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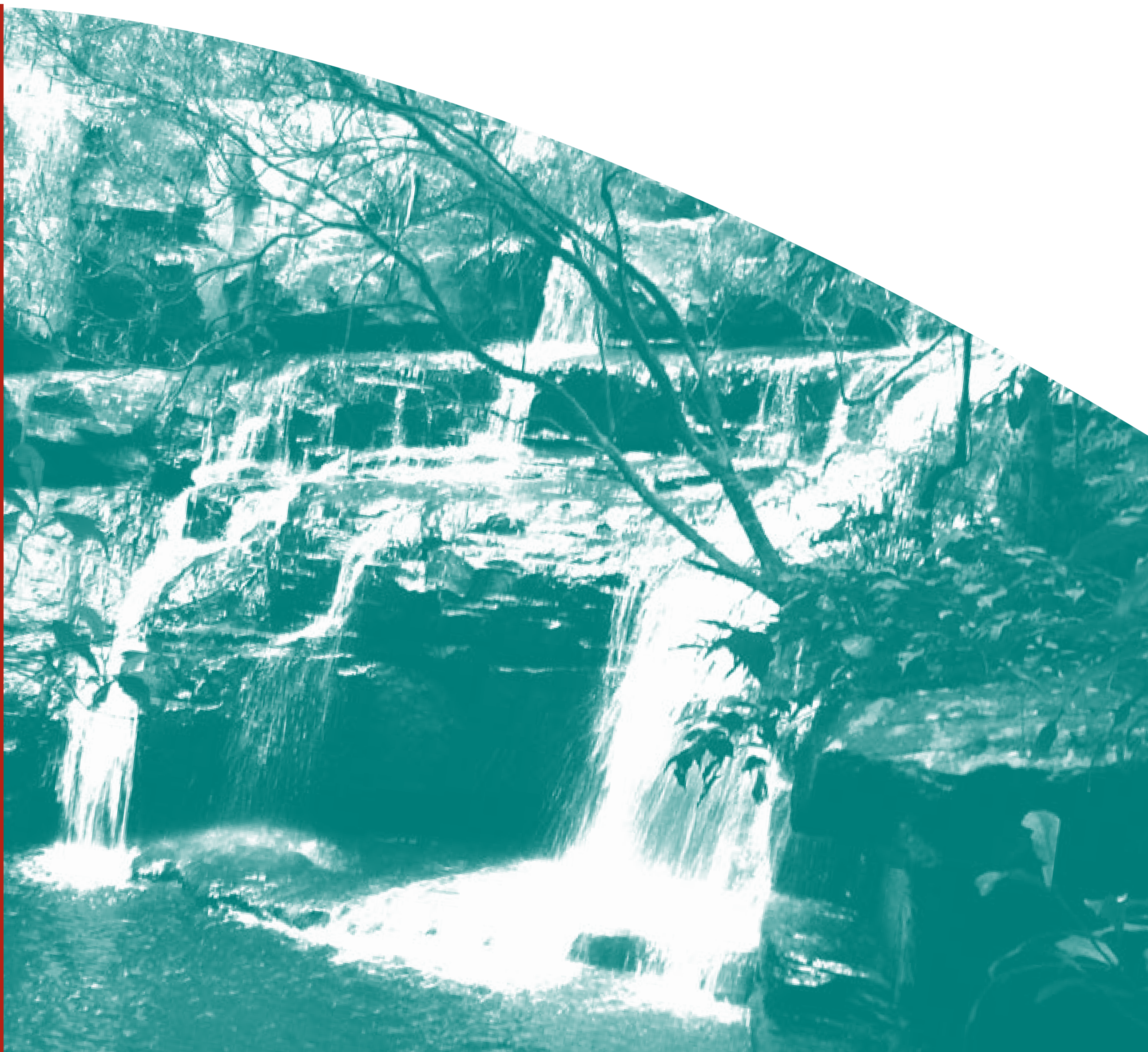

APPLYING GEOSCIENCE TO AUSTRALIA'S MOST IMPORTANT CHALLENGES

Drainage modification associated with the Northern Lapstone Structural Complex, New South Wales, Australia

GEOSCIENCE AUSTRALIA
RECORD 2009/06

by

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Introduction

Introduction and purpose

The Lapstone Structural Complex (LSC) comprises a series of major faults and monoclinal flexures that form the eastern margin of the Blue Mountains Plateau, an area of elevated topography west of the Sydney Basin (Branagan and Pedram, 1990). The LSC is located within the Southeast Australian highlands, one of the most seismically active areas of Australia (Quigley *et al*., in press). A large earthquake associated with deformation on the LSC could be devastating to the Sydney area. However, the evolution of the LSC, in particular the timing of its development, is not well understood. The aim of this study is to use stream profile analysis in order to better constrain the possible age of movement on structures associated with the LSC.

Background on Australian seismicity and the context of the LSC

The Australian continent is an intra-plate region characterised by low levels of seismicity. However, unusually high occurrences of historic earthquakes have been recorded compared to intraplate regions elsewhere (Sandiford, 2003). Several earthquakes have been large enough to cause visible surface ruptures (e.g., Gordon and Lewis, 1980, Crone *et al*., 1992, 1997). There is also evidence for Quaternary faulting in the form of surface scarps, although the record of such scarps remains far from complete (Clark and van Dissen, 2006).

Historic earthquake records and fault site investigations suggest that deformation within the Australian continent is clustered in both space and time (Clark and van Dissen, 2006). Prominent spatial clusters occur in the southeast of the continent in the Mt Lofty – Flinders Ranges and along the south-eastern margin of Australia (Fig. 1). The LSC is located towards the north of the latter region.

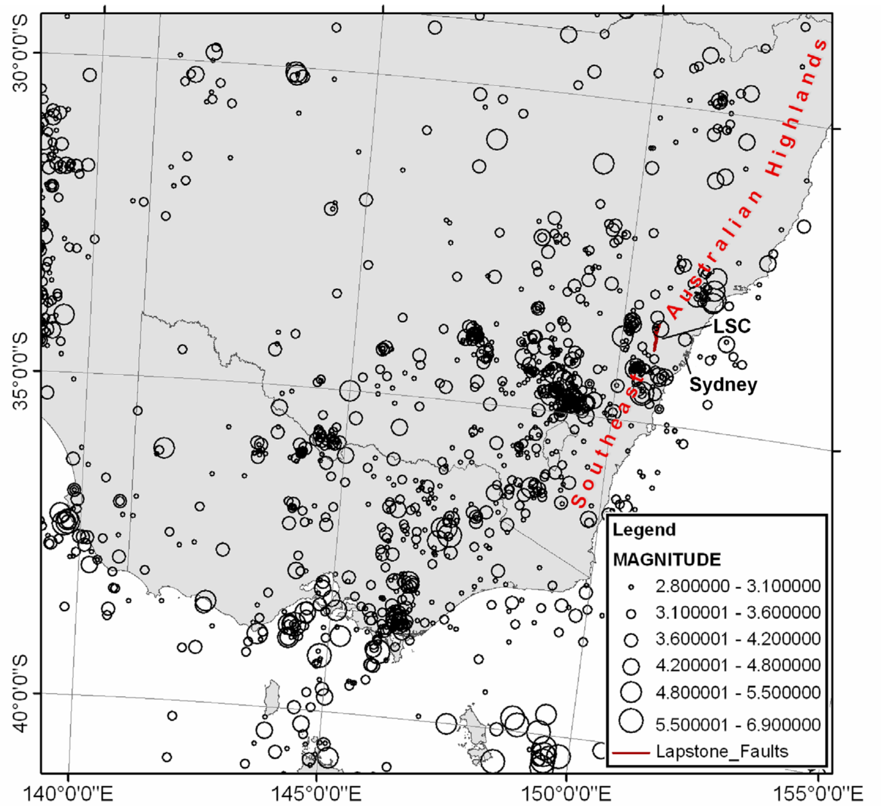


Figure 1: *Distribution of earthquakes of magnitude 2.8 or greater in the southeastern part of the Australian continent, showing important locations in this study: the Lapstone Structural Complex (LSC) and the Sydney CBD. Data sourced from Geoscience Australia QUAKES world earthquakes database on 16/09/2008 (https://www.ga.gov.au/products/servlet/controller?event=GEOCAT_DETAILS&catno=31425)*

The seismic risk associated with the LSC is poorly known. As is typical with Australian earthquakes, the recurrence rate of large events is low (of the order tens of thousands to millions of years; Clark and van Dissen, 2006), making the historic record of seismicity poorly suited to the assessment of long term seismic risk. Therefore, geological, paleoseismic, and geomorphic investigation is critical in defining earthquake hazard to underpin assessment of seismic risk associated with the LSC.

Geological setting

The Southeast Australian Highlands

Evolution and Landscape Development

The eastern margin of Australia is a high elevation passive margin formed during the break up of Gondwana at ~80 Ma (Ollier, 1982), and is characterised by high topography (500 – 1000 m above present sea level) in close proximity to the present coastline. The LSC is located near the centre of the Southeast Australian Highlands (Fig. 1). There are a large number of theories for the evolution of the Highlands, several of which are outlined here.

One model, first presented by Lambeck and Stephenson (1986), is that the Southeast Australian Highlands are an erosional remnant of a mountain belt that formed at ~250 Ma as part of the Kanimblan and Hunter-Bowen Orogenies. In this model, the present highlands have formed as a result of isostatic uplift in response to denudation of the original (much higher) topography.

Alternative models suggest that the Highlands were uplifted more recently. The occurrence of early Cretaceous sediments, deposited near sea level but now lying at the crest of the Highlands near the Queensland coast, suggests that uplift post-dates the early Cretaceous, at least in this northern part of the Highlands (Wellman, 1987). On the basis of their numerical modelling, van der Beek *et al*. (1995) argue that uplift continued into the Cenozoic, however there is a paucity of Cenozoic marker units with which to test this hypothesis (cf. Branagan and Pedram, 1990).

Ollier and Pain (1994) believe that southeast Australian landscape development occurred some time ago, extending to before the Miocene, and that while drainage disruption is widespread, it is also very old. They tested this hypothesis by comparing the volume of material lost from the Highlands along the New South Wales coast, from Newcastle in the north to Eden in the south, with the volume of sediment found in the accretionary wedge offshore. The calculated volumes were the same, which they interpreted as showing that no material had been introduced to the Highlands (i.e. no further uplift had occurred) during the period in which the streams were eroding. While Ollier and Pain (1994) do not present a mechanism for uplift of the Southeast Australian Highlands, they do suggest that rather than thinking in terms of uplift of the Southeast Australian Highlands, it may be more appropriate to consider their evolution in terms of downwarping of the basins that lie either side of the Highlands.

