Tertiary ‘deep lead’ palaeoriver systems and their relationship to basin evolution, Victoria

G.R. Holdgate, K.A. Cunningham, M.W. Wallace, S.J. Gallagher and D.H. Moore

Abstract

Basalt flows across the central highlands of Victoria have sealed in-place early to middle Tertiary palaeodrainage systems that once provided clastic sediments to the flanking Otway, Murray and Gippsland basins. Gravels of the palaeorivers were mined in the past for gold. Modern aeromagnetic/radiometric coverage is used to map this palaeodrainage system; water-mineral exploration drilling provides detail of sediment composition.

Palaeodrainage into the basins occurs radially from highland blocks centred on St Arnaud and Bendigo. The rivers discharged onto late Eocene to Miocene-aged peat swamps (coal) and delta/shoreline systems peripheral to the mainly marine carbonate environments of the Murray, Otway and Gippsland basins. The coal and gravel sub-basins include the Stawell to Horsham deep lead, the Wyceproof and Streatham sub-basins, the Campaspe-Goulburn valleys and the Warragul Sub-basin. Separating the two highlands is a major incised Loddon-Ballarat-Streatham-Port Phillip deep lead system that connects the Murray to the Otway and Port Phillip basins.

Early Tertiary coal and gravel basins formed along the lead systems, sediment isopachs suggest the ancestral Murray River could flow south to the Otway and Port Phillip basins. Radial flow directions off the highlands and a Murray source to the southern basins argue against the current east-west highland divide existing in the early-middle Tertiary, rather, two meridionally-orientated highlands lay parallel to the eastern highlands. The much younger (< 7 Ma) Plio-Pleistocene valley-infilling basalts flow from an east-west divide located up to 20 km south of the present, implying the modern east-west divide formed as a result of Neotectonic uplift.

Keywords: palaeovalleys, deep leads, central highlands, Victoria Basin, Otway Basin, Murray Basin, Gippsland Basin, uplift history.

Introduction

The deep lead palaeovalleys that underlie Cainozoic basalts of the central highlands (Fig. 1) are well known from the Victorian gold rushes of the 1860s to 1920s, and form one of the most extensive buried palaeoriver valley systems in Australia (Hunter 1909; Brown 1937; Canavan 1988; Taylor et al. 1996, 2000; Cayley & Taylor 2001; Carey & Hughes 2002). The deep leads (by definition alluvial gold workings > 30 m deep) produced about 0.2 million kg of gold between the 1860s and 1920s (Canavan 1988) and today are an important water resource. As well as being economically significant, it has also been suggested that the palaeovalleys represent a record of highland uplift during the Cainozoic when highland relief was thought to be similar to today. Subsequent incision by modern rivers makes the deep leads useful as indicators of ancestral highland relief (Wellman 1979), and the major source of siliciclastic sediments to the flanking basins.

It is not generally appreciated that buried palaeovalleys underlie all the basaltic Younger Volcanics that cover 15,000 km² of southern and central Victoria (Fig. 2). This paper concerns the Early-Middle Tertiary palaeoriver systems of the highlands and their immediate basin-edge influence. Although many younger palaeorivers can be seen on magnetics where they overlie late Tertiary carbonate sediments in the Otway and Port Phillip basins, they are not the subject of this paper. Age-equivalent palaeovalleys also occur in the eastern highlands of Victoria and New South Wales, but are mostly eroded remnants perched on top of the highest relief areas.

In this paper, we describe the distribution, stratigraphy, age, palaeogeography and neotectonic implications of the mostly Early to Middle Tertiary deep lead sediments and their interaction with the Otway, Murray and Gippsland basins. Detailed age determinations of the deep lead successions have been hindered in the past by the deep weathering of outcrops and a general lack of drill core with dateable palynological material. Major advances in this respect await sampling from further groundwater drilling, but sufficient dates gathered over the last 20 years give a consistency of ages that may not significantly alter with future drilling.

Recent high-resolution airborne geophysical data (largely total magnetic intensity, radiometric and digital elevation) allow recognition and detailed mapping of the basaltic infill of the deep lead palaeovalleys over large areas of southwestern Victoria (Taylor et al. 2000; Cayley & Taylor 2001) (Fig. 3). However, the large age discrepancy between the mainly K/Ar dated Plio-Pleistocene ages for the basalt infill and the much older palynology ages for the underlying deep lead sedimentary deposits has created some erroneous conclusions in the past. Here, we present the combined results of geophysical mapping, borehole mapping, field-work and palynology results and attempt to produce an integrated picture of the Tertiary deep leads in southern Victoria and their relationship with the adjoining basins.

