Late Neogene and Quaternary Vertical Motions in the Otway Coast, Southeast Australia (I): Development and Geochronology of Quaternary Marine Terraces

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호주 남동부 Otway 해안의 후기 신제3기 및 제4기 융기 운동(I): 제4기 해안단구 발달 및 지층서

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Abstract: This study investigates a neotectonic context of the past 5 Ma for the Otway Ranges along the southern Victoria coast, SE Australia by evaluating the distribution and development of marine terraces along the mountainous coastal area. Uplift rate derived from low terrace deposits using OSL dating method is determined to evaluate the extent to which mild intraplate tectonism has the capability to influence the geomorphic evolution of continental interiors. This study also investigates the stratigraphic relationship between Quaternary marine terraces and Pliocene strandlines, which suggests a change of tectonic activity in the Late Neogene. The intensified tectonic response is well addressed in terms of an increase of the Australian intraplate stress level due to the change of relative motion and increased forces in the boundary between the Australian and Pacific plate.

Keywords: Quaternary marine terrace, OSL dating, Pliocene shoreline, tectonic activity, SE Australia

요약: 본 연구는 호주 남동부 Victoria 남부 해안을 따라 발달하고 있는 Otway 산맥 일대에서 지난 5 Ma 동안의 신기 지체구조 운동의 성격을 해안 산악 지역을 따라 분포하고 있는 해안단구의 발달상을 통해 밝히고 있다. OSL 연대 측정 으로부터 얻은 저위 해안단구면의 융기율은 판 내부 구조운동의 영향이 현생 지형 발달에 미치는 결과를 명확히 보여주고 있다. 또한 본 연구는 제4기 해안단구와 플라이오세 고해수준 기록 간의 층서적 관계를 통해 후기 신제3기 이후에 나타나는 지구조 운동의 변화적 속성을 밝히고 있다. 이와 같은 후기 신제3기 이후 가속화된 지구조 운동 반응은 호주-태평양판의 이동성의 변화와 이에 따른 경계 응력의 증가가 대륙 내부 응력 수준에도 영향을 미친 결과로 이해된다.

주요어: 제4기 해안단구, OSL 연대측정, Pliocene 고해수준, 지구조 활동성, 호주 남동부

Introduction

One of the most tectonically active regions in Southeast Australia is the Otway Ranges in the southern Victoria. This is reflected by its geomorphic features such as its rugged, incised coastal mountains. Significant indications of the late Neogene tectonics in

the region are well illustrated by a preserved Pliocene strandplain (Hanson Plain Sand) deposited broadly across the western Victoria up into the northwestern flanks of the ranges (Fig. 1). These Pliocene ENE-trending strata are slightly folded about an axis parallel to the ranges, and are displaced by faults in many localities in the region bordering the ranges (Shoemaker and Uhlherr, 1999; Sandiford, 2003a). In places these strandlines are elevated as high as 240 m above sea level with individual strandlines having as much as 140 m of relief.

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Fig. 1. Study area with 50 m contours showing the Otway Ranges and the southern coast. The centre of the Newer Volcanism (Late Pliocene to Quaternary) is located in the north farther. The uplift increases away from the centre.

The ongoing deformation in the Otway Ranges correlates with mild tectonic activity across a much broader region in Southern Australia. For example, in South Australia, the Flinders Range is bounded by a set of scarps associated with active bounding faults with cumulative late Neogene displaces in excess of 100 meters (Sandiford, 2003b; Quigley et al., 2006). Another more subtle evidence for young tectonism occurs across the extensive Miocene-Pliocene Nullarbor Plain along the central southern margin of Australia. The elevations of these Miocene shorelines along the northern inland bordered the plain drop systematically eastwards from 200 to 30 m above sea level, implying a differential vertical motion in excess of 150 m over a ~1000 kms (James et al., 2006). The various modes and possible mechanisms for the Late Cenozoic deformations in South and Southeast Australia have been discussed by Celerier et al. (2005), Demidjuk et al. (2007) and Quigley et al. (2006), but remain enigmatic.