Denudation Rates

The Southeast Australian Highlands are believed to be characterised by generally low denudation rates and considerable stability since the Miocene (e.g. Young, 1983; Bishop, 1986; Young and McDougall, 1993). A compilation by Bishop and Goldrick (1999) from locations across the Southeast Australian Highlands showed stream incision rates, which the authors reasoned were approximately equivalent to plateau lowering rates, in the order of 1-10 m/Ma. A compilation of data restricted to the Blue Mountains Plateau gave rates of ~10-40 m/Ma (average: 21.5 m/Ma) (O'Sullivan *et al*., 1995; O'Sullivan *et a*l., 1996; Middleton and Schmidt, 1982; van der Beek *et al*., 2001; Tomkins *et al*., 2007). From these data, the highest calculated incision rate of 40 m/Ma was obtained for the Grose River; the elevated rate was attributed to knickpoint retreat following uplift on the LSC (van der Beek *et al*., 2001).

The Lapstone Structural Complex

Morphology

The LSC is located ~50 km west of Sydney, where it forms the western edge of the Cumberland Basin. It consists of an east-facing monocline and several associated faults. The topography associated with uplift of the LSC is highest (400m) in the north near Richmond, decreasing to the south (Branagan and Pedram, 1990; Fig. 2).

The eastern margin of the LSC is expressed variably as steeply dipping faults, fracture zones, and several monoclinal flexures (Branagan and Pedram, 1990). In the southernmost part of the LSC, the steeply dipping Nepean Fault is exposed. Interpretation of seismic reflection data suggests that this fault occurs within a fracture zone, the Nepean Fault system, located ~7 km to the east of a second fracture zone called the Oakdale Fault system (Branagan and Pedram, 1990, Herbert, 1989). Further north, the eastern margin of the LSC is expressed as 1-2 monoclinal flexures and occasional faults. Strata dips vary along the length of the monocline, from ~4-14° E near Kurrajong, to 89° E near the Mt Riverview Fault (Branagan and Pedram, 1990).

Bounding the LSC to the west is the Kurrajong Fault System (KFS), which consists of a series of approximately north striking *en echelon* reverse faults, downthrown to the west (Branagan and Pedram, 1990). The main faults in the KFS have been named (in order from north to south) the Kurrajong, Burralow, Grose, Fraser, Yellow Rock, and Glenbrook faults (Herbert, 1989). More recently the ~N striking Wheeny Gap Fault, downthrown to the east, was defined ~500 m east of the Kurrajong Fault at the northern end of the KFS (Clark and Rawson, in press). Faults of the KFS mimic the topography in that their offset decreases from north to south along the LSC from a maximum of 130 m on the Kurrajong Fault (David, 1902) to 70 m on the Glenbrook Fault toward the south (Branagan and Pedram, 1990). Many of these faults cut across streams, and potential evidence for damming or partial damming of the streams can be seen in the form of small or large swamps behind the faults (Crook, 1956; Henderson, 1975; Rawson, 1990).

Seismicity in proximity to the LSC is clustered to the west of the complex (Gibson, in press). The distribution is interpreted to result from a shallowly west-dipping reverse fault at depth which would project to the surface near the eastern side of the monocline. The KFS may converge with this fault at depth, which would imply that movement on the shallowly dipping fault is related to movement on the KFS (Clark and Rawson, in press).

Stratigraphy

The basic stratigraphy of the study area is shown in Fig. 2. The area is dominated by Permo–Triassic sedimentary rocks. These rocks are divided stratigraphically into the Narrabeen Group, the Hawkesbury Sandstone, the Mittagong Formation, and the Wianamatta Group (Jones and Clark, 1991).

Contained within the Narrabeen Group are the Banks Wall Sandstone and the Burralow Formation (David, 1889; Jones and Clark, 1991). These formations are Early Triassic in age, and outcrop along the lower gorge walls of the Grose River, Wheeny Creek, and Glenbrook Creek (Fig. 2).

The Banks Wall Sandstone was originally named by Goldbery (1972), and subsequently renamed by Bembrick and Holland (1972). It is a predominantly quartzose formation, but also contains abundant ironstone bands, occasional conglomerates and numerous claystone lenses several metres thick. It is friable, making it susceptible to erosion. Within the upper part of the Banks Wall Sandstone is the Wentworth Falls Claystone member, a red-brown to green claystone, which in the study area outcrops along the cliffs adjacent to the Grose River. The Wentworth Falls Claystone Member is overlain by the Burralow Formation, which in the study area is somewhat variable and contains mainly quartz sandstones, shales, and red-brown claystones (Crook, 1957).

Of the Wianamatta Group, the most extensive formation is the Ashfield Shale, which consists of a sequence of dark grey to black sideritic siltstone-claystone, grading up into a fine sandstone-siltstone (Jones and Clark, 1991). Also extensive is the Bringelly Shale, which consists predominantly of claystone and siltstone, and the quartz-lithic Minchinbury Sandstone (Herbert, 1989; Jones and Clark, 1991). Wianamatta Group rocks are not extensive over the northern LSC and are preserved only as erosional remnants; however they are more extensive at the southern end of the LSC, and to the east they are the predominant exposed formation (Fig. 2).

Post-Triassic rocks disconformably overlie the Triassic sequence. They include several Jurassic intrusions, Miocene basalts, and alluvial deposits that date to the Tertiary. The Jurassic rocks occur across the study area, but are more common within and to the west of the Lapstone Monocline (Jones and Clark, 1991). They are predominantly basaltic in composition, and consist of concordant intrusions, diatremes and dykes (Jones and Clark, 1991). Miocene basalts, dated at ~14-20 Ma, are located further west and are interpreted as flows (van der Beek *et al*., 2001). Alluvial deposits are most common to the east of the base of the Lapstone Monocline (Fig. 2). They include the Tertiary Rickaby's Creek Gravels, which are found both on and to the east of the Lapstone Monocline, and are considered to be a conglomerate derived from a braided stream environment (Nanson and Young, 1985).

Evolution

The timing and mode of evolution of the LSC is the subject of continuing debate. It is generally accepted that there is some basement influence on the complex (e.g., Branagan and Pedram, 1990; Pickett and Bishop, 1992). The sedimentary units of the Sydney Basin thicken to the east of the LSC, suggesting that it was active during their deposition in the Permo-Triassic (McElroy, 1965; Branagan and Pedram, 1990, Pickett and Bishop, 1992). Furthermore, numerical modelling of landscape evolution since 100 Ma carried out for the Sydney Basin area (van der Beek *et al*., 2001) suggests that the main physiographic features in the Sydney Basin could be reproduced only where uplift on the LSC was included subsequent to the main phase of rifting associated with opening of the Tasman Sea. The implication is that the LSC was not fully formed in the Permo–Triassic. This is supported by several lines of evidence.

The Blue Mountains Basalts were erupted onto a low relief (<200 m) surface west of the LSC, in contrast to the current relief of up to 750 m, suggesting significant relief building since ~20 Ma. This is consistent with uplift of the LSC during this period (van der Beek *et al*., 2001) or progressive erosional exhumation of a much larger feature (Pickett and Bishop, 1992). The 18.8 Ma Green Scrub Basalt (Wellman and McDougall, 1974) has been interpreted to have been cut by the Kurrajong Fault (Crook, 1956). The Tertiary Rickaby's Creek Gravels, interpreted as being deposited in an alluvial environment, overlie Hawkesbury Sandstone on the LSC, whereas they overlie Wianamatta Group Shale to the east, suggesting that they were deposited after significant exhumation (and presumably uplift) had occurred on the Lapstone Monocline. However, palaeomagnetic measurements of the Triassic Hawkesbury Sandstones exposed on the east-facing limb of the monocline suggest that significant rotation occurred prior to 8 Ma B.P. (Bishop *et al*., 1982; Pillans, 2003). Clark and Rawson (in press) suggest that if a low angle thrust fault underlying the monocline breached the surface at ~5-10 Ma, such that from this point on deformation on the monocline was dominated by stable sliding rather than flexure, then deformation may be ongoing. This assertion was also made by IGNS (1999).

Neotectonic Indicators: Stream morphology

Introduction

As discussed in the previous section, the timing of initiation and any subsequent movement along the LSC is not well constrained. Previous studies (e.g., van der Beek *et al.*, 2001; Pickett and Bishop, 1992) have highlighted the difficulties involved in constraining its temporal evolution. One way of potentially determining how recently the structure has been active is to examine the morphology of streams crossing the LSC to identify signs of the impact of recent tectonism.

The basis of identifying recent tectonism from longitudinal stream profiles is that streams in dynamic equilibrium, flowing across a uniform lithology, have an exponential 'concave up' longitudinal profile (Hack, 1973). Departures from this equilibrium profile can occur due to either a change in lithology or long profile