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Figure 1. Digital terrain map of central Victoria highlands and adjacent basin areas, showing main palaeovalley trends from magnetic data (red), post-10 Ma divide and present divide positions. Inset shows southern Australia with relief data both onshore and offshore.
Figure 2. Summary map of central Victorian highlands and adjacent basins, showing outcrop geology, basalt palaeovalleys defined from magnetics (black), other magnetic palaeodrainages (blue), post-10 Ma divide and present divide positions.
**Geological setting, previous work**

The early workers on deep leads (Wilkinson 1907; Hunter 1909; Brown 1937; Canavan 1988) displayed the palaeovalleys on cross-sections from bore data, underground mapping, and produced deep leads maps and their supposed positions in the lesser mined areas.

More recent Geological Survey 1:100,000 scale mapping in the central highlands has emphasised the Palaeozoic outcrop geology (e.g. Taylor et al. 2000; Cayley & Taylor 2001), only focussing on gravel terraces and sub-basaltic sediments occupying the sides of the modern river valleys. To date, little use has been made of the geophysical (magnetic/radiometric) expression of the deep leads. The Geological Survey Victoria (GSV) reports describe the sub-basaltic sediments as the Calivil Formation, modifying the Calivil ages as originally described by Macumber (1978, 1991) from late Miocene to Oligocene-Miocene aged gravel and sandy sediments extending beneath the Murray Basin and lower Loddon Valley. In turn Calivil Formation ‘leads’ appear to cut older Tertiary Renmark Group sediments downstream and in the Murray Basin (Fig. 4). The top of the Renmark Group includes a weathered Mologa surface (Macumber 1991).

The GSV 1:100,000 scale mapping also illustrates the extent of the Whites Hill Gravels, a lithologic unit that refers to extensive outcrops of alluvial gravels in the modern valley sides and across hill tops (Williams 1983), often directly overlying Palaeozoic rocks, which appear to be cut by the Calivil deep leads. Some of these gravels were worked for their placer gold. Canavan (1988) drew a distinction between ‘old’ high level gravels along present hill tops and ridges, and valley filling mostly non-auriferous terraces of supposed Tertiary age. The ‘old’ gravels are a series of sinuous elongated auriferous leads containing a ferruginous ‘Norval’ regolith capping that is resistant to the modern erosion (Cayley & McDonald 1995), whereas the terrace gravels are sheet-
like and follow the modern valley sides. The newer GSV mapping combines all these gravels with various geomorphic expressions under the one Whites Hill Gravel name. Although lacking any age dating, the cross-cutting evidence by the Oligo-Miocene Calivil Formation suggests the Whites Hill Gravels are of earlier age, as much as Cretaceous. This age, first suggested by Ollier & Pain (1994), considers the dispositions to the Whites Hill Gravels and is yet to be widely accepted. In this paper the GSV stratigraphy is mainly used (Fig. 4).

### Methods

Stratigraphic data were obtained as detailed bore logs and cross-sections from mining records, annual reports and groundwater data bases made available through the Department of Natural Resources and Environment, Victoria (DNRE) and Sinclair Knight Mertz Groundwater Consultants (SKM). Approximately 3,000 bore records were examined and are summarised as deep lead isopachs (Fig. 5). Of particular use are the Victorian Mines Department Annual Reports between about 1880 and 1910 that cover the main period of deep lead drilling undertaken by the government as assistance to the deep lead gold industry at the time. Exploration into the deep leads has continued to the present day. Annual reports of company results are lodged with the GSV, available as microfiche copy.

Digital elevation, radiometric and magnetic data were sourced from the GSV. Magnetic imagery (Fig. 3) was enhanced to better show detail of the Younger Volcanics. In large areas of flood basalt some of the buried palaeorivers can be seen as sinuous magnetic-high features either because the basalt is thicker in the river valleys and/or there are maghaemite/ferricrete layers associated with the top of the sediments beneath the basalt (Figs 6, 7). Some well-known deep leads, such as the Berry leads north of Creswick, are difficult to image, possibly due the greater thicknesses of basalt here (Fig. 6). Fortunately, the upper lead branches that extend into alluvial placers directly overlying Palaeozoic bedrock are clearly visible and traceable into areas of thicker basalt. The radiometric images are useful in distinguishing modern valley infills and also some older high-level Whites Hill Gravels that do not have a magnetic signature.