It is clear from these observations that elevation of Neogene marine shorelines and associated geomorphic features are crucial to evaluating the tectonic activity in Southern Australia. The preservation of marine terraces above present sea level signifies both the sea level stand at the formation time and subsequent tectonic uplift. With increasing information on past sea levels, marine terraces have increasingly used to evaluate rates of tectonic controls in intraplate settings (Murray-Wallace, 2002; Claessens et al., 2009). In this study geographic distributions and vertical elevations of the marine terraces in the southern coast of the Otway Ranges, SE Australia have been mapped, and quantitative uplift rates have been established using Optically Stimulated Luminescence (OSL) dating method from overlying terrace deposits. The relationship between tectonic uplift and geophysical analysis of gravity anomalies and the in-situ stress fields will be documented in the following paper in order to understand the nature and possible mechanism for the

Table 1. Distribution of Otway marine terraces and the chronology

Terrace number	Area									Inner edge (m apsl)	Formation age	
	Prince-town	Glenaire R	Apollo Bay	Skenes	Kennett R	Lorne	Airleys	Anglesea	Torquay		Estimated age	MIS stage
T-1	2-4 m apsl	2-4	2-6	2-4	2-5	2-5	5-8	5-7	4-8	4		MIS 5e
T-2	10-22	10-19	11-21	10-22	11-22	12-23	12-28	11-26	14-28	12	217±31 ka BP	MIS 7a
T-3	40-60	38-55	40-60	40-53	40-65	40-60	45-65	37-60	45-62	60		
T-4	70-90	70-90	70-90	75-90		70-90	80-90	80-90	70-90	90		
T-5	110-135	110-130	100-140	110-135		105-120	110-130	100-132		130	Likely Pliocene-Quaternary	
T-6		160-190	160-180	160-180		160-180	150-180	140-170				
T-7		190-220	200-220	190-210		180-220	190-220	190-220				

neotectonic movements associated with the Otway Ranges in Southeast Australia.

Coastal Geomorphology and Preservation of Marine Terraces

The investigated areas in this study include the southern coast of the Otway Ranges (the Otway coast) extending from Torquay in the east to Port Campbell in the west over a distance of ~160 km (Fig. 1). This coast displays extensively steepened sea bluffs of Tertiary marine and calcareous fluvio-deltaic successions. Yet, there has been little recognition of coastal terrace sequences in this region. Only one exception is the study of Gippsland region near Cape Liptrap, SE Australia by Gardner et al. (2008).

Survival of marine terraces after emergence is largely controlled by subsequent erosional and aeolian processes (Caputo, 2007; Claessens et al., 2009). Much of the southern Australian coastline experiences relatively high wave energy conditions with >20 % of waves over 2.5 m high for at least two quarters of the year (Davies, 1986). In addition, extensive eolianite successions have developed along the southern Australian coasts throughout the late Quaternary associated with regional aridity where evaporation far exceeds precipitation (Brooke, 2001). Both features tend to limit preservation of marine terraces to particularly favourable sites. In addition, some major high sea stands during the Quaternary can be only recorded as a flight of terraces, especially in relatively

slow uplifting regions. Coastal processes associated with younger high sea stand largely tend to obliterate or completely destroy evidence of older terraces whose relative altitude is lower than 10 m (Caputo, 2007). This may account for poor preservation of the early Quaternary marine terraces and a disconformable relationship between the Pliocene and Quaternary marine deposits in southern Victoria (Wallace et al., 2005).

Distribution of Marine Terraces

Seven distinct flights of terraces elevated up to 220 m above present sea level (apsl) have been mapped along the Otway coast, and are designated T-1 to T-7 from the youngest to oldest (Table 1, Fig. 2, Fig. 3). Positioning and altitude measurement were estimated using 1:25,000 scaled maps and calibrated GPS data. Vertical terrace profiles with OSL sample locations are illustrated in Fig. 4.

T-1

The T-1 terrace is the lowest level, ranging in elevation from 2 to 8 m apsl. The terraces are largely preserved in specific sites. In areas dominated by longshore transport of coastal sediments such as Torquay, Lorne and Apollo Bay, the T-1 is preserved as a small strandplain deposited in the inner bay. In headlands, this terrace is typically expressed as a shore platform most clearly observed in Sugarloaf and Skenes Creek. T-1 terrace is also observed as a

Fig. 2. Maps of marine terrace distribution along the Otway coasts. (a) The eastern section from Torquay to Lorne, (b) The central section from Kennett River to Apollo Bay, and (c) The western section from Glenaire to Princetown.

thalassostatic terrace along Anglesea River in Anglesea, Painkalac and Distillery creeks in Aireys Inlet, Aire River in Glenaire, Johanna River in Johanna, and in Gellibrand River in Princetown. The

areas are characterised as a large estuary or a back-barrier lagoon protected from sea-wave erosion by barrier spits and embayment.