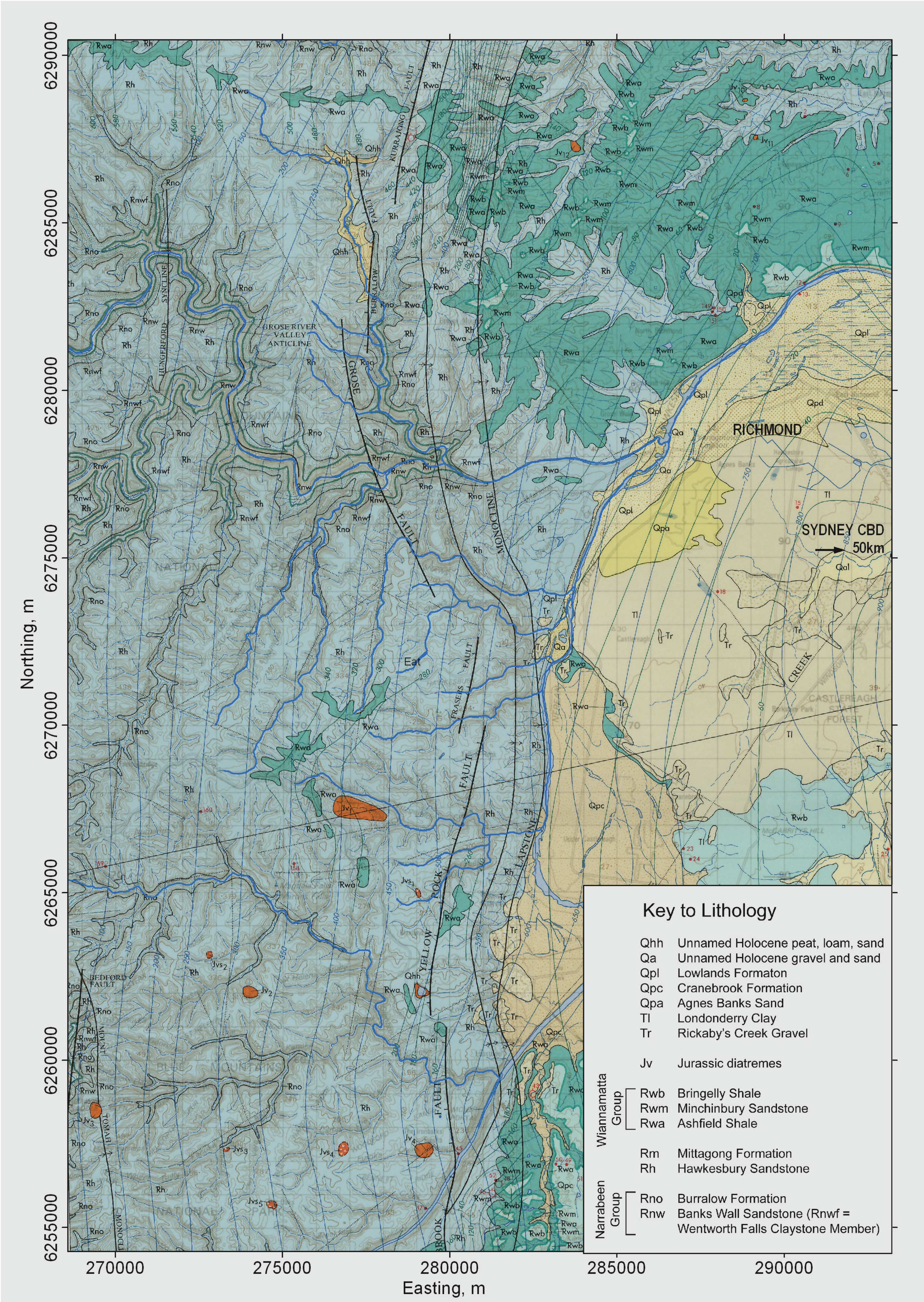


Figure 2: Geological map of the study area after Jones and Clark, 1991 showing the Kurrajong Fault System, which bounds the northern part of the LSC to the west.

disequilibrium as a result of, for example, surface deformation or base level fall (e.g., McKeown *et al*., 1988; Goldrick and Bishop, 1995). Therefore, if long profiles of streams crossing the LSC show a departure from the ideal longitudinal profile, and it is possible to discount lithology as a cause for this departure, then tectonic disequilibrium can be demonstrated. An implication of this would be that the age of last deformation on the LSC is less than the time it takes for a stream to re-equilibrate. If this time is known then it would provide an upper age limit for the most recent deformation event.

Previous work

Drainage analysis has been used previously in an attempt to constrain the age of recent movement on the LSC. In an earlier study, Rawson (1990) analysed the morphology of streams crossing faults of the KFS from the west. Longitudinal and cross-valley profiles were obtained from elevation data digitised from a 1:25 000 scale topographic map of the area. Of the streams analysed in the 1990 study, four (Fernhill, McLeod's, Morgan and Burralow) flow across lithological boundaries coincident with the faults, several (Glenbrook, Grose, Wheeny) flow across lithological boundaries not coincident with the faults, while the remainder flow across Hawkesbury Sandstone through their entire reach. Drainage modification not attributable to mapped changes in lithology (on the latter streams) was interpreted to be the result of tectonic disequilibrium.

Rawson (1990) plotted the longitudinal profiles on standard and semi-logarithmic axes, the latter because it has been shown that streams in dynamic equilibrium should have longitudinal profiles that plot as straight line segments on such plots, with breaks in slope occurring where there is disequilibrium or a change in lithology (Hack, 1973). Rawson (1990) also calculated slope-length (SL) indices (developed by Hack, 1973) for different segments of the profiles in an attempt to quantify any changes in slope. Rawson (1990) demonstrated that reaches downstream of the faults were consistently associated with significantly higher SL indices than those upstream, regardless of whether there was a mapped change in lithology at the fault.

Overall, Rawson (1990) noted several features from the longitudinal profiles. Most apparent was the marked similarity between all the profiles. Oversteepening at the fault was apparent in the longitudinal profiles of all but the two largest streams (Grose River and Wheeny Creek), regardless of whether a lithological change was mapped at the fault.

Rawson (1990) also analysed cross-valley profiles upstream and downstream of the faults. This analysis was based on work by Bull and McFadden (1977), who proposed an index of valley floor width to valley wall height (Vf ratio), to be used as an indication of active uplift. The index was based on the argument that in areas of uplift, vertical incision should outpace lateral erosion, and therefore streams should be deeper and narrower in such areas compared to those in stable areas. Rawson (1990) plotted cross profiles for each stream crossing the KFS, upstream and downstream of the fault, and calculated Vf for each cross profile. The analysis showed that for all of the small streams (i.e. all but the Grose River and Wheeny and Glenbrook Creeks), the valleys downstream of the faults were much more constricted than those upstream, and Vf was 6-128 times higher upstream of the fault than downstream.

The present study aims to build on the Rawson (1990) study by using improved analysis methods and higher resolution digital elevation data to assess whether disequilibrium steepening occurs in the stream long profiles, and where disequilibrium can be demonstrated, constrain the time it would take for equilibrium to be reached.

Longitudinal Stream Profiles

Data extraction and pre-processing

The longitudinal stream profiles of 18 streams crossing the LSC were extracted from 25 m resolution DEM data using Rivertools™ (RIVIX, LLC) (Fig. 3). These included 14 of the 16 streams analysed previously by Rawson (1990). All streams were plotted from their headwaters down to a base level typically defined by the Nepean River. Lithology and fault contacts were obtained from the 1:100 000 scale Penrith geology map (Jones and Clark, 1991), the 1:250 000 scale Sydney geology map (McElroy, 1962), and mapping in Wheeny Creek by Clark and Rawson (in press).

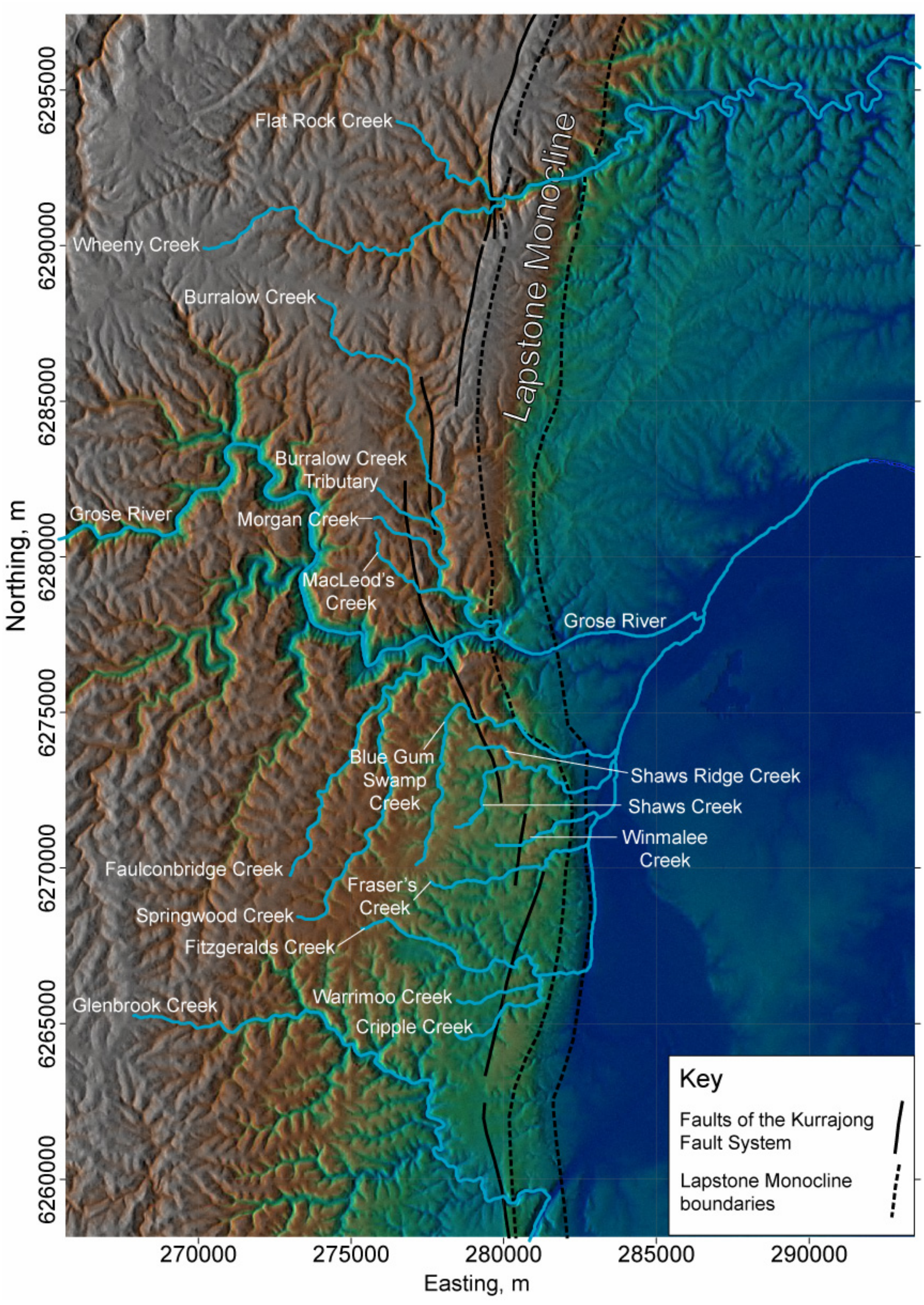


Figure 3: *Streams analysed in this study along with faults and monocline boundaries (after Herbert, 1979; Clark and Rawson, in prep) overlain on a Digital Elevation Model (DEM) of the area.*

Prior to investigation and analysis of the long profiles, several processing steps were applied in order to remove artefacts introduced through automatic extraction from the DEM data. First and foremost, processing was applied to remove spikes in the long profiles. Spikes may result from small inaccuracies in the horizontal locations of the streams picked out from the DEM, such that at some points stream elevations are picked on the sides rather than the bases of stream valleys. They were problematic in analysis as they introduced artificial uphill-flowing reaches, many of which were of sufficient magnitude that even a high degree of smoothing (resulting in loss of detail in the profiles) was ineffective in removing them.

In order to remove spikes, a formula was applied to the raw elevation-distance data prior to analysis. The formula used a test of the elevation of each point in the long profile for whether it was greater than or less than the previous point in the profile. Where the elevation was greater than that of the previous point it was set to the value of the previous point. The formula was applied iteratively to the entire long profile until all uphill reaches were removed, allowing the removal of spikes consisting of more than one data point. The resulting pool and riffle geometry is similar to that produced by similar algorithms in the Rivertools^{TM} software except that using this algorithm more detail is retained in the long profiles. From the spike-removed data, slopes were calculated at each point and smoothed using a 10 point running average. The longitudinal stream profiles (raw and processed) along with calculated (smoothed) slopes are presented in Figs. 4 a-r.