### Palaeovalley-basin isopachs

The thickness of the palaeovalley sediment plus basalt infill together with the adjacent basin thicknesses are depicted as an isopach map between ground surface and top of basement (Fig. 5). This map differs from previous ones (e.g. Bishop & Li 1997, Taylor & Gentle 2002) as it uses total isopach values rather than the modern (post-folded) structure top-of-basement contours. It covers all deep leads west of a line between Ballarat and Bendigo and follows them out into the Murray and Otway Basins. The combined sediment plus basalt thickness gives total valley infill and is comparable to the adjacent basin fill and where palaeovalleys have no basalt.

The main palaeodrainages into the basins appear to originate as river systems flowing in a radial manner from two large highland blocks centred on St Arnaud and Bendigo. The St Arnaud High trends north to south and is projected subsurface as the Warnambool Ridge in the Otway Basin and the Lake Boga granite in the Murray Basin. The Bendigo High is contiguous with the Mornington Ridge in the south and the Mt Terrick Terrick granite in the Murray Basin. The two highlands are separated by the major Loddon-Ballarat-Streatham-Port Phillip palaeovalley system that connects the Murray to the Otway and Port Phillip Basins. The combined sediment plus basalt thickness gives total valley infill and is comparable to the adjacent basin fill and where palaeovalleys have no basalt.

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In this scheme, the Late Eocene to mid Miocene Loddon River Group deep lead sedimentary succession encompasses the Calivil and Olney formations, most of the Renmark Group, and the Denicull Formation of Hughes et al. (1998). The authors did not cite the Bealiba and Stawell palynology dates, and placed the Whites Hill Gravels as Palaeocene/Eocene. This revised stratigraphy is not used in the current GSV mapping and is yet to be widely accepted. In this paper the GSV stratigraphy is mainly used (Fig. 4).
Figure 5. Isopach map of the incised valley infill - central Victoria highlands and adjacent basins.
140 m. The sediment proportion is roughly one quarter to one third with over a half in the centre of the palaeovalleys. For example, in 578 bores intersecting lead sediments within the Creswick Sheet, sediments averaged 9.2 m with a range between 0–80 m. For the same area the average basalt thickness was 57 m (Cunningham 1998). In the deep lead underground workings the placer gold usually occurred over channel widths of up to 300 m, most gold occurring immediately above basement or at the base of each channel succession (Wilkinson 1907). Drilling outside the main palaeochannel areas usually encountered either basalt with only minor sediment above basement, or mainly sediments in adjacent basins.

Where the leads flow out into the adjacent areas of the Murray Basin thicknesses are similar (Fig. 5), other than close to the Murray River where a few depressions exceed 200 m. In contrast, adjacent areas of the Otway Basin can be over 400 m deep. A series of borehole cross-sections across and along some areas of the leads are shown on Figures 8 to 10 (modified from Mines Department annual reports 1890–1905 and Hunter 1909). They indicate the upper one half to two thirds of infill is basalt, and a lower third is sediment. The basalts vary between one continuous 60 m thick succession (Figs 8C, 9D) to several flows separated by <10 m of clays and sands (Figs 8A, B; 10B, C). The interflow sediments may include aquifers and where auriferous were referred to as ‘upper leads’. The main sediments below the basalts usually consist of one or more fining-upwards successions of fluvial gravels, sands, clays and lignites, referred to here as the Calivil Formation. Figure 11 shows an outcrop of the Calivil Formation in the Berry Group deep lead succession beneath basalts at Creswick, with detail of a ferricrete surface on the top of the Calivil Formation. Figure 12 shows details of the Campaspe deep lead Calivil Formation near Lake Eppalock, also with a top ferricrete surface. In both cases the ferricrete could be the Karoonda (Timboon) Regolith that overlies Pliocene aged barrier systems in the Otway Basin (Dickinson et al. 2002).

