PALAEODRAINAGE AND ITS SIGNIFICANCE TO MINERAL EXPLORATION IN THE BATHURST REGION, NSW

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ABSTRACT

The complex drainage evolution in the Bathurst region has been influenced by both regional and local factors. Regional factors are tectonics, eustacy and climate. Local factors are bedrock lithology and structure, and Tertiary volcanism. Drainage evolution is traced back in time to the northeast-trending palaeodrainage to the Sydney Basin in Early Triassic times. Northerly drainage to the Coonamble Embayment of the Surat Basin in the Jurassic was overprinted by northwesterly drainage across the Surat Basin in the Late Cretaceous. Incision of Surat Basin sediments was initiated in the Late Cretaceous. Warping associated with initial stages of rifting in the Late Cretaceous initiated these latter events, which resulted in the formation of two major drainage divides Gorge erosion along rivers flowing to the Murray Basin accelerated in early Tertiary times. The onset of three periods of Tertiary volcanism and the formation of erosion bowls due to erosion of incompetant lithologies have also been significant factors in the drainage evolution of the Bathurst region. The sedimentation and erosion of drainage systems have been variously affected by sea level fluctuations, climatic change and tectonics.

Drainage evolution is the key to understanding landform evolution and associated regolith evolution, which have important ramifications for land use, the environment and mineral exploration. The framework for drainage evolution presented in this paper may assist mineral exploration in locating placer deposits and deep leads as it can be extrapolated to neighbouring regions of the highly prospective Lachlan Fold Belt where much of the palaeodrainage is buried.

INTRODUCTION

The Bathurst region is in the northeast of the Lachlan Fold Belt, bordering on the Sydney Basin (Figure 1). The Australian Geological Survey Organisation and the NSW Geological Survey carried out regional regolith-landform and geological mapping over the Bathurst 1:250 000 quadrangle (BATHURST) in the mid 1990s (Chan, 1998). Eight regolith-landform maps were produced, two at 1:250 000 scale (Chan et al, 1995a,b), and six at 100 000 scale: Bathurst (Chan and Kamprad, 1995), Orange (Chan and Fleming, 1995a), Molong (Chan and Fleming, 1995b), Cowra (Chan and Goldrick, 1995), Blayney (Chan, 1995) and Oberon (Hazell and Chan, 1995) sheets. Figure 2 shows the location of the six 1:100 000 sheets, as well as the main cultural and mining features.

Figure 3 shows the main regolith types and erosional scarps identified from this mapping. A central northwest-

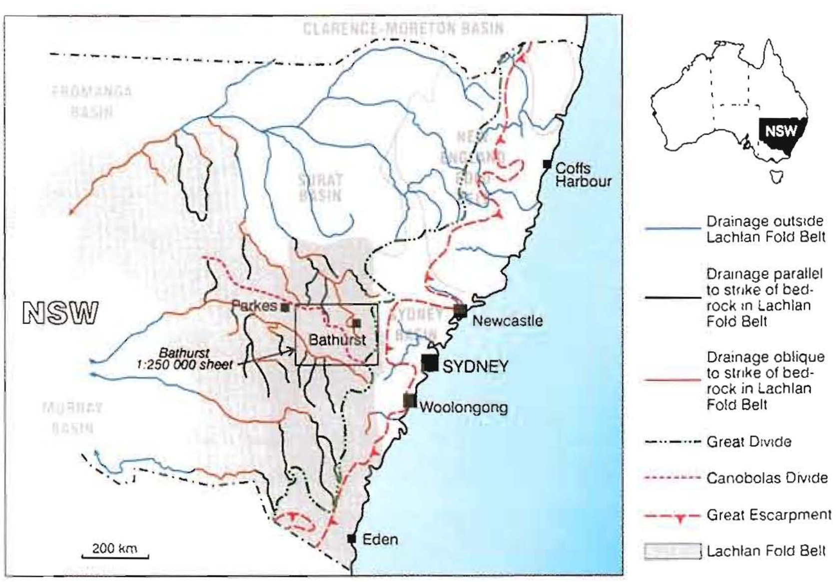

Figure 1: *Regional setting*

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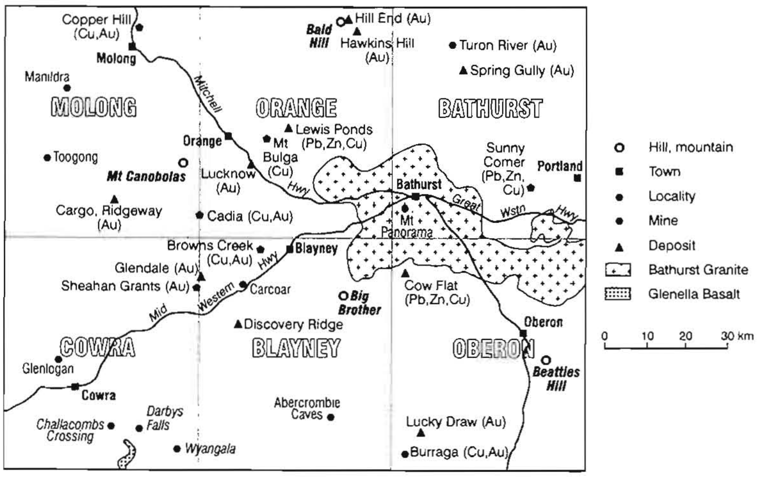


Figure 2: *BATHURST locality map*

trending highly weathered plateau dominates the area and transgresses the northerly trend of the underlying bedrock. Multiple weathering profiles and residual clay are associated with extensive Tertiary lava flows; residual and transported sand and gravel occur near and on the Canobolas Divide. Rugged hilly to mountainous terrain with moderately to unweathered bedrock predominate to the northeast and south. Large areas of transported colluvial and alluvial deposits overlying weathered bedrock occur on the western slopes associated with the Lachlan and Belubula Rivers and Mandagery Creek. High level alluvial sediments occur on the plateau west of Molong, and terraced alluvial sediments occur along the Macquarie River, especially in the highly weathered and eroded Bathurst Granite, and along the Lachlan River. Aeolian sediments are probably scattered over much of the area (Scott, 1999) but have yet to be defined regionally.