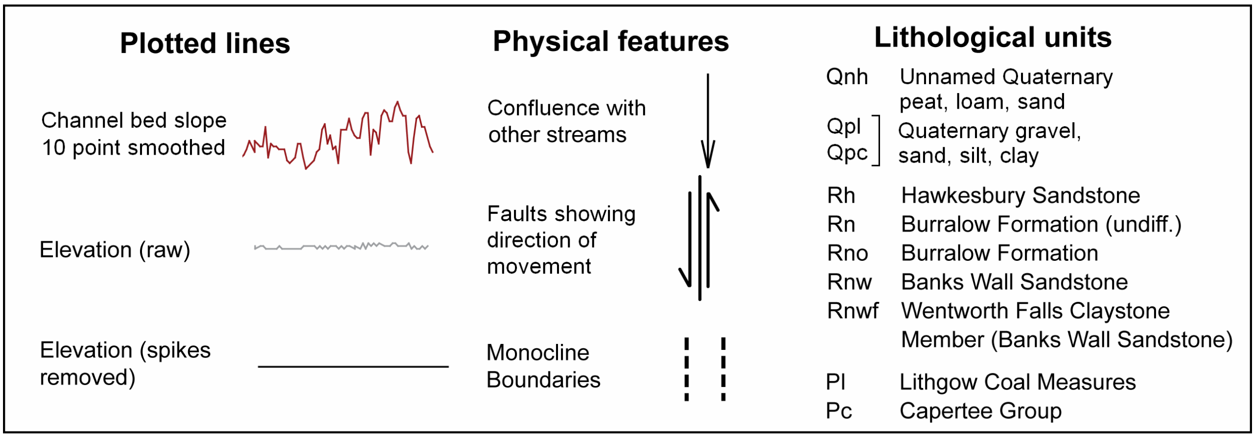


Figure 4: *Key to symbols on long profile plots*

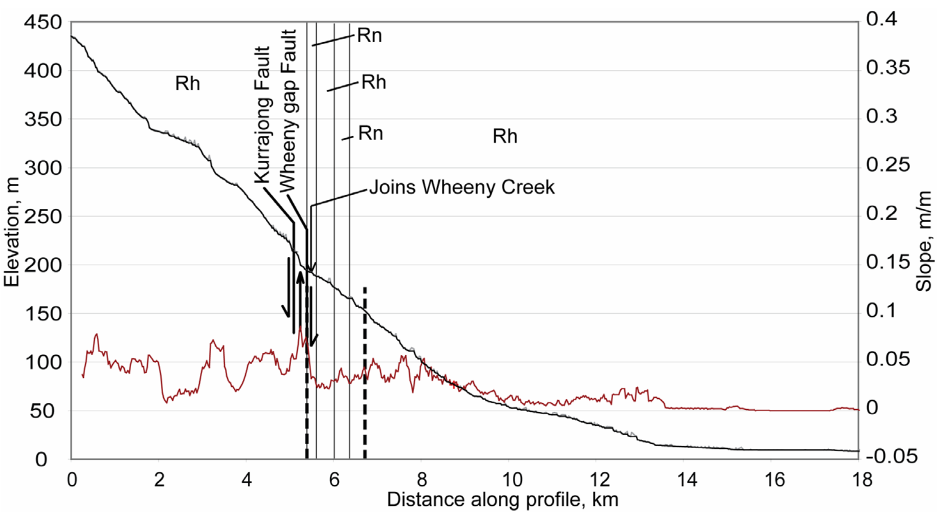


Figure 4a: *Longitudinal stream profile of Flat Rock Creek.*

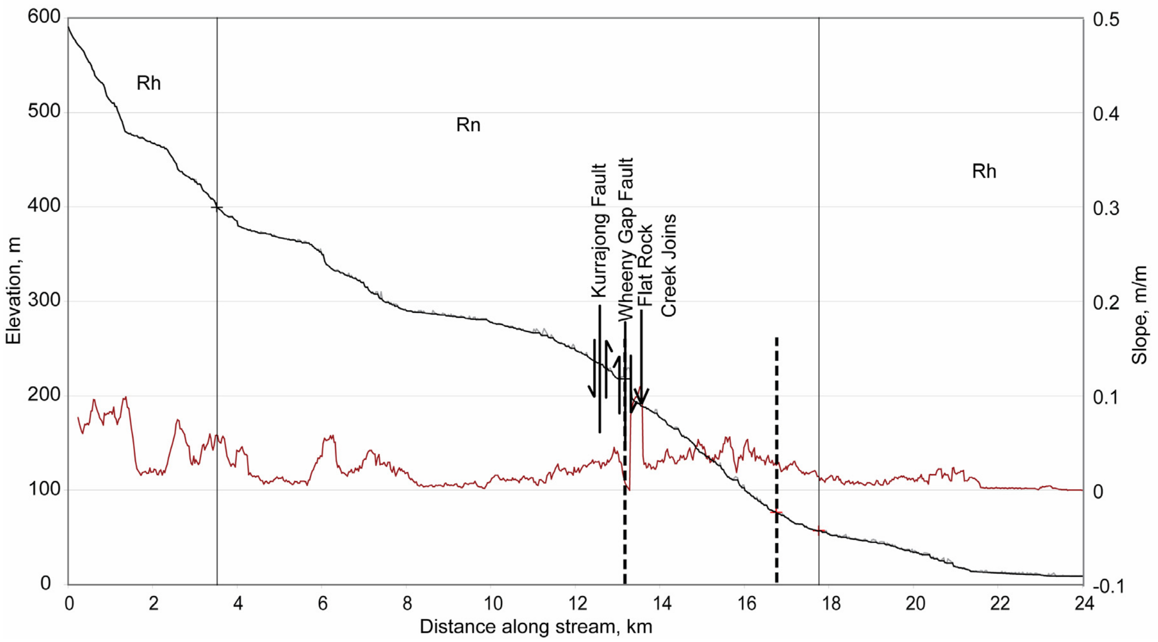


Figure 4b: *Longitudinal stream profile of Wheeny Creek.*

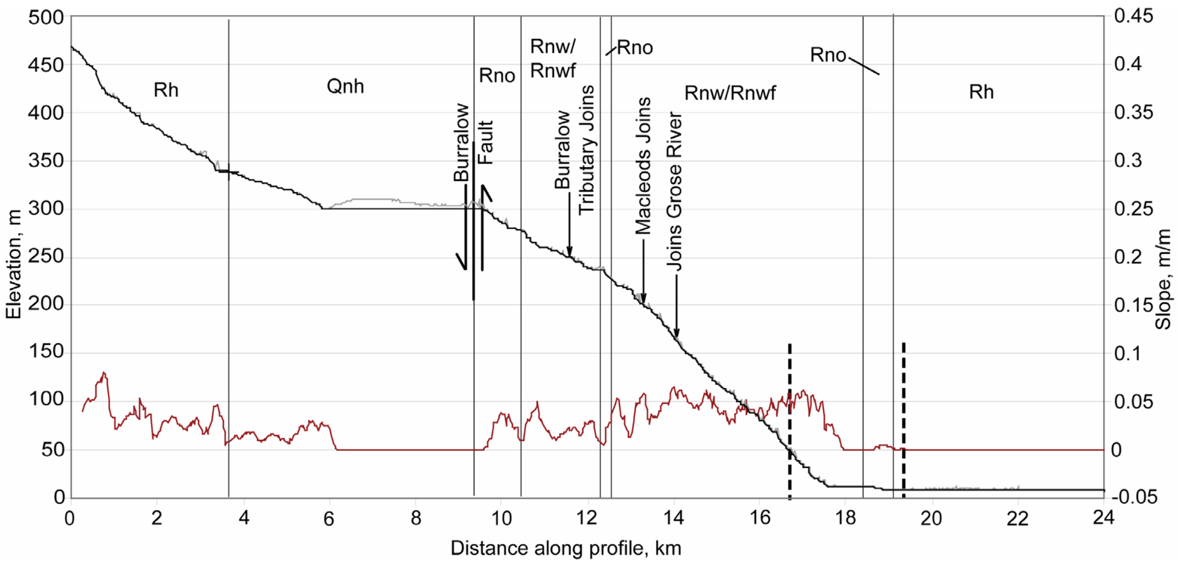


Figure 4c: *Longitudinal stream profile of Burralow Creek.*

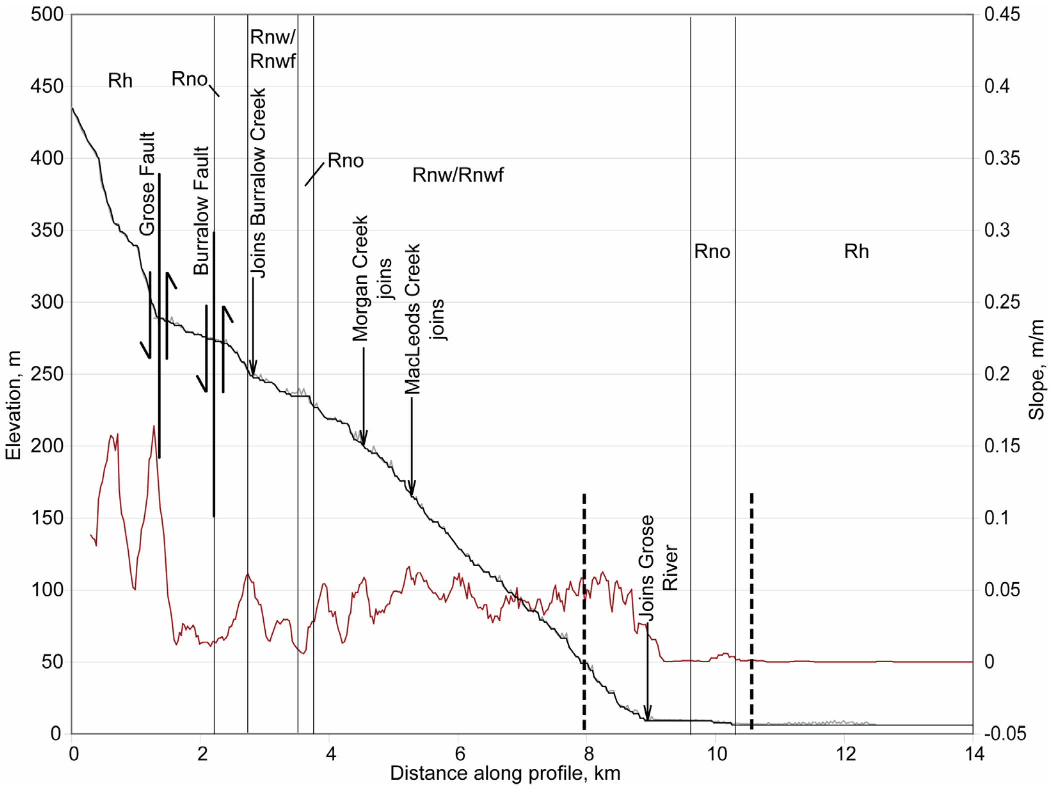


Figure 4d: *Longitudinal stream profile of Burralow Creek tributary*