Fig. 3. Field photographs from Otway marine terraces in Anglesea (a), Skenes Creek (b), Apollo Bay (c), and Princetown (d).

T-2

T-2 terraces are the most extensive and ubiquitous that the elevations vary from 10 to 28 m apsl. This terrace is best exposed in Torquay and Apollo Bay with a length of several hundred meters where planar surfaces with very low relief are exceptionally preserved. Exposed outcrops have been found in Kennett River, Apollo Bay and Gellibrand Lower that are mainly composed of sands, granules and well-rounded pebbles with horizontal or slightly seaward beddings. Granules and pebbles are well sorted, and seaward imbrications are generally prominent. In particular, the sedimentary units in Kennett River and Apollo Bay are deposited on the planar surface strata with centimeter-scale relief, suggesting that the planar surfaces were formed by sea wave actions and subsequent weathering processes. In places where a bedrock surface is exposed, the uppermost of bedrock strata is, in

general, deeply weathered and incised by streams. The elevations in the easternmost section of the investigated areas including Torquay, Anglesea and Aireys Inlet are a few meters higher than those to the west (Table 1). As this difference in elevation is observed on both the T-1 and the T-2 terrace, but not recognised above T-3 terraces, it is likely that the higher elevation in T-1 and T-2 in the easternmost areas reflects seaward depositional thickening, implying Quaternary high sea stands have likely contributed to thicker sediments aprons on terraces during their terrace formation periods. The eastern section is a locality characterised by relative depocenter of Tertiary marine sediments of clayey quartz sand, sandy clay and quartz gravel.

T-3

T-3 terraces occur as relatively small remnants

Fig. 4. Vertical terrace profiles with OSL sample locations.

gently sloping seaward at 40–65 m apsl. The T-3 terrace and higher terraces (T-4 to T-7) are commonly dissected and sloped elongated towards the T-1- and T-2 terraces: a feature that can be contributed to time for stream incisions. Extensive colluvial and aeolian deposits often cover the T-3 terraces for example, in Aireys Inlet and Apollo Bay. In Torquay, T-3 terraces are covered by thick (~2 m), fine to coarse-grained, quartzite sands with granules and pebbles. This terrace is best preserved in the southern flank of Mt. Ingoldsby along the coast between Anglesea and Aireys Inlet, but the surface strata are not well exposed, and are often colluviated. The surficial sediments consist of well-rounded pebbles and cobbles with fine sand and clay.

T-4

The T-4 terrace is the most extensive terrace set ranging in elevation from 70 to 90 m apsl. The terrace tread is exceptionally flat, and probably has been deflated by aeolian activity. The best outcrop has

found in Airley Inlet (38°27'00"S, 144°06'00"E), which consists of quartzite pebbles and granules with the matrix of fine to coarse sand. Although quartzite pebbles and granules are likely to be derived from local basements, relatively fresh sands and granules are distinct from basement geology. The exposed bedrock surfaces have been extensively mechanically weathered.

T-5, T-6 and T-7

Terraces from the T-5 to the T-7 occur as well defined, planar treads separated by distinct risers, although no marine deposits have been found. The T-5 terrace is elevated at 100–130 m apsl, and the T-6 and the T-7 terrace range at 140–180 m and at 190–220 m apsl, respectively. The T-5 to T-7 terraces are expressed as the most typical step-like morphology with sub-planar surfaces, and the altitudes are uniform over the entire investigated areas. In addition, geomorphic indications such as uniform altitudes, elongated seaward sloping aspects and occurrence

Fig. 5. Radial plots of samples: (a) APO01, (b) APO02, (c) KEN01, and (d) RGE01 showing the distribution of aliquots with their precisions. Optical ages were derived from the weighted mean D_e using the central age model of Galbraith et al. (1999). Statistically concordant aliquots at the 2σ confidence level are within ± 2 units on the y-axis (shades).

parallel to coastlines suggest their marine origin. These higher terraces are often expressed as flat-crested ridges or concordant summits at the foot of coastal mountains in Anglesea, Lorne, Gellibrand Lower and Princetown.