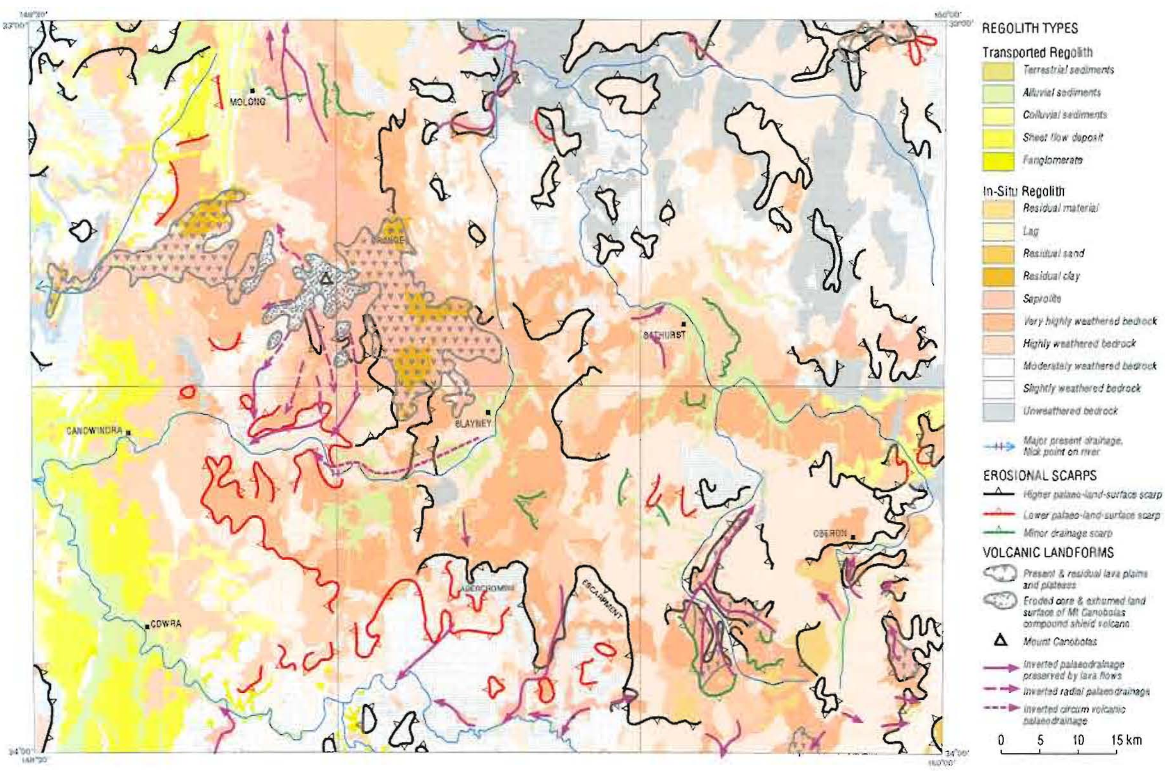


Figure 3: *BATHURST regolith types and erosional scarps*

Figure 4 displays the regional relief of BATHURST and the main present-day drainage and drainage divides. The Great Divide separates coastal from inland drainage, and the northwest-trending Canobolas Divide separates the Darling River drainage from the more southerly Lachlan River drainage (Figures 1 and 4). The tablelands of the Eastern Highlands grade to the western slopes in the western third of BATHURST. Figure 5 shows a perspective view of airborne gamma-ray spectrometric data draped over a digital terrain model on which some major regolith-landforms are indicated.

The geology dominantly consists of northerly trending belts of Ordovician to Devonian felsic to mafic volcanics and volcaniclastics, and metasediments of the Lachlan Fold Belt. The Silurian Wyangala Granite and the Carboniferous Bathurst Granite are the largest of a number of granite intrusions. Sydney Basin sediments onlap to the east. Tertiary volcanics, noteably the Canobolas complex shield volcano, overlie the older rocks.

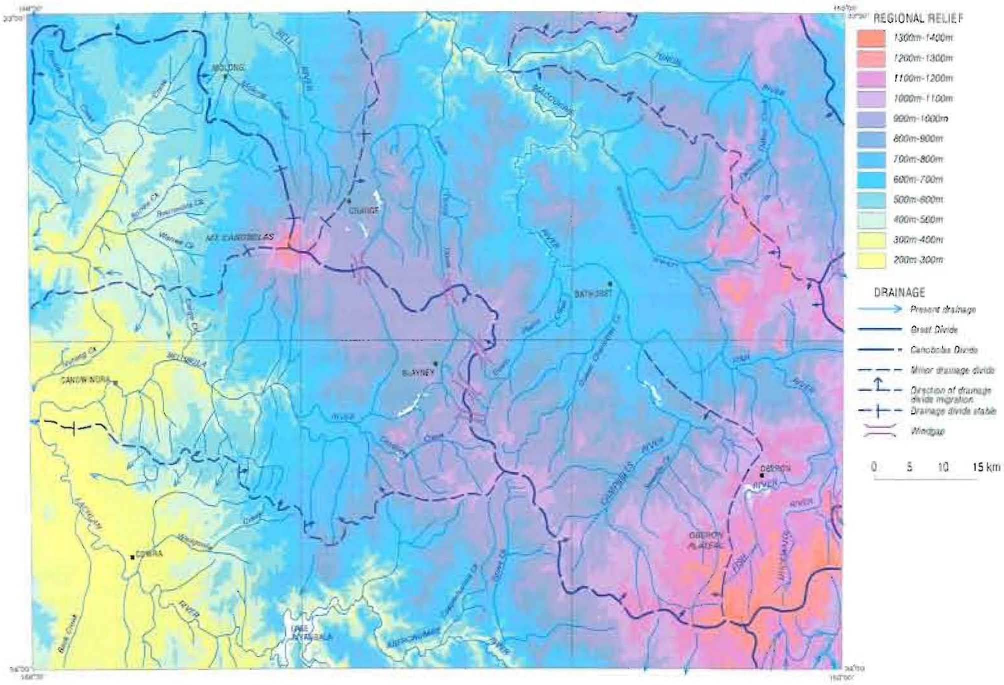


Figure 4: *BATHURST regional relief and drainage*

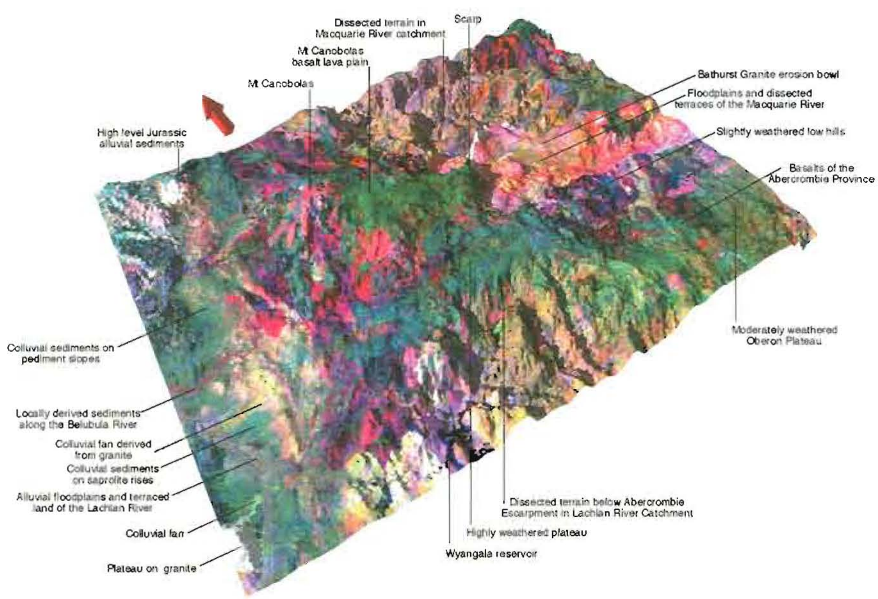


Figure 5: *BATHURST digital terrain model with 3-band composite gamma-ray spectrometric drape (potassium in red, thorium in green, uranium in blue)*

RECOGNITION OF DRAINAGE TRENDS

Evidence for drainage evolution is in the form of Tertiary lava flows (Figures 6 and 7), remnant high level alluvial materials (Figure 8), landforms such as windgaps (Figure 9), ponding and drainage patterns. Interpretations are of variable certainty. Sectors of present-day drainage align to form trends which may be remnants of older drainage systems. Figure 10 shows the dominant trends in BATHURST are in a northerly and northwesterly direction. Sub-dominant trends are to the northeast, west and southwest. Field evidence, such as cross-bedding, indicates these directions rather than their inverse. Cross-cutting drainage relationships indicate that drainage directions young in an anticlockwise direction.

The oldest recognised drainage is across strike draining towards the northeast; younger drainage parallels strike in a northerly direction; still younger drainage across strike drains a sector spanning from the northwest through to the southwest. Overprinting and disrupting these trends are trends associated with Tertiary volcanism which may relate to pre volcanic doming-induced radial drainage. More detailed mapping and dating of lava flows and high level alluvium is required to more fully understand the many complexities highlighted by this regional mapping.