The palaeochannel isopachs do not necessarily thicken in a modern down-valley direction. Rather, along the length of the leads deeper depressions alternate with shallower areas with little pattern, although the proportion of basalt to sediment remains fairly constant (Figs 5, 13). Some local divides, such as along a line through Maldon-Dunolly-Bealiba, affect several leads in the one area and the channel infill thickens away from what is probably localised sills/high spots or tighter valley sides. The cause of this could be localised faulting or harder areas of bedrock at the sill points. The modern drainage divide of today has little apparent influence on valley infill (basalt plus sediment) and many leads cross it with only some localised thinning effects not significantly different to other sills and divides found elsewhere along the leads (Fig. 5). The palaeovalleys average 2.5 km across, varying between steep sided 1 km wide valleys such as the Madam Hopkins Lead (Figs 6, 9D), to broad valleys 4 km wide east of Clunes (Figs 5, 8). Mapped faults in underground workings with throws of several metres are common (Dunn 1909) and some abrupt step-like changes seen in close-spaced bore data may also be a result of faulting (Canavan 1983, Cunningham 1998). However, in general, the valley floors are meandering and not necessarily fault controlled.

Heights in the surrounding hills may be up to 350 m above the valley infill (eg. 569 m at Mt Tarrengower near Maldon) giving an original combined hill to valley floor difference of up to 500 m. The occurrence of high-level auriferous gravels in the centres of the St Arnaud and Bendigo highlands suggests that some of this modern-day relief is inherited from the early Tertiary. Present basement contours indicate the deep lead gradients vary between 0.22% and 3.02% (Wilkinson 1907) but these gradient values have been affected by uplift and warping in the last 10 Ma. In the Otway Basin the leads grade into Miocene marine sediments at around
150 m above present sea level (Fig. 13). Where the leads enter the Murray Basin they have cut to present sea level. This suggests differential subsidence on opposing sides of the dividing range or subsequent basinal uplift on the southern side.

Subsidiary flanking sub-basins that juxtapose between the highlands and the Otway Basin proper are localised as northerly indentations to the main basin and are separated as such by east-west shallow basement divides (Fig. 5). One sub-basin located beneath the ‘Stony Rises’, described here as the Streatham Sub-basin, receives a number of highlands palaeodrainage inputs stemming from Ararat in the west to Beaufort in the east. One of the palaeodrainage systems is the gold-rich Langi Logan Lead (Mann et al. 1992), with many other more easterly palaeodrainages trending south into the sub-basin including some from north of the modern divide (eg. the Madam Hopkins Lead as shown on Fig. 5). The Streatham Sub-basin includes over 200 m of sub-basaltic sands, gravels, clays and brown coals that extend down to the Palaeocene Upper *L. balmei-M. diversus* spore-pollen zone (Stanley, 1983; 1988). The Streatham Sub-basin covers an area of 1,200 km², is entirely covered by younger basalt flows, and has not been detected before by geophysical means. Detailed aeromagnetics reveal the sub-basaltic palaeodrainage courses, and abundant groundwater and stratigraphic drilling provides detail and ages of the sedimentary fill. The sub-basin opens southward into the Otway Basin at Lake Gellie west of the Derrinallum granite high that formed the northern limit to the Miocene marine shoreline of the Gellibrand Formation. The Streatham Sub-basin has a deltaic geometry. Sub-basaltic sands, clays and brown coals were deposited as facies equivalents to the marine carbonate sediments, and older Tertiary siliciclastic sediments extended into the Otway Basin as facies equivalents of the Wangerrip Group.

A second coal-rich basin occurs near the main divide at Lal Lal 20 km southeast of Ballarat. The Lal Lal Sub-basin underlies the Bungaree palaeodrainage system that connects with the Moolort and Berry East gold-rich deep leads north of the present divide, and to the Ballan Graben-Port Phillip Basin south of the present divide. Within the Lal Lal Sub-basin up to 150 m of coals and clays include Eocene (Lower *N. asperus*) to Palaeocene (*L. balmei*) ages (Cookson 1953, Cookson & Pike 1954, Holdgate et al. 2002).

The Murray basin is a third coal-rich basin, immediately north of the central highlands and extending north to the present Murray River and west to a shoreline located between Kerang and Swan Hill where coal measures pass laterally into Murray Group marine sediments. The flat surface of the Murray Basin in this area conceals incised valley systems developed on Palaeozoic basement indicated by the thickness contours on Figure 5. The palaeovalleys are northern extensions to the main Avoca, Loddon, Campaspe and Goulburn deep leads and within each valley occur coal measures where individual seams can be up to 10 m thick (Preston 1981, Holdgate & Clarke 2000). The lignite-prone sediments together with their underlying basal gravels and sands are referred to as the Renmark Group, but their palynology ages are not dissimilar to the comparable stratigraphy in the highlands deep leads (Fig. 5).