OSL Chronology

Samples were collected by driving 50 mm diameter PVC tubes into vertical sections of terrace sediments. The outer few centimeters were discarded in laboratory as far as paleodose evaluation is concerned. The 90–125 mm quartz fraction was extracted for dating using the procedures of Galbraith et al. (1999).

Equivalent dose estimation

A Single-Aliquot Regenerative-dose (SAR) protocol was used to determine equivalent doses (D_e) (Murray and Roberts, 1998; Murray and Wintle, 2000). Small aliquots of ~5–10 grains were preheated at 220°C for 10 s and optically stimulated for 100 s at 125°C by either green-plus-blue (420–550 nm) light from a tungsten-halogen lamp (automated Risø TL-DA-12 apparatus) (Bøtter-Jensen and Duller, 1992) or blue (470 nm) light from a light-emitting diode array (automated Risø TL-DA-15 apparatus) (Markey et al., 1997; Bøtter-Jensen et al., 2000). Ultraviolet luminescence was detected using photomultiplier tubes with either a 7.5 mm Hoya U-340 filter (Risø TL-DA-

Table 2. Dose rate data, D_e estimates and optical ages from T-2 terrace deposits

Sample name	Depth (m)	Water ^a (%)	Radionuclide concentrations ^b			α radiation ^c (Gy Ka ⁻¹)	β radiation ^d (Gy Ka ⁻¹)	γ radiation ^e (Gy Ka ⁻¹)	Cosmicray radiation ^f (Gy Ka ⁻¹)	Total dose rate (Gy Ka ⁻¹)	Equivalent dose ^g	Optical age (ka)
			K (%)	Th (ppm)	U (ppm)							
APO01	2.0	10±3	0.49±0.02	7.70±0.24	1.28±0.10	0.03±0.01	0.61±0.03	0.56±0.11	0.15±0.02	1.35±0.15	>179	>133*
APO02	0.7	15±5	0.14±0.01	6.06±0.19	1.51±0.09	0.03±0.01	0.37±0.03	0.42±0.08	0.19±0.02	1.01±0.11	162±10	160±20
KEN01	2.5	15±5	0.92±0.04	5.82±0.19	1.81±0.12	0.03±0.01	0.85±0.06	0.60±0.12	0.14±0.01	1.62±0.18	139±9	86±11
RGE01	10.0	10±3	0.18±0.01	5.01±0.17	1.33±0.13	0.03±0.01	0.37±0.02	0.39±0.08	0.05±0.01	0.84±0.10	181±16	217±31

^aestimated time-averaged moisture content, base on measured field water value (% dry weight)^bobtained by INAA (Becquerel Laboratories, Mississauga, ON, Canada)^cassumed internal alpha dose rate^dderived from INAA radionuclide concentration measurements using the conversion factors of Adameic and Aitken (1998), corrected for attenuation by water and beta attenuation^ederived from INAA radionuclide concentration measurements using the conversion factors of Adameic and Aitken (1998), corrected for attenuation by water^fcalculated using the equation of Prescott and Hutton (1994), based on sediment density, time-averaged depth and site latitude, longitude and altitude^gcentral age model (Galbraith et al. 1999) (except for APO01 and STR01, where the minimum age model was used), including a ± 2% systematic uncertainty associated with calibration of the laboratory beta-source

*saturated: Equivalent dose calculated using minimum age model (Galbraith et al. 1999)

15) or two 3 mm Hoya U-340 filters (Risø TL-DA-12). Samples were then given applied doses using calibrated $^{90}\text{Sr}/^{90}\text{Y}$ beta-sources and re-stimulated to record their regenerative OSL signals. OSL sensitivity changes in the quartz crystals between the natural and regenerative cycles were monitored after each optical stimulation using test-doses of 1-2 Gy following a 160°C cut-heat. Preheat tests were carried out on twelve 100 grain aliquots of each sample by holding three aliquots at one of four preheat temperatures (160, 200, 240, 280 °C) for 10 s. The resultant flat plateau indicated no significant thermal transfer in the samples. They also displayed little appreciable radiative recombination in recuperation tests. These experiments, including recycling tests using duplicate regenerations of known dose, confirmed the reproducibility of the laboratory-induced luminescence signals. Output from the Risø apparatuses was analysed using TL-HR23 Data Reader version 8.0 and Analyst version 2.12 software. OSL signals were measured for 100 s (250 × 0.4 s channels) and integrated over the first 4.8 s of illumination with the final 20 s converted to the equivalent number of channels over 4.8 s and subtracted as background. The OSL data were corrected for any sensitivity changes and dose-response curves constructed

using two to six regenerative dose points, depending on the magnitude of the D_e of the samples. D_e was obtained from the intercept of the regenerated dose-response curve with the natural luminescence intensity. Weighted mean D_e and their uncertainties were calculated using the central age model of Galbraith et al. (1999).

