimated ages ranging from 80 ka (terrace VI) to 490 ka (terrace I). In this scenario, the lowest and most prominent terraces (V-VI) are correlated with the oxygen isotope stage 5-7 high stands, and higher terraces to stages 9-13. Based on these estimated ages, uplift rates range between 0.1 and 0.4 m/ka within the study area (Table 1).

Table 1: Estimated ages and uplift rates of terraces along WB 1, 7 and 10.

Terrace	Inner Edge Elv. (± 5 m)	Estimated Age (ka)	Uplift rate (m/ka)
Profile WB 1			
I	140	480-490	0.28-0.30
II	121	405-415	0.28-0.31
III	108	320-330	0.31-0.35
IV	82	300-310	0.25-0.29
V	58	193-195	0.27-0.33
VI	13	118-125	0.06-0.14
Profile WB 7			
II	108	405-415	0.25-0.28
III	90	320-330	0.26-0.30
IV	69	300-310	0.21-0.25
V	30	193-195	0.13-0.18
VI	8	118-125	0.02-0.11
Profile WB 10			
II	102	405-415	0.23-0.26
III	78	320-330	0.22-0.26
IV	62	300-310	0.18-0.22
V	28	193-195	0.12-0.17
VI	4	118-125	0.0-0.08

DISCUSSION

The well-developed flight of marine terraces at Waratah Bay provides evidence for late Cenozoic uplift along the Cape Liptrap peninsula. The northeastward tilt of terrace treads indicates maximum uplift centered along the Cape Liptrap axis and a decrease in uplift rate toward the Yanakie lowlands along Corner Inlet.

The tread of terrace VI, when projected eastward to the Yanakie isthmus, can be correlated with a 2 m elevation terrace at Corner Inlet dated at 122 ± 13 ka (T. Gardner, pers. com., 2003). This age suggests that terrace VI formed during the maximum late Pleistocene sea level highstand (OIS 5e). This age is consistent with ages estimated in this study from sea level curve correlations (Fig. 4).

While all terrace treads in the study area show a systematic tilt toward the northeast (Fig. 3), terrace V exhibits an unusual break in slope between profiles WB-1 and 7. This location coincides with the mapped trace of the Walkerville fault (see Fig. 1, Gardner, this volume). Where the fault extends onshore (Fig. 1), a bedrock intertidal platform and a narrow 1-2 m elevation wavecut bench occur northwest of the fault trace. The location of these features coincides with the high topographic relief of Cape Liptrap, consistent with greater uplift northwest of the fault.

Based on terrace inner edge elevations and estimated ages (Table 1), uplift rates at Waratah Bay range from 0.2 to 0.4 m/ka northwest of the Walkerville fault, and from 0.1 to 0.2 m/ka southeast of the fault.

In general, the marine terraces at Waratah Bay may be the product of uplift and tilting resulting from late Cenozoic slip on the northeast-trending Walkerville fault. Active crustal deformation along this segment of the southeastern Australian passive margin may result from denudation and isostatic flexure,

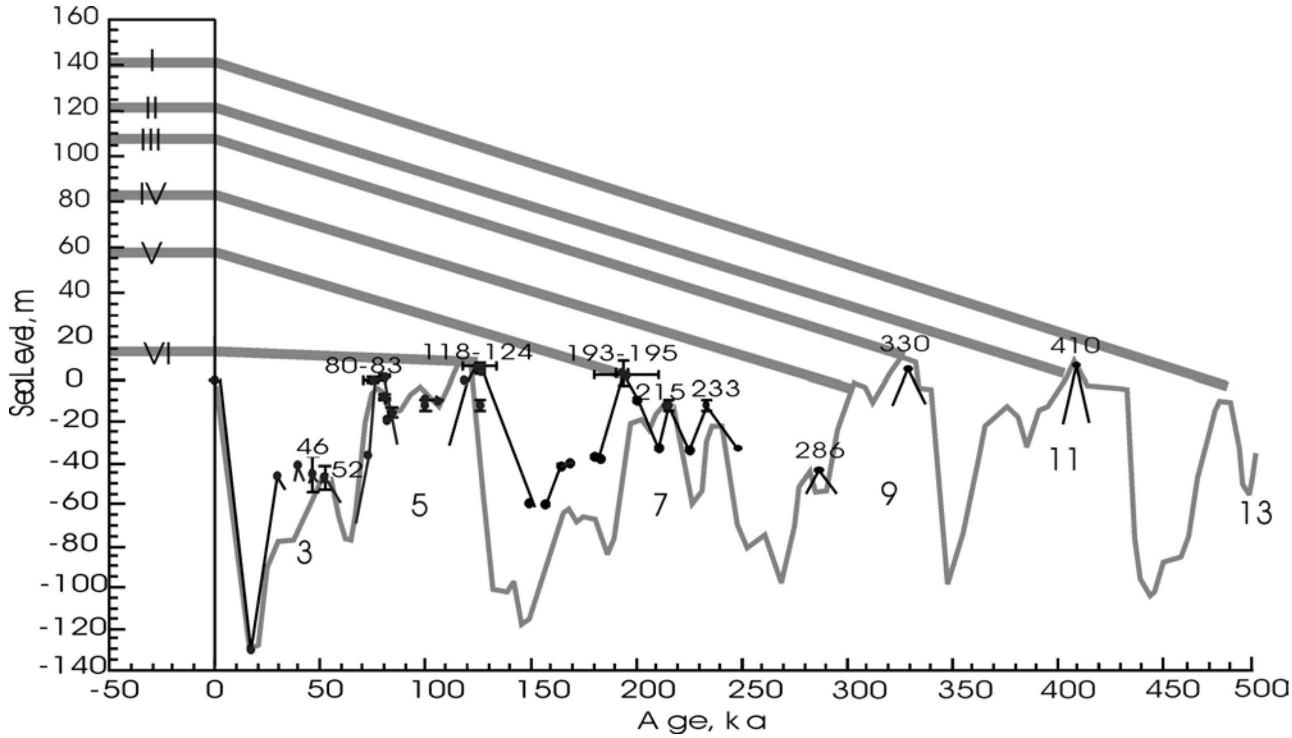

Figure 4: Sea level correlation diagram for terraces along profile WB1. Terrace inner edge elevations (at left) are linked to sea level high stands with heavy gray lines that represent uplift pathways (slope = uplift rate). Gray sea level curve based on marine oxygen isotope records (Imbrie et al., 1984; Chappell and Shackleton, 1986). Black dots indicate measured sea level data compiled from various sources by Darter (2000).

variations in the crust/mantle thermal structure, and/or far-field intraplate stress.

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