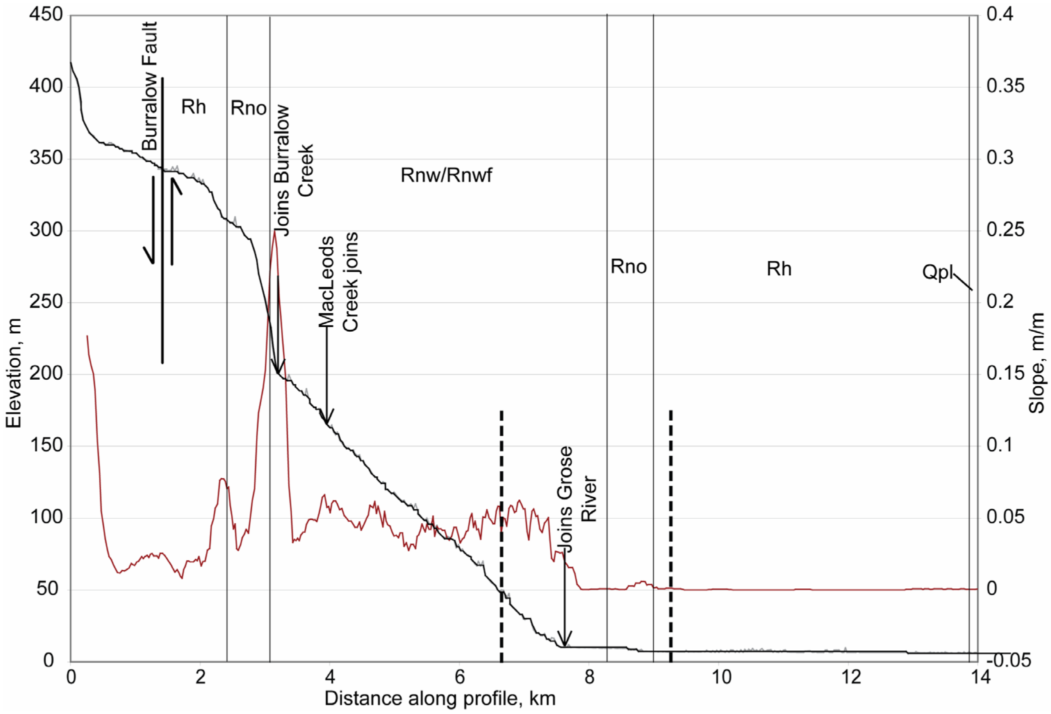


Figure 4e: *Longitudinal stream profile of Morgan Creek.*

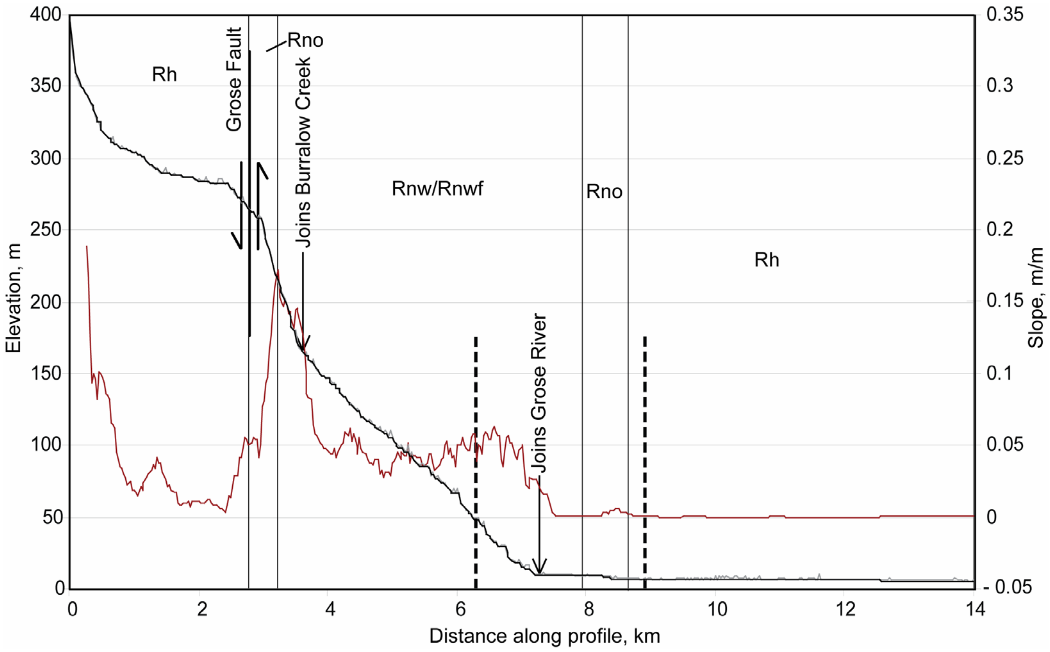
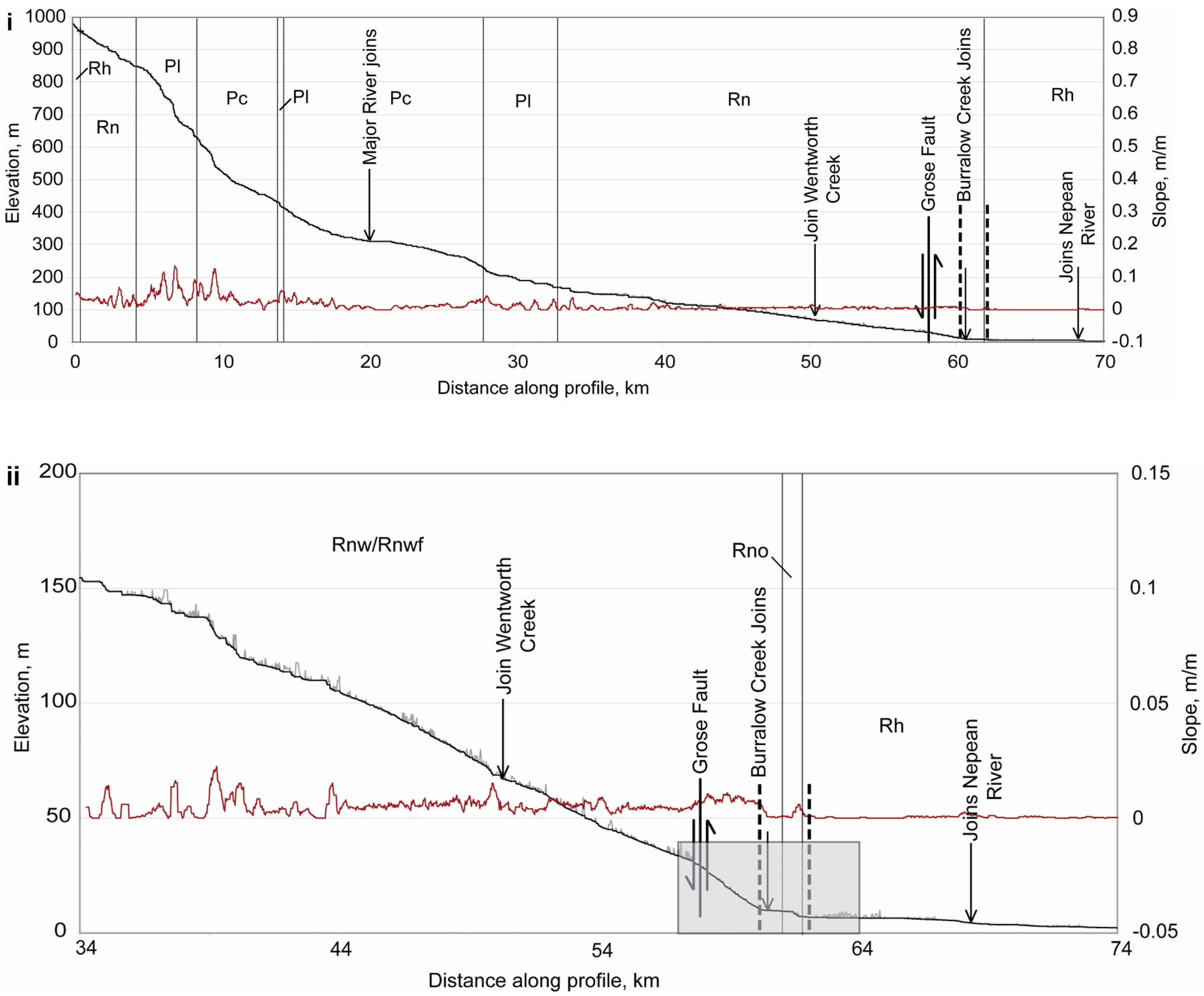


Figure 4f: *Longitudinal stream profile of McLeod's Creek.*



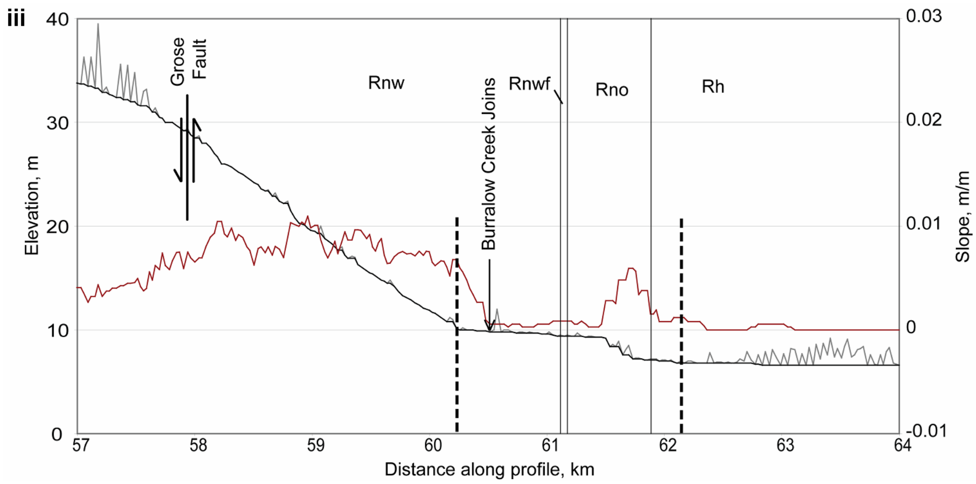


Figure 4g: *Longitudinal stream profile of the Grose River, i) the whole catchment, ii) the lower part of the catchment from 34km downstream of the headwaters, and iii) inset from shaded area in (ii).*