Figure 6: *Weathered 12 Ma Canobolas inverted basalt flow over alluvial gravels*

Figure 7: *View to west from inverted basalt in Figure 6 across incised Macquarie River valley*

Figure 8: *Late Jurassic conglomerate with rounded lithic and quartz pebbles over very coarse sandstone at Killonbutta Forest*

Figure 9: *Wind gap on Great Divide between Fish River flowing to the north-northwest and Jenolan River flowing to the south-southeast*

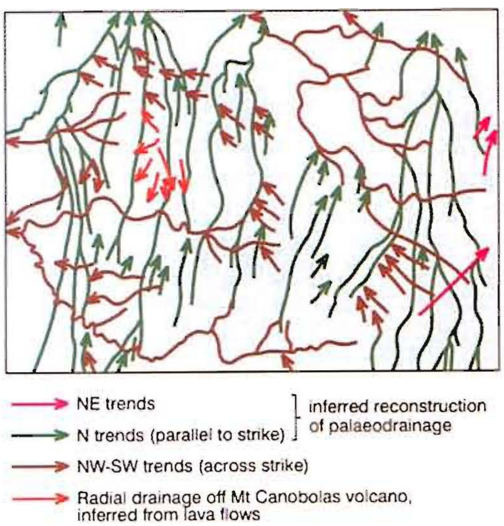


Figure 10: *BATHURST drainage trends*

Regional drainage patterns were analysed over much of the Lachlan Fold Belt in NSW to see if BATHURST trends were reflected regionally. This was largely the case as shown in Figure 1. Ollier and Pain (1994) previously noted the northwesterly trends over much of southeastern Australia.

REGOLITH FEATURES RELEVANT TO DRAINAGE

High Level Alluvial Sediments

The sediments on plateau remnants astride the Canobolas Divide northwest of Molong near the Killonbutta State Forest (Figures 3 and 4) are alluvial. Cross-bedding in quartz sandstone and conglomerate (Figure 8) indicates a northerly drainage direction and initial palynological dating of carbonaceous mudstones indicates a Late Jurassic age (time equivalent to Surat Basin Pilliga Sandstone) and a non-marine deposition environment (Gibson & Chan, 1999). Rounded quartz and lithic pebbles and cobbles are present. Lag from similar sediments is preserved 9 km to the east in a wind gap on the Canobolas Divide near the headwaters of Mandagery Creek. Cuttings from drilling associated with reflection seismic profiling by AGSO in 1997 have been interpreted to show a minimum original thickness of 70 m for sediments at Killonbutta and at least 100 m original maximum thickness in the area. These sediments are on variably weathered Gumble Granite and indicate a pre-depositional Jurassic terrain with more relief than today's. Sediments to the west of a bedrock granite high noted from seismic drilling are partly ferruginised and probably reflect palaeogroundwater controls. Clearly these sediments indicate a major drainage line to the Surat Basin in the north during the Jurassic prior to the existence of the Canobolas Divide. This scenario is parallelled further west in high level sediments around Gunningbland National Forest (Gibson & Chan, 1999).

High level quartz cobbles are also found north of Canobolas Divide in the Oberon area beneath north-trending Tertiary lava flows near Beatties Hill and on strath terraces flanking the upper Fish and Duckmaloi Rivers (Figures 2 and 4). Well rounded quartz cobbles, up to 15 cm diameter, underlie a topographically inverted 12 Ma (Wellman and McDougall, 1974) basalt, 60 m above the bedrock incised Lachlan River, at Glenella below Wyangala Dam (Figure 2). Glen Logan Gravel deposits with well rounded rounded quartz pebbles, mostly up to 3 cm in diameter, near Cowra form terraces up to 40 m above the present Lachlan River floodplain. Quartz gravels are found at various levels in the landscape and are buried further downstream in the Lachlan (see below) and Macquarie Rivers and further afield (Martin, 1991). The rounded quartz boulders, cobbles and gravels are likely to have been eroded from older high level sediments and redistributed and accumulated lower in the terrain over a widespread front. Ultimately, the original source of these quartz clasts is from erosion of a very highly and deeply weathered old regolith with only the most resistant minerals such as vein quartz left unweathered.

Lachlan Valley Deposits

The New South Wales Department of Water Resources has identified a buried palaeovalley beneath the broad floodplain of the present Lachlan River. This palaeovalley is up to 8 km wide and 100 m deep in BATHURST and has an irregular cross section profile (Figure 11). Williamson (1986) shows that the palaeovalley deepens downstream from 80m near Cowra to 140 m at Jemalong Gap west of BATHURST. Upstream of Cowra there appears to be a buried nickpoint of the palaeo Lachlan River. The increasing depth of the palaeovalley towards the west, and the age of the sediments within it, correlate with influences of the Murray Basin (Brown & Stephenson, 1991). The palaeovalley continues up Back Creek (also known as Koorawatha Creek and Crowther Creek), a north trending southern tributary of the Lachlan River, and here is up to 85 m deep (Williamson, 1986).

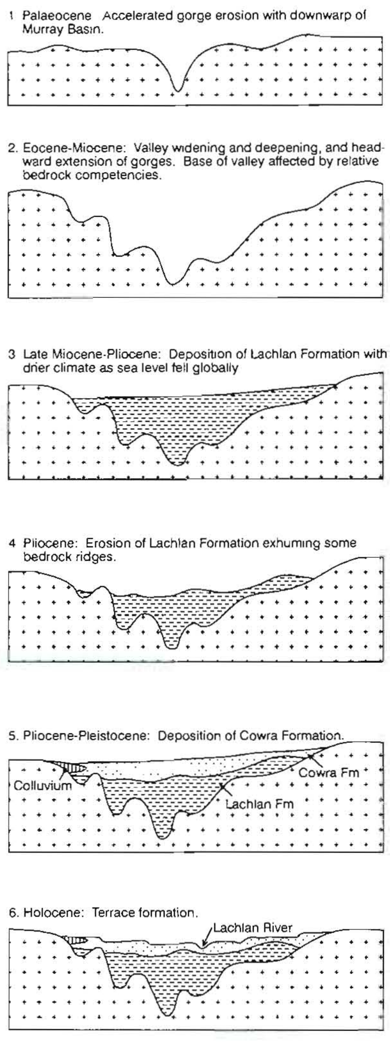


Figure 11: *Sedimentation of the Lachlan palaeovalley*

Based on interpretation of water bore logs of the Lachlan Valley by NSW Department of Water Resources, Williamson (1986) reports that basal quartz gravels occur within grey sands and gravels of the Late Miocene to Pliocene Lachlan Formation deposited in a reduced swampy environment, and to a lesser extent in the brown gravels to clay in the more oxidising environment of the Pliocene to Pleistocene Cowra Formation in the palaeo Lachlan Valley. Gravels in the Cowra Formation are uniformly distributed across the valley indicating constant reworking by braided stream channels and reflect the local catchment lithologies (Williamson, 1986), as well as containing quartz pebbles from an older regolith mantle.

Inspection of Williamson's seismic and bore sections indicates a complex history of sedimentation and erosion. The simplest possible sequence of events is shown in Figure 7: erosion of a deep narrow valley; valley widening, deepening and extension, and deposition of the Lachlan Formation; erosion of the Lachlan Formation and deposition of the Cowra Formation with interfingering of colluvial sediments along valley edges; formation of terraces due to fluctuations in sediment supply and erosion. Williamson's (1986) seismic profiles show the Lachlan palaeovalley deflects considerably from its present course in places downstream of Cowra.

The Belubula Formation in the lower Belubula River has a maximum thickness of 24 m downstream of Canowindra (Williamson, 1986) and has been dated from pollen as Pleistocene (Martin, 1973); it is time equivalent of the upper part of the Cowra Formation (Williamson, 1986). Sediments associated with the sequence of sedimentation in the Cowra and Belubula Formations are still being deposited and eroded today.

Colluvial slope sediments are presently accumulating on wide low angle pediments, fans and rises adjacent to the Lachlan River near Cowra, along Nyrang Creek and its tributaries in the Belubula River catchment, and the upper Mandagery Creek catchment. Alluvial floodplain sediments have aggraded along the Lachlan River downstream of Wyangala Dam. The floodplain widens downstream of Challacombs Crossing with multiple terraces and meanders whose amplitude is less downstream of Cowra than upstream.