Dose rate measurements

K, Th, and U concentrations were measured using Instrumental Neutron Activation Analysis (INAA) by Becquerel Laboratories, Mississauga, Ontario, Canada. Beta and gamma dose rates were derived from INAA radionuclide concentration measurements using the conversion factors of Adameic and Aitken (1998). Internal alpha dose rates were assumed to be 0.03 ± 0.01 Gy ka⁻¹ (Bowler et al., 2003). Cosmic-ray dose rates were determined from established equations (Prescott and Hutton, 1994) based on sediment density, time-averaged depth and site latitude, longitude and altitude. Moisture contents of the sediments were considered representative of long-time averages based on measured field water value (% dry weight), and used to correct attenuation of b and g rays by water (Aitken, 1998). The dose rates, equivalent dose

Fig. 6. Cross-sections of T-2 terraces in Glenaire (a) and Apollo Bay (b) showing sampling points and estimated optical ages.

estimates and the obtained optical ages are presented in Table 2. These are the relative standard deviations of the D_e distributions after accounting for measurement uncertainties associated with each aliquot. The ages represent sensible internal consistency with relative stratigraphic succession. The single aliquot D_e distributions are displayed in radial plots (Fig. 5). These show the distribution of aliquots with their precisions. Statistically concordant aliquots at the 2 σ confidence level are within ± 2 units on the y-axis (shades).

Results

Four samples were taken from deposits overlying bedrock surfaces of T-2 terraces. RGE01 was collected in Gellibrand Lower (38°43'37"S, 143°15'59"E) (Fig. 6a). Although the sampling site is a few kilometers away from sea, thalassostatic terraces are occurred

continuously from Princetown to Gellibrand Lower along the Gellibrand River. Terraces along the river are genetically coeval with marine terraces in the coastlines corresponding to eustatic sea level changes during the late Quaternary (Fairbridge, 2005). The current large estuary is likely to have formed by the development of longshore bar and aeolian dunes in Princetown beach. The sedimentary unit of RGE01 is composed of a number of distinct layers including grey silt, fine sand, oxidised yellow coarse sand, granules and pebbles. Sorting of grains in each layer is good, and beddings decline gradually toward Gellibrand River. The thickness of sediments is ~8 meters. The obtained optical age of RGE01 is 217±31 ka BP. The age of RGE01 is well assigned to the MIS (marine oxygen isotope stage) 7 around ca. 190-240 ka BP, although there may be some influence from fluvial depositional thickening.

APO01 and APO02 were collected from estuarine

Fig. 7. Estimation of uplift rate derived from T-2 assuming by consistent uplift rate during the Quaternary (MIS 7:190-240 ka, 12 m apsl of inner edge elevation, 0 m for paleo-sea level). T-5 is situated at the boundary of Pliocene and Quaternary in the graph.

clay and clayey sand in Apollo Bay (38°45'36"S, 143°39'49"E) (Fig. 6b). The Early Cretaceous feldspathic and lithic sandstone underlies the 3 m-thick sediments, and the samples were selected from different layers of the same outcrop in depth of 2 and 0.7 m, respectively. In the sediment unit, a brown to yellow brown clay sediment layer (lower layer) turn to top brown black to black silt and silty sand (upper layer). The basement elevation at the sampling site is 14 m apsl. APO01 and APO02 samples yielded the burial ages of >133 ka BP and 160 ± 20 ka BP, respectively. The OSL ages and geomorphic set around the sampling site suggest that they were deposited in a fluvial origin by the meandering Barham River and its distributaries. However, the obtained ages provides a temporal constraint for the formation age of the T-2 terrace in Apollo Bay. If assumed that the T-2 terrace underlying APO01 and APO02 was formed corresponding to the former interglacial from deposition of the sediments, it is possibly considered that the T-2 terrace corresponds to a substage of the penultimate interglacial time (MIS 7).