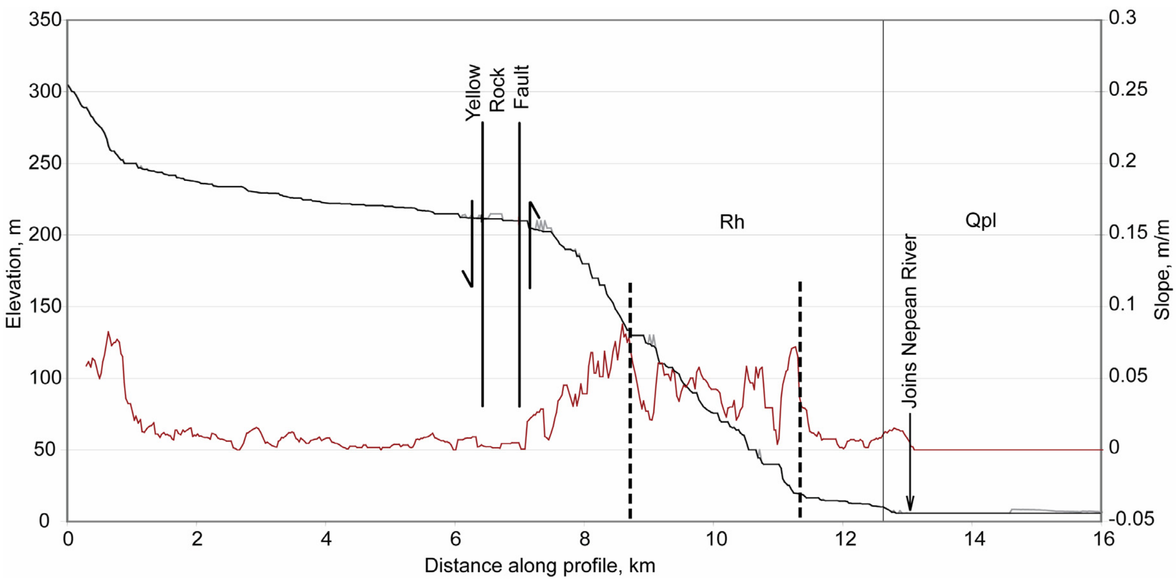


Figure 4h: *Longitudinal stream profile of Blue Gum Swamp Creek.*

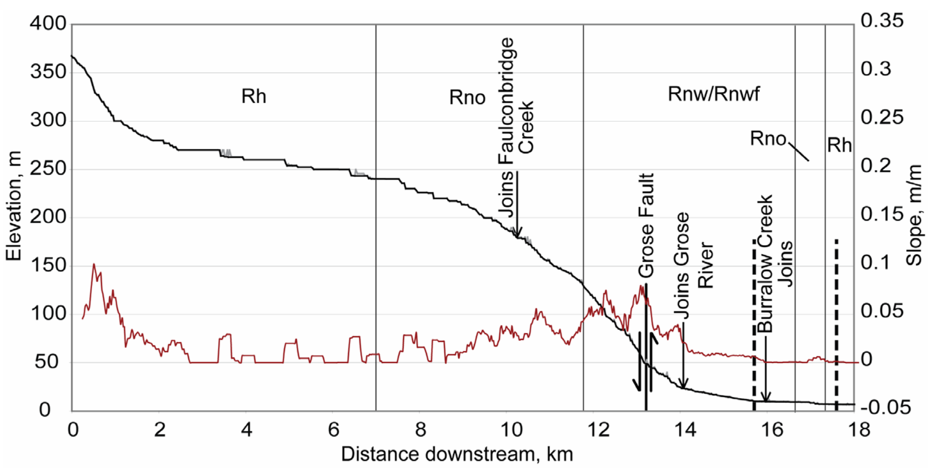


Figure 4i: *Longitudinal stream profile of Springwood Creek.*

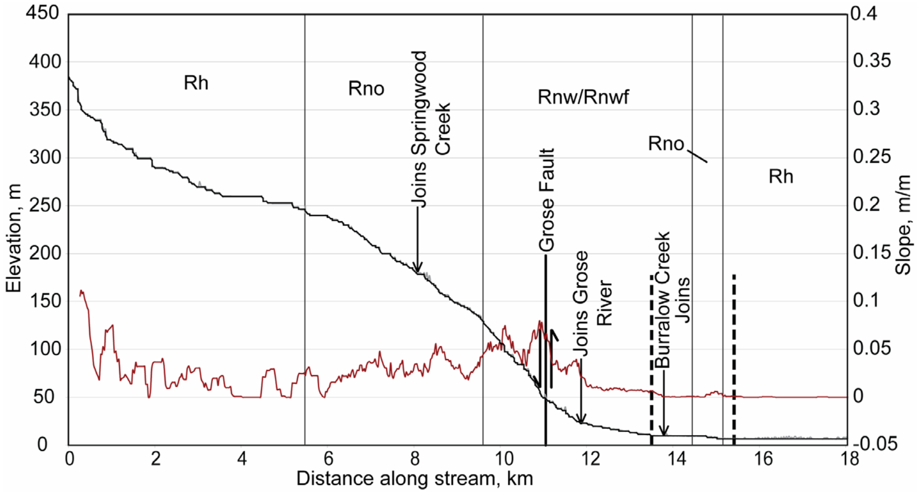


Figure 4j: Longitudinal stream profile of Faulconbridge Creek.

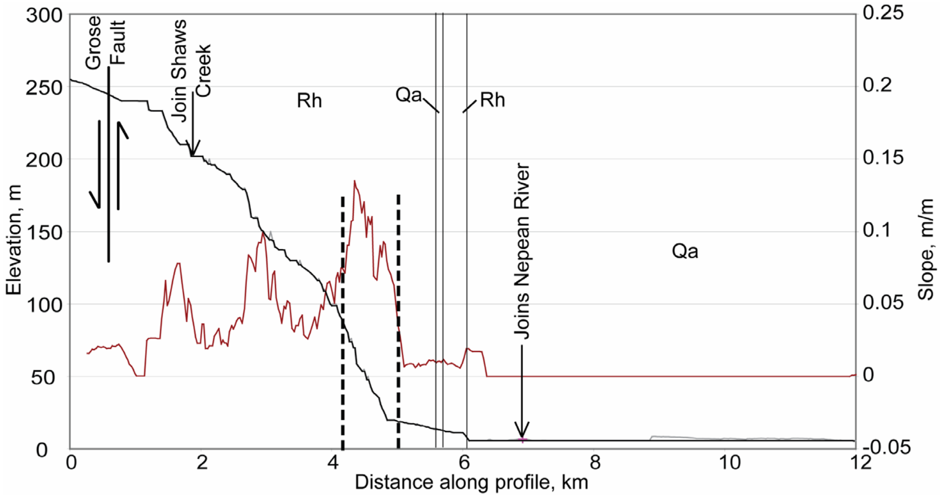


Figure 4k: Longitudinal stream profile of Shaws Ridge Creek.

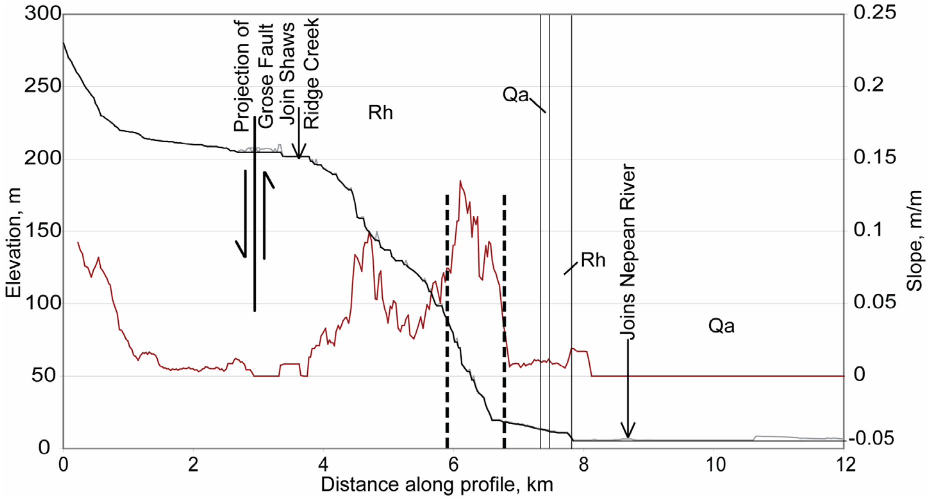


Figure 4l: Longitudinal stream profile of Shaws Creek.