Deep Leads

A reappraisal of deep leads in the Parkes-Forbes area west of BATHURST by Wilson and McNally (1996) indicates narrow deep palaeovalleys containing chaotic deposits with floors lying at depths of 30-140 m below the present land surface. They note the similarity of incision and channel fill to that of the Lachlan Formation in the base of the Lachlan palaeovalley and suggest the sediments are part of the same Late Miocene to Pliocene depositional event. The valley floors of the deep leads are the proximal parts of an integrated incised valley system graded to the base of the Lachlan River palaeovalley.

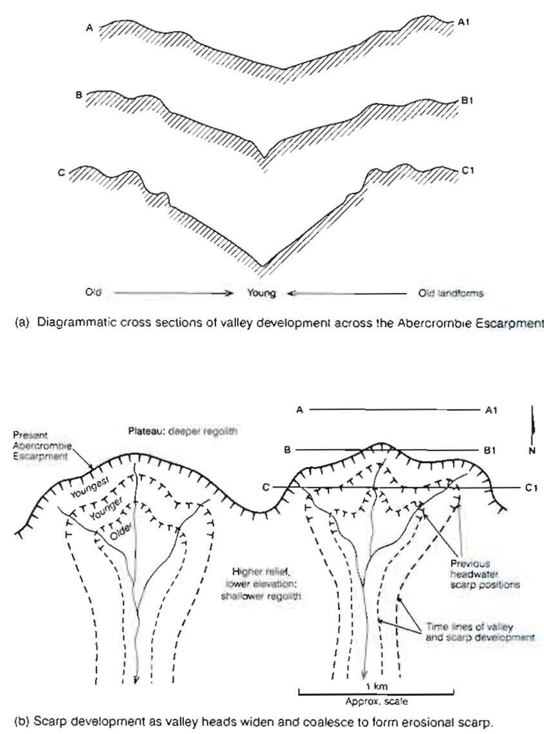
A wind gap in the Belubula-Mandagery drainage divide at the head of the south flowing Cargo Creek, a few kilometres to the west of Cargo, indicates a possible palaeodrainage line, which is substantiated by records of mining in the Cargo Goldfield from 1870. A summary description of the deep leads by J.E. Carne from shafts sunk in 1878 is reproduced in Andrews and Morrison (1915). Carne states that "two sets of deep leads, the upper one of which, with the black clays and fossil leaves, will be found resting in places in the older rounded quartz pebble drift" and occur at depths up to 120 m below the present surface at the headwaters of Cargo Creek. The northerly trending buried channel has steep, almost vertical sides with slope debris fan sediments. Also, a shaft immediately to the north of the wind gap in the Belubula-Mandagery drainage divide, is reported to still be in alluvium at 34 m depth. Thus the sediments cross and pre-date the Belubula-Mandagery divide and so may be as old as Mesozoic. Andrews and Morrison also report "river wash and gravels" on hills 90 m to 120 m above Cargo village.

DRAINAGE AS A CONTROL ON LANDFORM EVOLUTION

EROSION

The most active erosion in the area is via incision along the Belubula River, the upper Lachlan River and Mandagery Creek south of Canobolas Divide, and the headwaters of the Macquarie River, Turon River, Lewis Ponds Creek and Bell River to the north of Canobolas Divide. Headward erosion of the Belubula River into the highly weathered plateau to the east has been fast. The incision rate of the Belubula River below its nick point northwest of Junction Reefs is 15.4 m/My. Here the river is 200 m below a basalt-edged plateau where the 13 Ma precurser of the Belubula River flowed prior to the Canobolas eruption. The Macquarie River just downstream from its junction with the Turon River has incised over 210 m since sub-basaltic sediments were deposited 12 Ma ago, a rate of 18 m/My (Figures 6 and 7). These are some of the highest incision rates determined in the area. In contrast the incision rate of the Boree Creek on the Western Slopes near Toogong has only been a few metres in 12 Ma since lava flowed from Mt Canobolas, ie 0.4 m/My.

Valley widening in conjunction with headward erosion results in scarps (Figure 3) that are activity fronts separating more deeply and highly weathered bedrock plateaus above, from a less weathered and shallower weathered mantle, often with a transported component, below. Valley heads from headward erosion coalesce and form a scarp which then effectively retreats headwards. Scarp retreat occurs on both sides of the Great Divide and the Canobolas Divide, the Great Escarpment being to the east of the Great Divide (Ollier, 1982). Figure 12 is an example of valley development across the Abercrombie Escarpment north of Darbys Falls downstream from Wyangala Dam: the valley deepens from the stream outwards by slope retreat as it crosses the scarp and approaches the Lachlan River to the south. Valley widening along floodplains of the Lachlan and Belubula Rivers, mainly downstream from higher scarp dominated terrain, results in meanders of various amplitudes incising terraces. The progression from mainly alluvial terraces south of Bathurst to strath terraces north of Bathurst along the Macquarie River and its tributaries indicates progressive valley widening and deepening as the meanders of the Macquarie River entrench across bedrock lithology and structure towards a lower base level to the northwest.



(a) Diagrammatic cross sections of valley development across the Abercrombie Escarpment

(b) Scarp development as valley heads widen and coalesce to form erosional scarp.

Figure 12: *Example of valley development: Darbys Falls*

Drainage migration is apparent along the Macquarie River at Bathurst. Basalt remnants overlying alluvial sediments on Mt Panorama and adjacent hills, dated at 16-19 Ma (Wellman and McDougall, 1974), form a parallel arc to the southwest of the present Macquarie River which suggests a former course of the Macquarie River. To the northeast near Kelso, a parallel arc of highly weathered granite rises occurs above a southwest facing scarp. Swampy clay depressions and rounded quartz pebbles in red soil in this area indicate a remnant palaeoplain of the Macquarie River. The associated terrace deposits have since been eroded through towards the southwest as the Macquarie River migrated to its present course. Near Cowra, Back Creek has migrated to the northwest at its confluence with the Lachlan River due to build-up of sediment on the southern side of the Lachlan River.

Landsurface lowering from at least 3 successive waves of scarp retreat, and denudation from weathering and removal of regolith by overland water, gravity, wind and solution is moderated by the rate of lowering of the weathering front. The rate of landsurface lowering on moderately weathered plateaus based on elevations of 40 Ma lava remnants varies from 3.4 m/My at Big Brother, southeast of Blayney, to 1.2 m/My at Bald Hill near Hill End. As the rate of landsurface lowering outstrips the lowering of the weathering front, drainage is superimposed from the regolith mantle (insitu weathered bedrock or sediments) onto bedrock. A drainage line may keep its former pattern by entrenching itself and forming gorges across more resistant lithologies, or the drainage line may be deflected by bedrock structure and alter its course accordingly. As only the eroded core and minor ramparts remain of the volcanic pile associated with the 11 to 13 Ma Mt Canobolas shield volcano complex, significant stripping is inferred.

Aggradation

Lava and sediments have accumulated in a number of drainage lines. In the Oberon area multiple lava flows partially infilled certain valleys and drainage lines, some of which are now inverted in relief. Around Mt Canobolas, lavas infilled lower terrain to form a protective lava plain. Just west of BATHURST alluvial sediments conceal a lava flow in the lower Mandagery Creek (Williamson, 1986).