Other sub-basins that include coal measures occur near the southern end of the Grampian Ranges (Stanley 1983), beneath the Avoca River near Archdale (Macumber 1991). Feeding into the Gippsland Basin is a major palaeodrainage system beneath early Miocene basalts across the Warragul Block and southern margins of the eastern highlands. Many of the earlier sub-basin infills are...
now isolated by Late Tertiary highlands uplift, and attest to a more widespread basin system that probably extended between the two highs of the central highlands and formed a connecting conduit between the Murray and Otway basins.
Radiometric (mostly K/Ar) ages for the outcropping Younger Volcanics basalts and basaltic cones in the western plains and central highlands range between 7.2 and 1.5 Ma (Late Miocene to Pleistocene) (McDougall et al. 1966, Aziz-Ur-Rahman & McDougall 1972, Bowen 1974, Wellman 1974, McKenzie et al. 1984, Willman 1995 and Cayley & McDonald 1995). The ages come from published data, but Price (2003) implies there are many more additional but unpublished ages. To our knowledge no dates have been obtained for basalts within the stratigraphically lower parts of the lead valleys, many of which appear from drilling evidence to be confined within the deeper parts of the valleys and do not outcrop. They could conceivably be dated from drill core or chip samples in the future.

The palynology ages for the lead sediments underlying the basalts mostly show a significant difference in age to the basalt dates, suggesting a considerable time period of non-deposition/erosion exists between the two main valley infilling periods. A dozen bore samples now exist (Fig. 5) with ages for Calivil Formation sediments mainly varying between Middle–Upper *N. asperus* (Upper Eocene–Early Oligocene) to *P. tuberculatus* (Late Oligocene–Early Miocene) (Archer in Holdgate & Galimberti 1980, Partridge & Wilkinson 1982, Archer 1983, 1986, MacPhail 1991, Partridge 1993, 1998, Holdgate et al. 2002).
The locations for these bore samples are shown on Figure 5. The youngest Pliocene ages obtained from the Bet Bet Lead at Eddington (Partridge, 2002) probably are the result of younger alluvial infill across the localised Maldon-Bealiba divide. Two other Pliocene dates were obtained from the Goulburn valley near Tabilk and Molka (Archer 1983) and may reflect younger ages for the Goulburn deep lead palaeovalley. The plant species seen in lignite-prone beds in the Calivil Formation deep leads include abundant Nothofagus pollen and tropical Elaeocarpus fruits comparable to extant species in north Queensland today (Rozefelds & Christophel 1996).

Shelly marine sediments in the lower reaches of leads near Rokewood (Otway Basin) contain Early-Middle Miocene foraminifera (Kenny 1937, Carter 1958), and marine shells were recorded in the adjacent Pittfield Plains lead. Marine fossils in higher level leads at Stawell are undated and were noted by Cayley & Taylor (2001) to be casts of shells.

Dating problems exist with the Whites Hill Gravels, because the outcrops lack dateable material. However, at two locations where mapped Whites Hill Gravels overlie underlying valley infill at Bealiba and Stawell (Fig. 5), bores have penetrated through the gravels to palynologically-dated Oligocene sediments beneath (Archer 1983, Partridge 1993). This suggests that some widespread sheet-like gravel terraces, which are present along the modern river valley sides and mapped as Whites Hill Gravels, are younger than Calivil Oligo-Miocene ages and are possibly Plio-Pleistocene. In this respect their flow directions conform to that of the modern stream directions. However, instances where the Whites Hill Gravels form basement hill-top veneers could indicate they are remnants of an earlier pre-Oligocene drainage system.

**Magnetic-radiometric images of the deep leads**

Using the methods previously described, the deep leads were magnetically mapped throughout the central highlands and out into the adjacent basins (Figs 1–3). Magnetic images of the basalt can be traced both in the surface and subsurface as sinuous river-like patterns that can be corroborated by mining and drilling data. In the Creswick sheet area a correlation of magnetic mapping and the basalt thicknesses, as derived from 2,469 boreholes (Cunningham 1998), confirms that the thickest areas of basalt isopach correspond with the higher magnetic values (Fig. 14).