KEN01 was obtained in the mouth of Kennett River (38°39'58"S, 143°51'45"E). The sediments are underlain by a planar bedrock surface (13.5 m apsl) of the Early Cretaceous sandstone, which is mostly composed of deoxidized grey clayey sand with rich organic

materials. The thickness of sedimentary unit is 3 meters. The optical age of KEN01 was obtained as 86 ± 11 ka BP. Sea level around 80-90 ka BP was ~30 m below present sea level (MIS 5a substage), suggesting the sediment was deposited in a fluvial origin after the formation of the T-2 terrace. This is supported as well by the exceptionally planar bedrock surface with centimeter-scale relief underlying KEN01. The uppermost of the bedrock is deeply weathered, implying that the T-2 represents a longer period of exposure and erosion before deposition of the sediment.

Based on the interpretation with the estimated optical ages and the stratigraphic order, it is proposed that the formation time of the T-2 terrace confines the penultimate interglacial (MIS 7, 190-240 ka BP), then likely formation ages of the T-1 terrace is the last interglacial time (MIS 5e, 125 ka BP). These formation ages have been used for calculating the Quaternary uplift rate of the Otway coast with the estimated paleo-shoreline elevations of each terrace.

Discussion

Quaternary uplift rate

Information on the Quaternary sea level records is essential in order to calculate uplift rate of a coastal region. In the Australian continent, terrestrial sea level

Fig. 8. Shaded topography of the study area derived from ASTER GDEM. The inset is represented with 5 m amplitude (white arrows) in the Pliocene Strandplains (Sandiford, 2003a).

records of the middle-late Quaternary are extensively well preserved as high-stand marine successions in the Coorong Coastal Plains, South Australia. From these successions, sea level for MIS 7 was estimated from -6 to 0 m with assumption of $+2$ m reference level of MIS 5e stage (Murray-Wallace, 2002). It is assumed herein that the sea level at MIS 7 stage was as high as present level. The age-altitude curve with the uplift rate derived from the T-2 is shown in Fig. 7. The formation age of the T-2 terrace has been assigned as MIS 7 stage (190–240 ka BP), and the elevation of inner edge measured in field is 12 m a.s.l. As a result, the calculated uplift rate is 56.6 ± 6.6 m Myr^{-1} during the late Quaternary, higher terraces above the T-2 are located in time of the early Pleistocene on the graph with assumption of a constant uplift during the entire Quaternary.

Stratigraphic relationship with Pliocene strandlines

Pliocene strandlines are extensively well developed in the northwestern flanks of the Otway Ranges (Fig. 8), and they provide constraints on the late Neogene tectonic activity. The geomorphic expression of these strandlines has been greatly accentuated by erosional

landsculpting resulting in the development of a dramatic trellised drainage net (Sandiford, 2003a). Profiles along strandlines rise from less than 120 m to up to 280 m on the northwestern flanks, stepping over a series of small faults and monoclinical flexures, for example the Simpson and Ferguson Hill anticlines bound by an east-northeast-trending array of en échelon faults. The maximum elevation of the preserved strandlines coincides with a prominent break in slope at ~ 230 – 280 m. Sandiford (2003a) interpreted that this break in slope almost reflects the position of the Pliocene coastline (Fig. 9). The depositional time of the strandlines were estimated as the early-middle Pliocene by Wallace et al. (2005). Strontium isotope ages from well-preserved molluscan assemblages of the strandplain successions indicate that the earliest sediments were deposited above the late Miocene unconformity at around 5.8 ± 0.2 Ma (latest Miocene). The youngest exposed strandplain sediments were deposited during the early Quaternary time (ca. 2.0 Ma).