Sedimentation, interrupted by major erosion events, has buried the Lachlan palaeovalley and some major tributaries. Such tributaries are Back Creek south of Cowra, Bland Creek adjacent to Lake Cowal, the lower Belubula River, and the lower Mandagery Creek. Williamson (1986) reports that 73 m of sediments overlies 12 Ma basalt, which overlies a further 9 m of alluvium, on the lower Mandagery Creek west of BATHURST. The upstream limit of the buried palaeovalley is at Challacombs Crossing on the Lachlan River where broad floodplains over the palaeovalley narrow to an incised bedrock valley. Six kilometres upstream of Challacombs Crossing there has been 60 m of incision into bedrock since basalt erupted at 12 Ma (Wellman & McDougall, 1974) at Glenella. Between Challacombs Crossing and Cowra a series of terraces on Pliocene to Pleistocene palaeovalley sediments up to 40 m above the present Lachlan River floodplain indicate substantial incision in the Quaternary. Downstream of Cowra there has been less incision into the palaeovalley sediments. A similar situation occurs along the Mandagery Creek and its eastern tributary, Bourimbla Creek, where there is net incision upstream of Toogong and net accumulation downstream since eruption of basalt at 12 Ma from Canobolas Volcano (Gibson & Chan, 1998; Bishop & Brown, 1992).

Alluvial terraces also occur further east in BATHURST in erosional terrains. Narrower terraces occur along the Lachlan River upstream to at least Wyangala Dam, in places along the Belubula River, such as north of Mandurama just above a nick point, and along the Fish and Macquarie Rivers near Bathurst. Strath terraces occur on the eroded interfluves of the upper Fish River. Grossly oversized alluvial terraces and a wide floodplain along Windburndale Rivulet possibly indicate a former course of the Macquarie River.

Climate has influenced vegetation and runoff in southeastern Australia, which in turn has influenced aggradation. Climate trended from extremely wet and cool in Late Miocene to Pliocene to drier and warm in the Pleistocene, but the rainfall was always much higher than at present (Martin, 1991). Martin indicates that sea level falls change a coastal climate to a continental climate with lower precipitation. She considers the Early to Middle Oligocene low sea level to have had little impact on vegetation because fluctuations in a higher precipitation time were insufficient to become limiting and cause disruption to the vegetation. However, a global sea level fall of at least 180 m (Pigram et al, 1992), in the Late Miocene (6-11 Ma) (Haq et al., 1988), in the drier Miocene-Pliocene tipped the balance between rainforest and wet sclerophyll forest (Martin, 1991). The resulting combination of less water flowing down the rivers, and so less water power to transport sediments, and increased sediment available for transport due to decreased vegetation cover, gave rise to increased sedimentation in the rivers draining off the Eastern Highlands into the Murray Basin. The Miocene to Pliocene Lachlan Formation in the Lachlan palaeovalley correlates with the late Miocene sea level low and equivalent sediments have been identified in all of the major valleys of the Western Slopes of the Eastern Highlands in N.S.W. (Martin, 1991). The terraces along the Lachlan River may, in part, reflect further Quaternary climate changes.

LOCAL DRAINAGE MODIFIERS

Tertiary Volcanism

Lava flows from three volcanic provinces (Canobolas, 11-13 Ma; Abercrombie, 18-23 Ma; Airly; 41 Ma) (Wellman and McDougall, 1974), have preserved some earlier drainage lines and modified or obliterated others (Figure 3). Doming associated with the Mt Canobolas compound shield volcano (Wellman, 1986) followed by lava flows disrupted the palaeo-north to northeasterly and northwesterly trending drainage systems. Lava flows in close proximity to Mt Canobolas may indicate radial drainage due to the doming, (Figure 10). Multiple lava flows have coalesced to form lava plains (Figure 3) up to at least 150 m thick (Middlemost, 1981) to the southeast and west of Mt Canobolas which have completely obliterated prior drainage. The elongated east-west flows through Toogong, west of Mt Canobolas, indicate that an east-west palaeovalley was already in existence 11 to 13 Ma and had entrenched, and perhaps superimposed itself, across the fold complex further west. The Boree Creek - Bourimbia Creek - Warree Creek system now drains this lava plain flowing west into Mandagery Creek.

Many lava flows are now inverted in relief (Figure 3) due to the relative resistance of the lavas to weathering. Some flows are locally inverted but still within valleys as seen close to the Canobolas Divide in the Oberon area. Here, partly dissected multiple basalt flows partly fill 100 m deep valleys which are incised into a weathered plateau. Due to the damming of palaeostreams post-lava streams have incised their new courses on one side or both sides of the flows, the latter being termed 'twin lateral streams". Examples of twin lateral streams are Copperhania Creek and Grove Creek in the vicinity of the Abercrombie Caves, and Campbells River and Sewells Creek west of Oberon. Some streams cut across the inverted relief flows, such as Lewis Ponds Creek and Macquarie River in the vicinity of their confluence, and Bell River northeast of Molong.

Bedrock Lithology And Structure

There is strong lithological and structural control on drainage in some areas in BATHURST, especially associated with north-south trending bedrock lithologies east of Orange, southwest of Blayney, northeast of Cowra to south of Toogong, and in the Molong area. Less resistant lithologies weather more deeply and are more easily eroded, and so form valleys. Northwest trending drainage to the northwest of Toogong follows similarly trending lithologies in the nose of a fold complex. The Belubula River to the west of Carcoar and to the east of its nick point has some structural and lithological control on its meanders. To the northwest of Manildra, there appears to be some lineament control, eg Bocobra Creek. Fault delimited lithological units to the east of Orange and just north of the Canobolas Divide have valleys up to 2.5km wide with extremely underfit streams. This indicates that their headwaters probably were more extensive in the past than now and so these valleys probably were in existence before the Canobolas Divide. This is verified by rounded quartz gravels occurring immediately to the south of the Canobolas Divide (Fleming, 1992) in the headwaters of the Belubula River, and a wind gap on the Canobolas Divide between the Belubula River to the south and Lewis Ponds Creek to the north (Figure 4).

The Bathurst Granite and a few small intrusions of granite about 30 km north of Bathurst also show lithological control on drainage. Due to its low resistance to weathering, a large deep (300 to 500 m) erosion bowl has formed in the Bathurst Granite, and smaller shallower ones have formed further north. The 19 Ma basalt capping Mt Panorama is on strongly weathered granite, and is about 100 m below the scarp edging the Bathurst Granite and 180 m above the floor of the erosion bowl, indicating a rate of surface lowering of 9.5 m/My since the basalt flow due to the incision and migration of the Macquarie River. The resulting local low base level has increased the eroding power of the southerly tributaries of the Macquarie River, as evidenced by stripping and entrenchment in this area (Figure 3), and has deflected, or possibly captured this drainage (eg Fish and Campbells Rivers, and Queen Charlottes and Evans Plains Creeks) to the northwest (Figure 4). Accelerated headward erosion has resulted in scarp retreat towards the southwest, east of Blayney, which has resulted in the migration of the Canobolas Divide to the southwest and capture and reversal of northwesterly flowing boathook tributaries of the southwesterly flowing Belubula River, to southeasterly flowing boathook tributaries of the northeasterly flowing Evans Plains Creek (Figure 4).

A number of northwesterly trending lineaments traverse the mapping area and probably relate to the "Lachlan River Lineament" which Scheibner and Stevens (1974) define as a zone of linear features of a fossil fracture zone 40 to 50 km wide. A major west-northwest trending lineament defines the southern edge of the Bathurst Granite which when extrapolated to the west passes through Mt Canobolas, and aligns with the Lachlan River west of Condobolin. To the south a northwest trending lineament, which can be seen on airborne magnetic imagery, aligns with the Lachlan River through Cowra. To the north a west-northwest trending lineament aligns with the Turon River through Sofala.

Structural control of drainage is evident to the west of BATHURST in the Parkes area, both in deep leads and present drainage (I. Wilson, Uni. NSW, pers com 1996). A V-shaped low lying sediment dominated zone, narrowing to the south, between south of Parkes and West Wyalong seems to be bounded by faults which align with the east and west edges of the Coonamble Embayment of the Surat Basin. To the northwest of BATHURST the Macquarie Marshes are controlled by Pleistocene block faulting and a gentle tilt to the east has caused the Macquarie River to migrate to the east (Watkins & Meekin, 1996). It should be noted that even a small tectonic disruption on the flatter deeply weathered and depositional terrain to the west and northwest of the Bathurst region can have major impact on drainage as streams have long low gradient profiles. The same disruption in the higher relief erosional terrain of the Bathurst region would have relatively little affect on drainage as the higher energy higher gradient streams may well keep pace with the displacement and become antecedent streams. Having said this, no definite antecedent streams were found in the Bathurst region. However, many superimposed and entrenched streams, some with broadly dendritic patterns, are present. These imply the denudation of a higher palaeosurface with a relatively uniform weathered or sedimentary mantle onto bedrock with its localised structural and lithological control.