Flow directions for the basalts can be interpreted from their valley intersections and tributary branching (Figs 6, 7). For the most part this indicates an approximate east–west-trending main divide was in existence by 7 Ma—the age of the oldest basalts—although in the Ballarat area we consider it was located up to 20 km to the south of its present position (Figs 2, 7). South of the basalt divide the tributaries flow south to the Otway and Port Phillip basins and north of this divide they flow to the Murray Basin. The contradictory flow directions of leads in the Ballarat area, as

![Figure 14. Isopach map of basalt thickness in the Creswick 1: 100.000 sheet area based on 2469 bores (Cunningham 1998), overlain by palaeovalley magnetic lead positions (black) from aeromagnetic data.](image-url)
Some of the older high-level non-magnetic leads can be identified on the radiometric images appearing as dark-blue stream-like profiles. Their ubiquitous ferruginous cementation, although non-magnetic, contains a low-level thorium content judging by their colour presentation. The same radiometric images also occur in some nearby river valley sediments or within some high-level auriferous gravel terraces (e.g. near Bealiba and Logan, shown as a radiometric image on Fig. 15). On the St Arnaud High, discontinuously connected radiometric images with the above patterns suggest some radiating stream-like flow directions northeast and east off the centre of the highland near St Arnaud township. These may be ancestral flow directions for the pre-Oligocene? Whites Hill Gravels (Fig. 5). Examples of typical radiometric images of early river systems include the high-level Puzzle Flat lead at Bealiba (Fig. 15), the Dunolly Lead at Dunolly, and many of the high-level leads around Stawell and Ararat.

**Figure 15.** Radiometric image of the Bealiba-Logan area in the Avoca Valley showing interpreted Whites Hill Gravel leads in brown, and younger valley trends in yellow and blue. For location see Figures 2 and 5.
Figure 16. Total aeromagnetic image of the onshore Gippsland Basin and adjacent Eastern Highlands showing main palaeovalley trends for the sub-basaltic sediments. The Thorpdale Volcanics are mainly around Warragul and southern margins of the Eastern Highlands. The older Carrajung Volcanics occur around the Balook Block. High-level basalts on top of the Eastern Highlands are shown at Mt Magdala, Howitt and Dargo High Plains. The Mt Hotham leads are just off the northeast corner of the map.
Figure 17. Digital terrain image of the central Victorian highlands and adjacent basin areas overlain by isopach map of palaeovalley/basin infill. The remnant palaeotopography of the St Arnaud and Bendigo highs are readily apparent, whereas the present east-west divide is less well expressed.
the general palaevally flow directions for these appear to be towards the north, particularly in the case of the Dargo High Plains and Mt Hotham, suggesting they represent possible early palaevallys to the Murray Basin. They do not appear connected with the Thorpdale palaevally system on the southern margins of the Eastern Highalnds. Radiometric K/Ar dates for the basaltic faces range between 25.1 and 36.3 Ma (Late Oocene–Eocene) (Wellman 1974). Sub-basaltic lignitic sediments and gravels include Palaeocene–Eocene palynology ages (Partridge 1998; Greenwood et al. 2000).

Discussion

The configuration and existence of the central highlands near the southern margin basins has significance for sediment types, river sources and rates of supply to these basins. From this study a number of facts indicate the existence of at least two major highland blocks during the early and middle Tertiary that were orientated north-south unlike the present east-west divide. These were the St Arnaud High and the Bendigo High. Inherited relief from these blocks is still present today as shown when the palaevally infill is overlain on the present digital terrain model (DTM) image of highland relief (Fig. 17). The St Arnaud High clearly maintains its north-south relief as the Pyrenees granitic metasedimentary complexes west of Avoca, and the Bendigo High maintains its north-south relief centred on the Mt Alexander granites east of Castlemaine. The Loddon-Ballarat palaevally system occupies the lower ground between the two highs and splays southward through a number of valley and sub-basin systems into the Otway and Port Phillip basins.

Southern thickening and southern splaying palaevally systems argue against the present central highlands east-west divide being in existence during the early-middle Tertiary. It suggests connection at this time between the Murray and Otway basins, so that a proto-Murray River could have entered the southern basins between the two highs. A proto-Murray River would have had a substantial watershed, would have tapped the Murrumbidgee/Lachlan watersheds, and provided large sediment volumes into the Otway and Port Phillip basins.

Much argument has been made over timing of highland uplift (Oliger & Pain 1994) but little consideration in the arguments has been given to a substantially thicker and greater time range for Otway Basin sediments compared to similar units in the Murray Basin. A source for the large volumes of Otway siliciclastics has been discussed but not resolved in a few papers (e.g. Holdgate 1981—Dilwyn Formation; Gallagher & Holdgate 2000—Nirranda Group; Norvick & Smith 2001—Sherbrook/Wangerrup Groups). These authors imply a need for large rivers and deltas, difficult to substantiate from proximal sources such as the present dividing range, and infer incised valley sources from the Murray Basin. However, evidence for incised valleys and their logical pathways across the central highlands has been lacking to date. We show on Figure 5 that the Loddon-Ballarat palaevally has significant infill thicknesses, and is a logical connection from the Murray to the Otway Basin. Low overall gradients and sediment thickness continuity over the present divide position indicates that east-west uplift was a late Tertiary phenomena now isolating the two basins (Fig. 13).