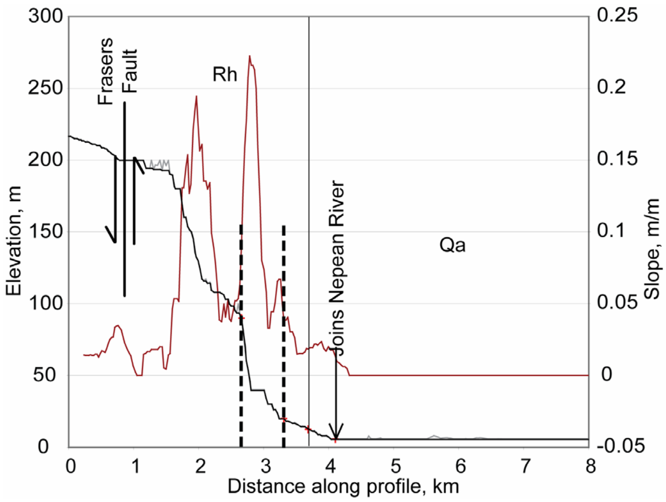


Figure 4m: *Longitudinal stream profile of Winmalee Creek.*

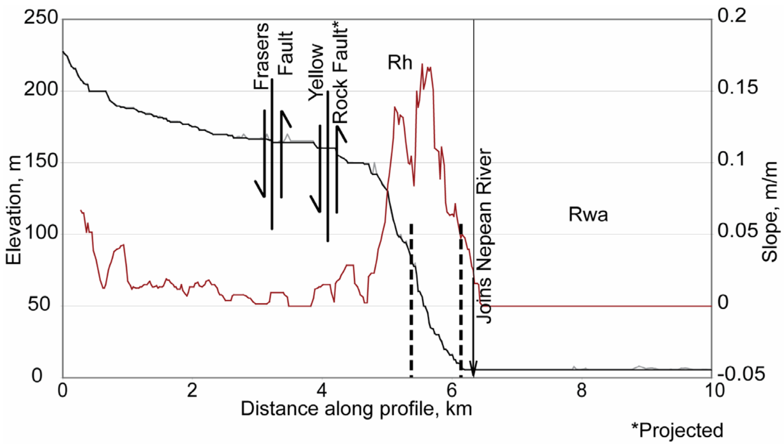


Figure 4n: *Longitudinal stream profile of Fraser's Creek*

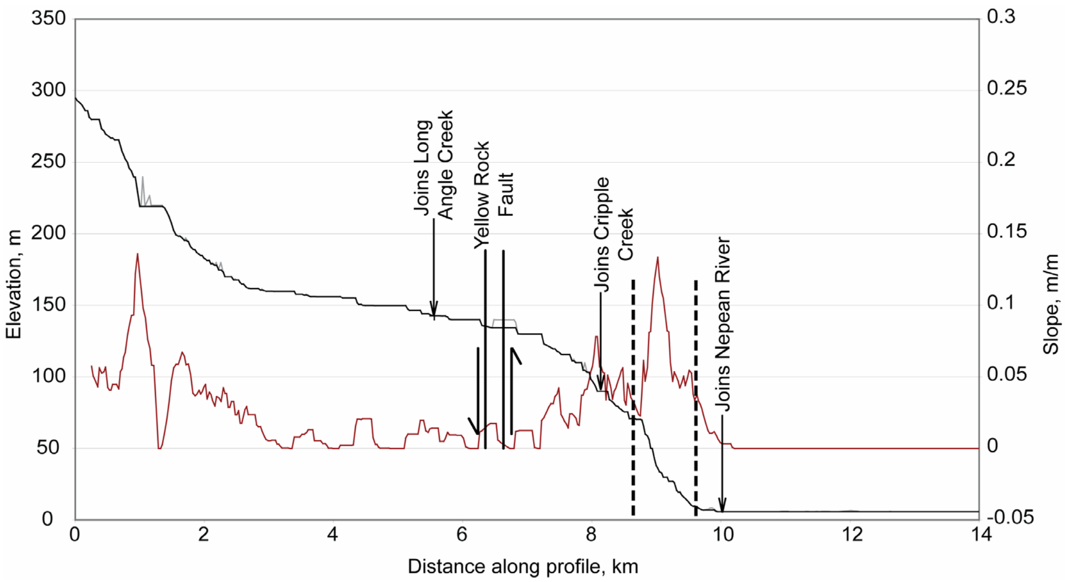


Figure 4o: *Longitudinal stream profile of Fitzgerald's Creek.*

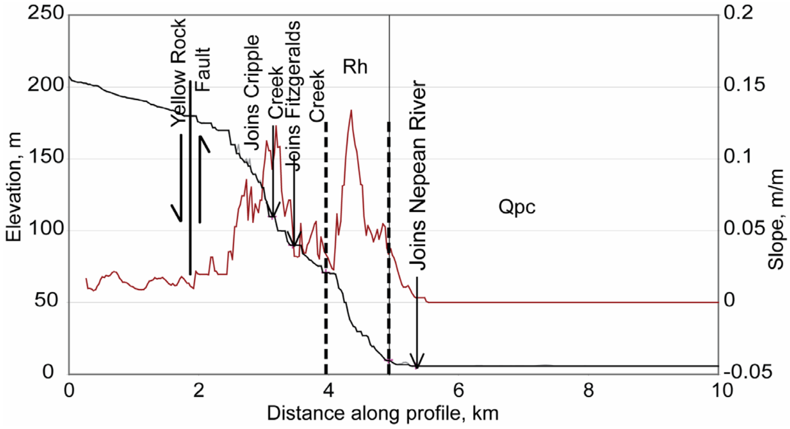


Figure 4p: *Longitudinal stream profile of Warrimoo Creek*

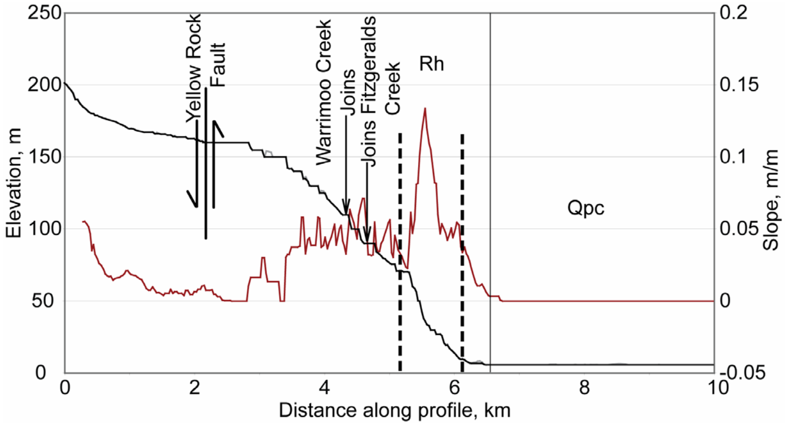


Figure 4q: *Longitudinal stream profile of Cripple Creek.*

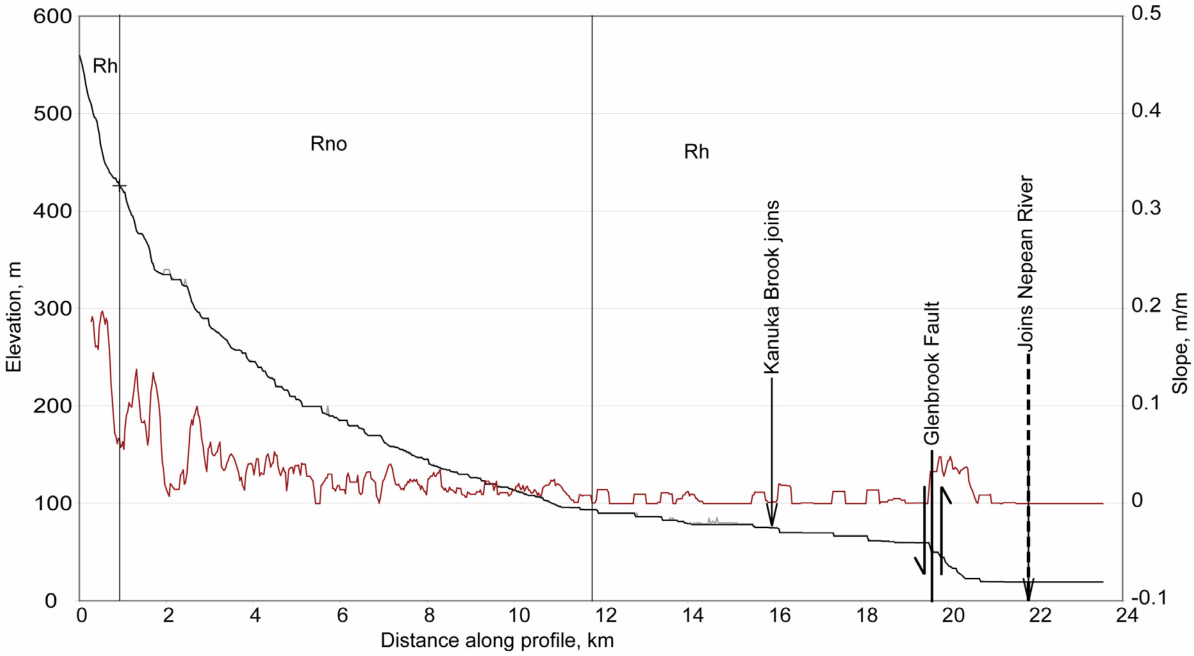


Figure 4r: *Longitudinal stream profile of Glenbrook Creek.*

Description of the long profiles

Figs. 4 a-r show that drainage modification is evident at the faults in all streams, including the larger drainages of Wheeny Creek and Grose River. At all but Springwood and Faulconbridge creeks, drainage modification is expressed as a marked oversteepening (an increase in slope by a factor of ~2-5) either at, or immediately downstream of, the faults. As noted by Rawson (1990), the oversteepening occurs regardless of whether a lithological change is mapped at the faults. The oversteepening (at the faults) is less marked in Wheeny Creek (Fig. 4b) and the Grose River (Fig. 4g), suggesting that knickpoints in these streams have been eroded more than in others, presumably as a result of their greater catchment area and consequent higher stream power.

The Grose River extends ~35km west of the main study area where two Permian units are exposed: the Lithgow Coal Measures, consisting of shale, sandstone, conglomerate and chert with coal and torbanite seams; and the Capertee Group, a marine sequence consisting of shale, conglomerate and sandstone. Fig. 4gi shows 6 knickpoints occurring between ~4 and 27 km downstream of the Grose River headwaters, within the Permian units. These knickpoints appear more pronounced than those within the Narrabeen Group rocks. They could result from either (or both) variations in lithology between or within units, since several of the oversteepening points are within 1km of a mapped lithological boundary, and in any case the Permian units described above have multiple lithologies within them, or retreating knickpoints as a result of faulting at the KFS. Knickpoints could be expected to become more pronounced as relief increases in the upper catchment.

The total offset between the top of the knickpoints in the streams and base level varies from north to south. Offsets are highest (~350 m) in the northernmost streams (e.g., Burralow Creek), decreasing to ~50 m in the southernmost analysed stream, Glenbrook Creek. The variation in offset is consistent with the topographic expression of the monocline, which decreases toward the south. It is also consistent with the degree of displacement on the faults.

The oversteepening evident in the long profiles has been confirmed by field observations at several locations. The reaches downstream from the faults in the Grose River and Wheeny Creek are characterised by several cascades and loose boulders. The Grose River flows through Banks Wall Sandstone from >20km upstream to 3km downstream of the Grose Fault (Fig. 4g). It is therefore unlikely that oversteepening observable in both the Grose River long profile and in the field is caused by a lithological variation. Formations within the Narrabeen Group are not differentiated in Wheeny Creek. However, similar to the Grose River, oversteepening occurs entirely within Narrabeen Group rocks.

In the smaller streams (field checked streams include Burralow, Blue Gum Swamp and Warrimoo creeks) sediment and boulders occur upstream of the faults coinciding with a relatively gentle channel bed slope. The sediment accumulation can be attributed to landslide/block fall material from the steep valley walls surrounding the streams together with (probably to a lesser extent) material eroded from the stream beds. Downstream of the faults, there are less boulders and stream sediments and bedrock is exposed in places, suggesting that in these reaches stream power is sufficient to remove the blocks and transport them downstream.

At Springwood and Faulconbridge creeks (Figs. 4i and j respectively), both of which are major tributaries of the Grose River, there is a decrease in long profile slope at the faults. Both creeks show broadly smooth concave downward profiles downstream of the furthest upstream Hawkesbury Sandstone/Narrabeen Group geological boundary. This changes to concave upward profiles ~500 m upstream of the Grose Fault (Figs. 4i & j). The profile form in these streams is unusual compared to other streams crossing the LSC. The concave downward profile may be a result of lithological change from Hawkesbury Sandstone to the Burralow Formation of the Narrabeen Group. However, other streams such as Burralow Creek (Fig. 4c), Morgan Creek (Fig. 4e), Macleod's Creek (Fig. 4f), and Glenbrook Creek (Fig. 4r), that also flow through Burralow Formation, do not show a similar profile form and therefore this explanation would require that there is lithological variation within the Narrabeen Group (specifically in its resistance to erosion) in the study area. Alternatively, there may be as yet unmapped structures (faults or folds) across these streams, upstream of the Grose Fault, that relate to the unusual profile shape.

In the following sections, two analyses are carried out on the long profiles with the aim of distinguishing between the effects of lithology and tectonism on the longitudinal profiles.