REGIONAL DRAINAGE MODIFIERS

TECTONICS

Convergent Margin

To the northeast of BATHURST west to southwest directed thrusting in the New England Orogen, which began in the Permian with maximum effect in the Early Triassic, caused subsidence due to foreland loading of the lithosphere so forming the Sydney and Gunnedah Basins (see eg Korsch & Totterdell, 1995) (Figure 1). Continued thrusting of the New England Orogen over the Sydney Basin along this convergent margin caused upwarping of the Lachlan Fold Belt due to the development of a peripheral forebulge (Figure 13a) which resulted in tilting and erosion of the Permian and Early Triassic sediments (Herbert, 1970), and formation of a northwest trending divide. The rapid denudation of this uplifted mass may be reflected in a sudden major cooling event in the northeast Lachlan Fold Belt during the Early Triassic (around 245 Ma) as predicted by apatite fission track analysis of data collected over the Bathurst area (O'Sullivan et al, 1996).

Northeast flowing drainage off this northwest trending divide eroded mainly upper Devonian quartzites of the northern Lachlan Fold Belt and deposited this sediment as the Middle Triassic Hawkesbury Sandstone which has a mean palaeocurrent direction of 34 degrees in this area (Conaghan, 1980). North-east aligned segments of present-day drainage along the upper Fish River and Duckmaloi River downstream from Beatties Hill south of Oberon and the Pipers Flat Creek south of Portland (Figure 10) may be incised traces of this Triassic palaeodrainage to the Sydney Basin. Energetic braided streams, as determined from sedimentological studies (Branagan et al, 1979), with strong unimodal current directions imply a moderately steep northeasterly palaeogradient (Standard, 1964).

Passive Margin

In contrast to the convergent margin tectonic regime, divergent or passive margin tectonics were initiated in the Late Cretaceous as a prelude to the rifting of Pacifica (ie. that part of Gondwana to the east of the present coast) from southeastern Australia. Crustal underplating with associated northeast trending doming (Lister and Etheridge, 1989) is interpreted to have occurred to the west of a zone of thinning of the crust between 100 and 80 Ma at the start of tectonic extension prior to the initiation of rifting along a northeast trending zone to the east of the present coastline of Australia (Raza et al, 1995; Korsch and Totterdell, 1996). Tilting perpendicular to this uplifted zone would have produced a palaeoslope to the northwest on the western side of this zone and initiation of northwest trending drainage. Apatite fission track data over the Bathurst area indicates a major cooling event about this time, i.e. around 95 Ma (O'Sullivan et al, 1995, 1996). The data indicate rapid denudation, decreasing in magnitude towards the northwest.

The proto-Great Divide is a tectonically induced divide initiated by the pre-rift doming. The present Great Divide separates coastal drainage from inland drainage along the east coast of Australia, and touches on the eastern edge of BATHURST (Figure 4). It has been modified by capture of headwater catchments, for example in the Kowmung River area west of Jenolan Caves, which caused the Great Divide to jump to the west. In most areas the Great Divide is well inland of the Great Escarpment (Ollier, 1982) with evidence of prior drainage crossing the divide, for example, Pipers Flat Creek and Jenolan River (Figure 9) are two reversed streams on the east of the Great Divide.

If Surat Basin sediments extended across the proto-Great Divide, (see below) signs of possible reversed drainage to the east of the divide would probably not survive to be superimposed onto the rocks below. However, a possible mechanism for the reversal and capture in evidence is differential downwarp, increasing to the east, and occurring after complete stripping of the Surat Basin sediments. This downwarp may have accompanied the initiation of rifting at about 65 Ma, and if so post-dates the initial upwarp associated with pre-rift doming. Alternatively, the proto Great Divide may have migrated westwards with possible westward movement of the dissipating heat source from underplating.

BASINS

Surat Basin

The Surat Basin unconformably overlies parts of the Permo-Triassic Bowen-Gunnedah-Sydney Basin system and the northern perimeter of the Lachlan Fold Belt. The Surat Basin contains a Middle Jurassic to Early Cretaceous transgressive sequence of fluvial and fluviolacustrine sediments through to marine muds. The Coonamble Embayment is the southern lobe of the Surat Basin onlapping the Lachlan Fold Belt. Pre-Surat Basin drainage would have been largely within strike controlled north trending valleys continuing northwards beneath the Surat Basin (Figure 13b) and then draining to the east via the Clarence-Morton Basin (Struckmeyer and Totterdell, 1992). Surat Basin sediments infilled and probably buried (Figure 13c) northerly trending strike controlled valleys, and extended across the Canobolas Divide to at least as far south as Molong in BATHURST and Gunningbland west of Parkes. Towards the close of Surat Basin sedimentation, drainage would have flowed as dendritic meandering or braided streams in a northerly direction across a low relief floodplain (Figure 13d).

It is feasible that Surat Basin sediments covered a much larger area of the Lachlan Fold Belt and have since been stripped away. Indeed, they may well have also covered the southwestern part of the New England Fold Belt, and parts of the Sydney Basin, as indicated by anomalously high vitrinite reflectance data in the Sydney Basin (Middleton, 1989; Branagan, 1983). Apatite fission track and vitrinite reflectance data indicate a much thicker sediment sequence in the Surat Basin than presently exists (Raza et al, 1999 in press). This sediment cover, along with a palaeoslope to the northwest resulting from doming associated with the onset of continental extension at 80-100 Ma, would give a mechanism for a shift in drainage direction via migration due to evulsion, and perhaps capture, from the north to the northwest. The upwarp from which this northwesterly palaeoslope is derived also gives a mechanism for increased incision to strip the Surat Basin sediments.

The 95 Ma apatite fission track date may indicate when much of the Surat Basin cover was stripped over BATHURST. The denudation rate must have been at least 50 m/My (ie. 1 km denudation between 100 and 80 Ma), over most of BATHURST, which is 3 times higher than the highest incision rate over BATHURST since 12 Ma. This extremely high denudation rate is unlikely unless there was a great thickness of unconsolidated sediment, for example, volcanically derived mudstone from an island arc to the east of Australia (Jones & Veevers, 1983). A large volume of Late Cretaceous sediments up to 4.5 km thick in a southwesterly prograding delta forms the Ceduna Terrace in the eastern Great Australian Bight (Fraser & Tilbury, 1979). These sediments may well include the Surat Basin sediments that were eroded off the highlands in the Lachlan Fold Belt and elsewhere.

Two major new northwest trending trunk streams, the proto-Macquarie and proto-Lachlan Rivers developed on this northwest palaeoslope, separated by the proto Canobolas Divide (Figure 13e). The Canobolas Divide thus predates the initiation of the Murray Basin. As these rivers eroded through the Surat Basin cover they superimposed their courses onto the bedrock below, for example, the Macquarie River meanders across bedrock trends northwest of Bathurst. Some major tributaries, for example, the proto-Turon River also superimposed their courses, but others preferentially exhumed and re-established their courses on the pre-Surat Basin topography in north trending strike controlled valleys. However, now the old north flowing streams are fragmented and in part reversed, as they are diverted into the northwest trending trunk streams.

This is reflected in some north trending segments of the Canobolas Divide which are exhumed pre-Surat Basin local divides.