We infer that this uplift occurred at around or shortly before the major Younger Volcanics lava outpourings (ie. 7.2 Ma) and to be the same event as the Moorabool Unconformity of Dickinson et al. (2001, 2002) timed at 10 Ma. In all the southern basins this event is seen as a low angular unconformity, usually expressed as folded Miocene marine carbonate sediments below flat-lying Pliocene siliciclastic sediments. The Younger Volcanics lavas flowed into a partially sediment-infilled uplifted valley system sealing in-place the sediments. Many of the lavas emanate around a divide located about 20 km south of the present divide from which valleys were either tilted south to the Otway and Port Phillip basins or north to the Murray Basin (Figs 2, 7). In some cases the lavas completed the infilling of the pre-existing valleys, flooding back into the headwaters of many blind side valleys of the main Loddon/Ballarat system, such as towards the Creswick basement block (Fig. 2). Continuing uplift and lava extrusions have shifted the divide northwards to its present position and westwards into the Dundas highlands where pre-3.0 Ma Parilla Formation Pliocene barrier systems are uplifted some 240 m above their counterparts across the Murray Basin (Wallace et al. in press).

The Victorian Eastern Highalnds, in contrast, appear to have been similar to their current configuration in the Early Tertiary, but may have been lower as suggested by the now substantial elevation of former valley lava flows. The Eastern Highalnds are separated from the Bendigo High by the major Thorpdale palaevally system in the southwest and the Goulburn valley system in the northwest. Both valley systems have infill thicknesses and vecment ages comparable to the Loddon/Ballarat system, albeit mid Tertiary basalt infills the Thorpdale palaevally. These palaevallys discharged sediment into the Gippsland and Murray basins but the volumes had insufficient effect to overwhelm or else bypassed the cold measure successions that were forming in the basin at the same time.

The Strzelecki and Otway Ranges lack first-hand evidence for young perched Tertiary deposits or young basaltic lavas. However, they do have early Tertiary inliers and basaltic on the range crests including Yarram Formation sub-basaltic gravels at Blackwarry and the Palaeocene Benwerrin coal field on the Otway Ranges, with seismic evidence suggesting removal of over 600 m of sediments in the later Tertiary (Dickinson et al. 2001).

The issue of when the earliest highland relief developed has been frequently debated with some authors extending it as far back as the Permo-Triassic. The occurrence of Permian glacial sediments below some of the deep leads of the Loddon was interpreted by Macumber (1978) to indicate inherited valley structuring from Permian times. However a plot of known Permian outcrop and subsurface occurrences on Figure 5 indicates there to be many Permian outcrops in areas where no palaevallys occur, including the large Nurkmurkah Trough—a Permian infrabasin beneath the Murray Basin (Holdgate 1995). Arguments that these valleys were first cut as highland glacial valleys (Branagan 2003) is difficult to substantiate as much of the Permian outcropping at Bacchus Marsh and in the Ovens Valley contains marine foraminifera and, therefore, is likely to have been deposited as marine diamictites rather than land-based glaciers (Abele in Holdgate 1986; McCann pers comm. Deakin University 2003). It could be argued that even the localised glacial scoring of pre-Permian surfaces could reflect grounding of floating icebergs. Much of the aptite and zircon fission track analysis (AFTA/ZFTA) used to interpret highland uplift and denudation has focussed on the Victorian Eastern Highalnds. However, Cretaceous to early Tertiary ages obtained from AFTA/ZFTA data in the central highlands (Kohn et al. 2002, Foster & Gleadow 1992) indicate between 1–3 km of section has been removed since the Cretaceous. These data imply substantial relief development in the Tertiary.