Estimates for mid-Pliocene sea levels range from 10 to 40 m above sea level (Lisiecki and Raymo, 2005; Dwyer and Chandler, 2009), and recently a numerical

Fig. 9. Correlation between T-5 and Pliocene strandplain (Hanson Plain Sand) cross the Otway Ranges. (a) Three-dimensional topography of the Pliocene strandplains and the Otway Ranges, (b) T-5 terraces and Low strandplain are corresponded in the profile cross the ranges, and (c) the suggested position of the Pliocene shoreline on the ancestral range front by Sandiford (2003a).

model (Raymo et al., 2011) predicted elevation of a +14 m eustatic change with adjustment of glacial isostatic effects up to the middle Pliocene (ca. 3 Ma). A value of +14 m is adopted in this study for Pliocene eustatic signal, then implying that the northwestern side of the Otway Ranges has been experienced 216–264 m of post-Miocene (5.5 Ma) uplift. The elevation (at around 120 m) and ages (2 Ma old) of the youngest strandplain in the northwestern side of the ranges correlate to those of the T-5 terrace in the southeastern side, suggesting that a tectonic uplift has

been essentially uniform across the ranges since the Pliocene. Based on this correlation, an uplift rate for the Pliocene has been calculated, as illustrated in Fig. 10. In this graph, it is clearly seen that there is a significant change of tectonic intensity between the Pliocene and the Quaternary.

Changing Neogene tectonic activity

A change of tectonic activity since Pliocene is certainly recognised based on the stratigraphic relationships between Quaternary marine terrace

Fig. 10. (a) Inferred Pliocene uplift rate based on the correlation between Quaternary terraces and Pliocene strandplains. (b) Stack of globally distributed benthic $\delta^{18}O$ records showing pattern of climate variability over past 5 Ma. Approximately, a variation of 0.1‰ of the $\delta^{18}O$ corresponds to a variation of about 10 m of the sea level (Lisiecki and Raymo, 2005). With adjustment of glacial isostatic effects up to the middle Pliocene (ca. 3 Ma), a value of +14 m for Pliocene eustatic signal (Raymo et al., 2011) is adopted in this study.

sequences and Pliocene strandlines. The uplift rate over the last 240 ka records 56.6 ± 6.6 m Myr⁻¹, likely to have been constant during the Quaternary, whereas the cumulative uplift rate since the Pliocene was estimated as 43.8 ± 4.6 m Myr⁻¹. A similar observation was also suggested by an unconformable relationship between the Pliocene and Quaternary strandlines, implying either renewed Quaternary tectonism or eustatic factors, although the nature of the change is still arguable. Dickinson et al. (2002) suggested two

successive pulses of tectonism in Southeast Australia since the Late Miocene. Of these two pulses Late Pliocene to Pleistocene uplift is less significant than late Miocene uplift and exhumation, although both events were initiated under the same stress regime. Similarly, Sandiford et al. (2004) noted that an emphasised neotectonic activity in Southeast Australia terminated in the late Miocene at around 5 Ma, followed by ongoing deformation, possibly at somewhat lower bulk strain rates since then. Coblenz et al.

(1998) analysed the role of collisional forces generated by the Himalayan, New Guinea and New Zealand collision zones in balancing plate driving forces of ridge push and slab pull, with the SHmax aligning to a near-orthogonal direction in the vicinity of each of these collisional orogens (Sandiford et al., 2009). For instance, the convergence between the Pacific and Indo-Australian plates responsible of the South Alps collision zone in New Zealand is related to progressive changes in plate rotation poles in the period 10-5 Ma (Sandiford et al., 2004). As such, the intensified tectonic response during the Late Miocene (10-5 Ma) is well addressed in terms of the increase of the Australian intra-plate stress level due to the change of relative motion and increased forces at the boundary between the Australian and Pacific Plates (Walcott, 1998; Dickinson et al. 2002; Cande and Stock, 2004). The onset of renewed Quaternary tectonism in Southeast Australia is presumably attributed to an accumulative increase in stress level, although there is yet insufficient information to discuss time intervals and detailed causative factors.

Conclusion

Seven marine terraces elevated up to 220 m amsl have been mapped along the Otway coast, and the numerical formation age of the T-2 terrace at 12 m amsl has been assigned as MIS 7 stage (190-240 ka BP) using OSL dating method. The calculated uplift rate during the late Quaternary is 56.6 ± 6.6 m Myr⁻¹, and the higher terraces above the T-2 are assigned in time of the early Pleistocene with assumption of a constant uplift during the Quaternary. A change of tectonic activity since the Pliocene is recognised based on the stratigraphic relationships between the Quaternary marine terraces and the Pliocene strandlines. The intensified tectonic response during the Late Miocene (10-5 Ma) is well addressed in terms of an increase of the Australian intra-plate stress level due to the change of relative motion and increased forces at the boundary between the Australian and Pacific plates.

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