Murray Basin

The Murray Basin to the west of the Lachlan Fold Belt was initiated at the beginning of the Tertiary by structural downwarping from very late thermal subsidence over an older reactivated rift basin (P. O'Brien, AGSO, pers com 1996). The sediment derived from erosion of the northwest palaeoslope would have probably been transported to the southern continental margin prior to inception of Murray Basin sedimentation. As the volume of clastic sediment in the Murray Basin requires only a small amount of stripping from its catchment (D. Gibson, CRC LEME / AGSO, pers com 1998), it is inferred that most stripping occurred during the Late Cretaceous, prior to Murray Basin sedimentation. The erosion of the Surat Basin sediments in Late Cretaceous is not due to changes in base levels associated with the Murray Basin, but to the northwest palaeoslope resulting from upwarp which preceeded continental breakup.

Fluctuations in base level in the Murray Basin and climate resulted in periods of accelerated erosion and valley infilling in the river systems draining to the Murray Basin. Isostatic readjustment (for example, Bishop and Brown, 1992) to the stripping off of the Surat Basin cover and subtle movements on basement faults in the Murray Basin may well have been factors contributing to the initiation of gorge formation on the northwesterly tilted slope (Figure 13f). Gorges up to at least 140m deep along the palaeo Lachlan River developed prior to the Eocene sedimentation in the Murray Basin which extended upstream to Hillston on the Lachlan River and Narranderra on the Murrumbidgee River (Martin, 1991). A climate change to one with lower precipitation due to a global sea level fall in the Late Miocene resulted in the deposition of the Lachlan Formation (Figure 13g), which occurs in the Lachlan palaeovalley from just upstream of Cowra, and passes laterally into other time equivalent Murray Basin units downstream of BATHURST (Brown and Stephenson, 1991). Erosion of the Lachlan Formation at the end of the Tertiary resulted in valley widening followed by deposition of the Pleistocene to Pliocene (Williamson, 1986) Cowra Formation (Figure 13h). However, sedimentation of the Lachlan valley west of the highlands seems to have more or less continued into the Holocene and still continues presently, but at a slower rate.

DRAINAGE HISTORY

The previous sections have presented relevant regolith, landform and bedrock geology features of the study area in the context of sediment deposition and erosion history. These ideas are drawn together in this section as a history of drainage development.

Mid Triassic (Figure 13a)

- Northeasterly drainage eroding Devonian quartzites on north Lachlan Fold Belt and depositing sediments as Hawkesbury Sandstone in the Sydney Basin.

Early Jurassic (Figure 13b)

- North to north-northeasterly trending and flowing drainage in strike controlled valleys within the Lachlan Fold Belt perhaps ultimately draining to the eastern seaboard via the Clarence-Morton Basin.

Late Jurassic to Early Cretaceous (Figure 13c)

- In-filling of structurally controlled valleys by fluvial sediments of mixed provenance transported from the south and deposited as Surat Basin sediments. Interbedded lacustrine sediments deposited.

Early Cretaceous (Figure 13d)

- Dendritic meandering or braided drainage flows to north across Surat Basin floodplains into a fluviolacustrine environment as a prelude to the inundation by Cretaceous seas from the Gulf of Carpentaria. Marine conditions may have then been established in BATHURST, but no record remains. Sea regresses northwards, leaving north-flowing drainage across a low gradient depositional plain.

Late Cretaceous (Figure 13e)

- Commencement of crustal thinning (between 100 and 80 Ma) to the east of the present coastline and associated doming across BATHURST as a prelude to rifting of south-east Australia from Pacifica. Proto Great Divide formed along axis of doming.
- Shift of northerly drainage across Surat Basin floodplains towards the northwest on western flank of upwarp.

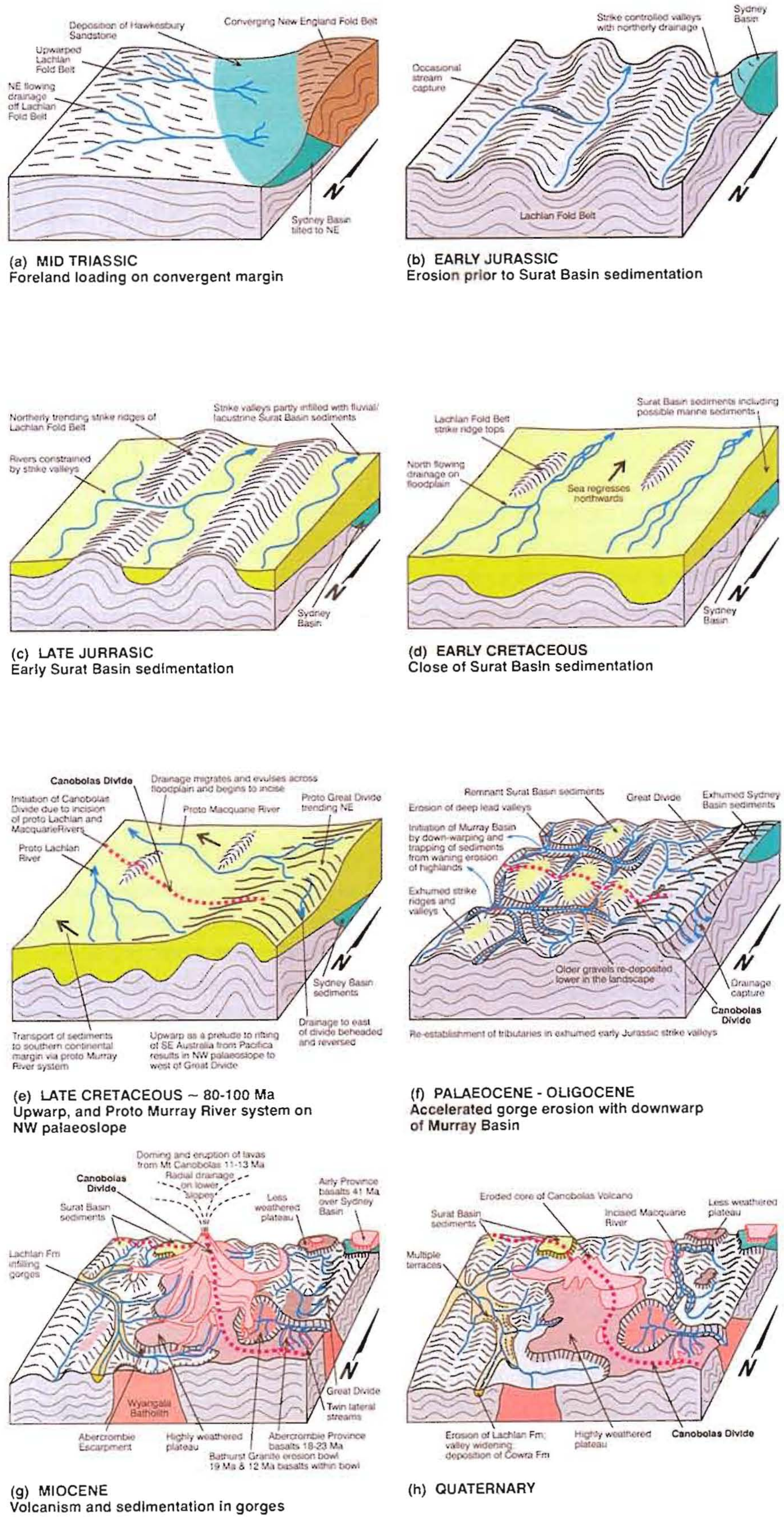


Figure 13: *Stages of Drainage Evolution in BATHURST*

- Initiation of incision of Surat Basin (around 95 Ma) by northwest flowing rivers, draining ultimately to the southern ocean and consequent development of erosional divides, eg Canobolas Divide, prior to initiation of the Murray Basin.
- Superimposition and entrenchment of drainage onto exhumed Jurassic topography, for example, Macquarie River. Some streams defeated by bedrock lithology and structure and consequently diverted. Scarp retreat by headward erosion via nick point retreat, and valley widening via slope retreat, on both sides of the proto Great Divide.
- Downwarp to the east results in westerly migration of the Great Divide and beheading, reversal and capture of drainage adjacent to the Great Divide. The Great Escarpment to the east of the divide forms as heads of valleys coalesce.
- Redistribution of older rounded quartz gravels from higher levels and possible deposition as Glen Logan Gravel and time equivalents; may be derived from stripping of Surat Basin cover.