We can illustrate some existing pre-Eocene highland relief in the St Arnaud and Bendigo highs where denudation and downcut by Whites Hill Gravel palaevallys occurred, but the age of the gravels remains to be established. The existence of early Tertiary coal basins such as Lal Lal and Streatham imply existing basin and highlands. However, this relief could have been less than a few hundreds of metres between the sub-basins and similar aged (Wangerrup) sediments in the Otway Basin. The Norval regolith cementing on some Whites Hill Gravel outcrops reflects some form of hiatus between this unit and the Calivil Formation that.
cross-cuts it, and suggests a period of uplift and denudation sometime before/during the middle Eocene—the oldest age for the Calivil Formation (Fig. 4). A widespread basin unconformity formed at this time, the Latrobe Unconformity, is expressed in Gippsland, Torquay and Otway basins as a low angular unconformity (Holdgate et al. 2003). Although this unconformity was correlated with increasing Australian-Antarctic spreading rates, highland uplift may also be a consequence of increased spreading rates. A net result was down-cutting by the main deep leads to provide highland to valley floor relief of up to 500 m. Relatively high eustatic sea levels during the late Eocene to Middle Miocene episodically inundated most parts of the southern basins with carbonate sediments, ponded the highlands incised-valley sediments behind coastal barriers and deltas, and partially infilled some lower reaches of the highland valleys. High rainfall, warm paleoecological conditions produced high runoff abundant sediments and rainforest debris to the Calivil Formation palaeoclimatic conditions produced high runoff abundant sediments and rainforest debris to the Calivil Formation.

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Along the courses of some palaeovalleys Palaeocene to Early Eocene sediments and lignites connected with the main basins such as in the Streatham Sub-basin. Other more localised perched sub-basins such as at Lal Lal preserve dominantly Palaeocene lignites that may have been of wider extent but were stripped back by early highlands uplift and erosion.

The largest area of palaeovalleys underlie the eastern end of the Victorian Murray Basin, include lignites and basal gravels within confining valley walls, and are continuous with the highland deep leads.

Data from over 3,000 bores indicate the palaeovalleys are infilled by greater than 75 m of sediments, plus basalt with a maximum infill of 140 m. The infill thickness is variable, but along the main palaeovalley centres proportionally averages about half sediment and half basalt.

Flow directions based on downslope thickening are equivocal. Southern thickening is common, implying flow may have once been from the Murray to the Otway-Port Phillip basins. In contrast, overlying basalt flow directions usually conform to modern river directions, except south of Bendigo where a basalt drainage divide is indicated to be up to 20 km south of the present position.

7) Highlands existed as two meridional-trending uplands centred on the Pyrenees Ranges in the more westerly St Arnaud High, and on the Mt Alexander granites of the more easterly Bendigo High. A complete east-west divide between the Murray and Otway basins was not established until post-10 Ma uplift.

8) Similar aged sediments infill palaeovalleys underlying mid Tertiary basaltic across the Gippsland Basin. These drain southeasterly from the Bendigo High and southwest off the Eastern Highlands. Their extent into the Gippsland Basin can be discerned from their magnetics profile.

9) Some raised Whites Hill Gravel deposits flow radially from the tops of the St Arnaud High, suggesting early Tertiary relief. Other Whites Hill Gravels occur as terraces within the modern valley systems and dated sediments beneath suggest post-Oligo/Miocene, possibly Quaternary ages. Therefore, the naming of Whites Hill Gravel deposits is confused and a distinction on geomorphological criteria is required.

**Conclusions**

1) Most sediment successions in the deep lead palaeovalleys include gravels, sands, lesser clays, with lignite deposits generally towards the upper part. A similar succession predominates in the sub-basins. The sediment succession is generally overlain, probably disconformably, by Younger Volcanics basaltic lavas that sealed in-place the sedimentary record below. Placer mining beneath the volcanics became historically famous for its rich alluvial deep leads gold.

2) Sedimentation in the central highlands palaeovalley systems (the Calivil Formation) was most active in the middle Tertiary, approximately the late Eocene to Miocene. In the flankng basins sedimentation was dominated by shelfal marine carbonates. Therefore, most of the incised valley sediments ended up as peripheral coastal deposits/deltas or in sub-basins barred by basement highs from the main basins.

3) Along the courses of some palaeovalleys Palaeocene to Early Eocene sediments and lignites connected with the main basins such as in the Streatham Sub-basin. Other more localised perched sub-basins such as at Lal Lal preserve dominantly Palaeocene lignites that may have been of wider extent but were stripped back by early highlands uplift and erosion.

4) The largest area of palaeovalleys underlie the eastern end of the Victorian Murray Basin, include lignites and basal gravels within confining valley walls, and are continuous with the highland deep leads.

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**References**