Palaeocene (Figure 13f)

- Initiation of the Murray Basin by structural downwarping and trapping of sediments derived from waning erosion in highlands.
- Accelerated gorge erosion along rivers flowing to the Murray Basin from the new lower base level associated with the downwarped Murray Basin.

Eocene to Oligocene (Figure 13f)

- Continued erosion of Surat Basin cover and underlying bedrocks with major incision of the pre-Surat Basin palaeosurface along the Macquarie and Lachlan Rivers on both sides of Canobolas Divide. Narrow deep gorges erode back into the palaeosurface along low order tributaries, for example, deep lead valleys.
- Weathering of exhumed unconformity surface beneath Surat Basin sediments.
- Airly Province volcanism in Eocene (41 Ma).
- Initial deposition of palaeo Lachlan Valley sediments downstream in the Lachlan River as an extension of Murray Basin sedimentation.
- Initiation of relief inversion of lava flows.

Miocene (Figure 13g)

- Abercrombie Province volcanism in Early Miocene (18-23 Ma). Lava flows preserved drainage lines as inverted relief, and twin lateral streams formed.
- Erosion of the Bathurst Granite to form an erosion bowl and consequent rearrangement of drainage due to local drainage capture around its perimeter.
- Canobolas Province volcanism in Middle Miocene (11-13 Ma). Widespread lava flows and plains buried the pre-Miocene topography and rearranged drainage. Doming of Mt Canobolas induced radial drainage and consequent radial lava flows. Initiation of twin lateral streams.
- Lower rainfall induces increased sediment availability due to reduced vegetation cover as a result of a global sea level fall in the Late Miocene. Widespread increased deposition of sediments in the Lachlan palaeovalley in the Late Miocene as Lachlan Formation and time equivalent sediments in other palaeo valleys draining into the Murray Basin from the Eastern Highlands; high order tributaries, for example, deep lead valleys at Parkes and Forbes, also infilled.

Pliocene

- Continued deposition of Lachlan Formation and time equivalent sediments in palaeo valleys.
- Erosion of Lachlan Formation and valley widening associated with hiatus in sedimentation in eastern Murray Basin at the end of the Pliocene.
- Continued weathering and erosion, and deepening of Bathurst Granite erosion bowl.
- Relief inversion of lava flows continued.

Quaternary (Figure 13h)

- Deposition of Cowra and Belubula Formations in palaeo Lachlan and palaeo Belubula Valleys.
- Continued drainage superimposition or structural/lithological realignment, and entrenchment continue with denudation.
- Continued scarp retreat from both sides of the Canobolas and Great Divides. The present Lachlan River catchment basin is expanding northwards into the Macquarie River catchment basin but the Macquarie River catchment is expanding on the western rim of the Bathurst Granite.
- Formation of multiple terraces and meandering river on Lachlan Valley floodplain and establishment of present Lachlan River course.
- Migration of some drainage lines towards the southwest, for example, the Macquarie River at Bathurst as it erodes its old floodplain. Back Creek is diverted in its confluence with the Lachlan River due to sediment accumulation.
- Local tectonic movements in areas to the west of BATHURST.
- Continued weathering and denudation of plateaus, which mostly occur astride divides.
- Continued exhumation of pre-lava topography, especially immediately to the west of Mt Canobolas, and pre- and syn-Sydney Basin topography astride the Great Divide to the northeast of Bathurst.

MINERAL EXPLORATION IMPLICATIONS

Results from the Bathurst regolith-landform mapping have been fundamental in analysing the drainage evolution of this region and, in conjunction with results of more regional work (for example, Gibson and Chan, 1999), related studies (for example, Martin, 1991; Williamson, 1986) and historical mining records (for example, Andrews and Morrison, 1915), have elucidated a complex history of drainage evolution. In turn, drainage evolution is the key to understanding landform evolution and associated regolith evolution, in particular the processes involved, and their dimension, timing and sequence. This knowledge is highly relevant to land use, environmental issues and mineral exploration, all of which are pertinent to the Bathurst region.

Much of this area has a history from "gold rush" days of alluvial gold and gemstones, such as diamonds (for example, Sofala, Hill End, Oberon, Peak Hill, Dubbo, Forbes, Parkes, Young etc). In recent years there has been an upsurge in bedrock exploration for gold and copper and several major new mines have opened. The main mines and deposits are shown in Figure 2. By understanding the linkage between bedrock mineralisation, deep leads and placer deposits (Figure 14) a greatly expanded exploration potential is made available. Palaeodrainage lines may not only define mineral deposits directly associated with them, but they may also be vectors to bedrock mineralisation as they can give the provenance and geochemical signature of potential bedrock mineralisation.

Figure 14: *Relationships of placer gold deposits*

A number of Palaeozoic volcanic centres containing hydrothermal alteration have recently been discovered and are presently under investigation for their mineral potential. By distinguishing transported material associated with drainage lines from insitu regolith, geochemical and hydrogeochemical results can be interpreted more effectively. The influences of bedrock can then be better discerned from those of the regolith. Thus, the degree to which structure (for example, mineralisation associated with faults and lineaments), lithology and hydrothermal alteration (leading to mineral enrichment) interact with the regolith evolution to effect mineralisation can be qualified.

Apparently discrete and isolated sediment deposits may be related to each other within a palaeodrainage framework. Such palaeodrainage lines may be extrapolated under cover, whether lava flows or sediment For example, northerly trending structurally controlled drainage east of Orange is probably inherited from Early Jurassic times, and can be inferred under the Canobolas lava plains to link with present drainage lines within more weathered terrain to the south of the lava field (Figures 3, 10).

By incorporating an understanding of the processes of placer deposition (for example, riffles) with knowledge of physical attributes of potential trap sites (for example, terraces and constrictions due to competant lithologies) and the location of historical workings, prospective type areas for placer deposits may be delineated. In this context the Macquarie and Turon Rivers would be good to study in terms of alluvial gold. Since all of the obvious locations have already been worked through, this model could be extrapolated with more benefit under cover. Similarly, placer deposits of diamonds may be located by tying together a model for the source of diamonds with a model for the weathering and erosion history of these source areas (for example, Chan, 1998) and associated fluvial pathways and architecture. One such working model that accounts for the known location of diamond sources in southeastern Australia is active subduction of oceanic crust and associated sediments under the eastern margin of the Australian plate (Barron et al, 1994). These diamonds have been brought to the surface in the Oberon area with Cainozoic alkali basalts.

New deep leads of the style at Cargo on the tablelands may be discovered in otherwise unlikely places due to an understanding of the palaeodrainage. Buried deep leads may be discovered by tracing projected palaeodrainage under cover and verifying its existence by focussed studies, such as enhanced airborne magnetic imagery to trace maghemite/magnetite, seismic surveys, selected drilling for lithological logging, mineralogy, geochemistry (including partial extraction methods), transient electro magnetics and hydrogeochemical studies. Geochemical studies would also be beneficial to check for anomalies in exposed areas where the only trace of palaeodrainage is highly weathered inverted relief, for example, in the vicinity of the Abercrombie Caves south of Blayney, a sinuous ridge of highly weathered bedrock may have been covered by a lava flow but has since been removed.

This study provides a framework for extrapolating palaeodrainage further afield on the exposed Lachlan Fold Belt and under cover on and adjacent to the north Lachlan Fold Belt. Additionally, it may well provide a model for linking alluvial and deep lead deposits much further afield, such as linking historic alluvial and deep lead finds to possible palaeovalleys throughout the Lachlan Fold Belt and under the margins of the Surat and Murray Basins.

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