The DS form of the longitudinal profile

Background

The Hack (1973) formulation for the equilibrium long profile is an empirical formula:

$$S = 25\, M^{0.6}\, L^{-1} \qquad (1)$$

where S = stream gradient, *M* = mean particle size (mm) and *L* = distance downstream. Based on this formulation, and assuming *M* is constant, this gives

$$H = k \ln L + c \qquad (2)$$

where *H* is elevation and *k* and *c* are constants.

Goldrick and Bishop (2007) develop a more generalised form of this equation, derived from stream erosion laws:

$$S = kL^{-\lambda} \qquad (3)$$

where *k* is a constant dependent on stream power and lithology, and λ is a constant influenced by drainage geometry and climate. An important implication of this formulation is that a plot of ln (*L*) versus ln (*S*), that is, a distance–slope (DS) plot, should, for a stream in equilibrium, produce a straight line with slope λ and intercept *k* (Fig. 5; Goldrick and Bishop, 2007). Changes in lithology should produce parallel shifts in the data, while disequilibrium reaches should plot as disordered outliers (Fig. 5). Therefore, based on a DS plot, it should be possible to distinguish between equilibrium and disequilibrium steepening.

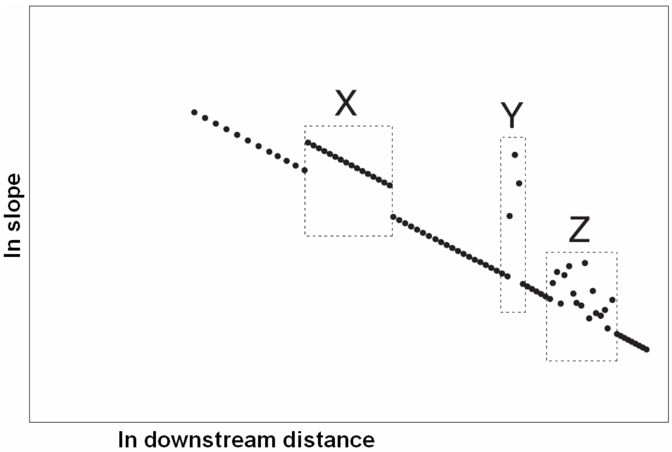


Figure 5: *A DS plot of a hypothetical stream showing a change in lithology at X, a knickpoint at Y, and a broad zone of lithological steepening (a knickzone) at Z. After Goldrick and Bishop (2007).*

From the distance–slope relationship (Eqn. 3), the corresponding formulation for *H* is:

$$H = H_0 - k\frac{L^{-\lambda}}{1-\lambda} \qquad (4)$$

where H_0 is the theoretical elevation at the head of the drainage. This formulation can be used to calculate the form of an ideal stream profile using λ and *k* calculated from equilibrium reaches on the DS plot. Goldrick and Bishop (2007) tested this long profile formulation on streams draining the Lachlan Valley in southeast

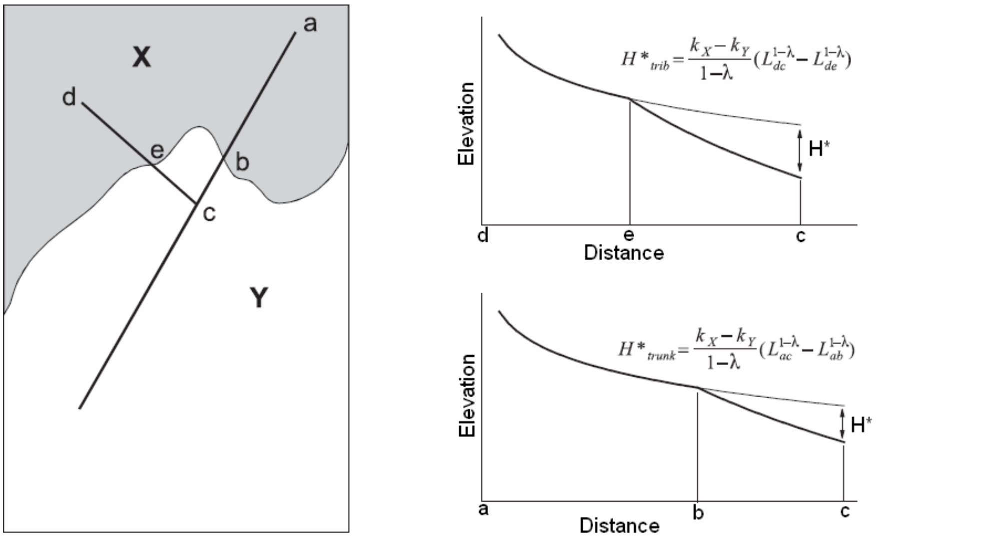


Figure 6: *Hypothetical trunk stream and tributary, each of which flows across a lithological boundary upstream of their confluence. The trunk stream rises at a on lithology X and flows across the boundary between lithologies X and Y at b before joining the tributary at c. The tributary rises at d on lithology X and flows across the boundary between X and Y at e. After Goldrick and Bishop (2007).*

Australia, and showed that their new formulation better described the longitudinal profiles than the Hack (1973) formulation.

Goldrick and Bishop (2007) also developed a calculation intended to distinguish between equilibrium and disequilibrium steepening. The formulation is designed to be applied to two streams where oversteepening, coincident with a change in lithology, occurs upstream of their confluence (Fig. 6). The formulation claims to be able to distinguish whether the oversteepening is a result of the change in lithology, or the result of knickpoint retreat from a disturbance downstream of the confluence between the two streams.

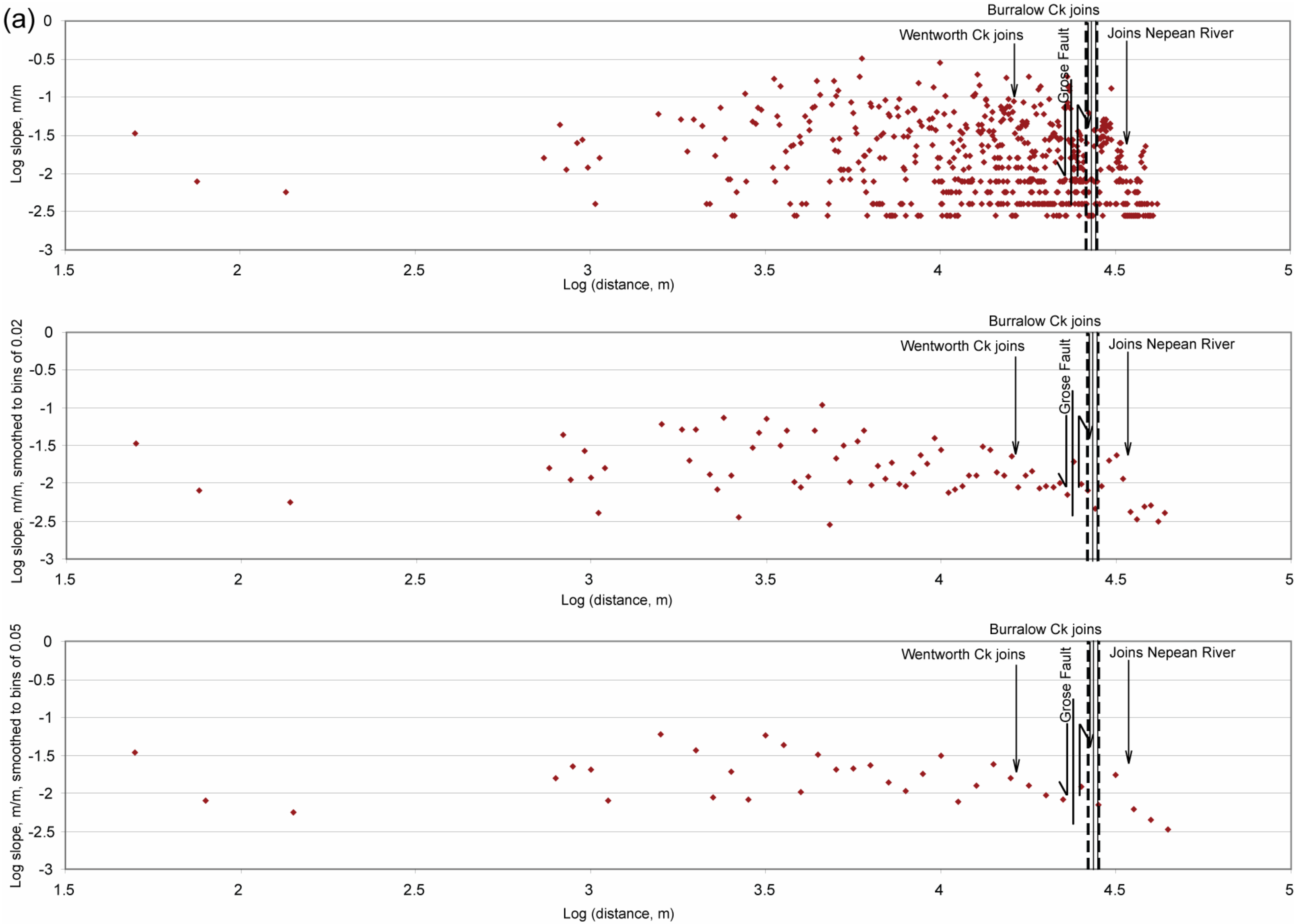
DS plots of streams crossing the LSC

DS plots were produced for all analysed streams crossing the KFS using unsmoothed (but with spikes removed) slopes, as well as data smoothed using 5 point and 9 point running averages. The plots for the Grose River and Fitzgerald's Creek are presented in Fig. 7.

In the Grose River (Fig. 7a) a parallel shift occurs at the Narrabeen Group/Hawkesbury Sandstone boundary, as would be expected for a lithological change. However, the scatter in the data is large, and is no more or less so at the fault, so it is not possible to tell if disordered outliers, expected for disequilibrium, occur at the fault. Fitzgerald's Creek (Fig. 7b) provides an example where no lithological changes are mapped. There are many 'disordered outliers' both upstream and downstream of the fault.

Ideal profile plots

Goldrick and Bishop's (2007) formulation for H as a function of L for an undisturbed profile was tested on data for several streams crossing the LSC. However, due to the large amount of scatter in the DS plots it was difficult to constrain with any certainty the slope (i.e., λ) or the y intercept (i.e., k). Furthermore, for many of the streams, reaches upstream of the faults of the KFS appear to have adjusted to a local base level at the faults; this base level is reflected in the predicted long profiles. Consequently, the predicted profiles generally did not appear to represent the actual profiles well, and were therefore regarded as being of little use.


(a)
Burralow Ck joins
Wentworth Ck joins
Grose Fault
Joins Nepean River
Log slope, m/m
Log slope, m/m, smoothed to bins of 0.02
Log slope, m/m, smoothed to bins of 0.05
Log (distance, m)

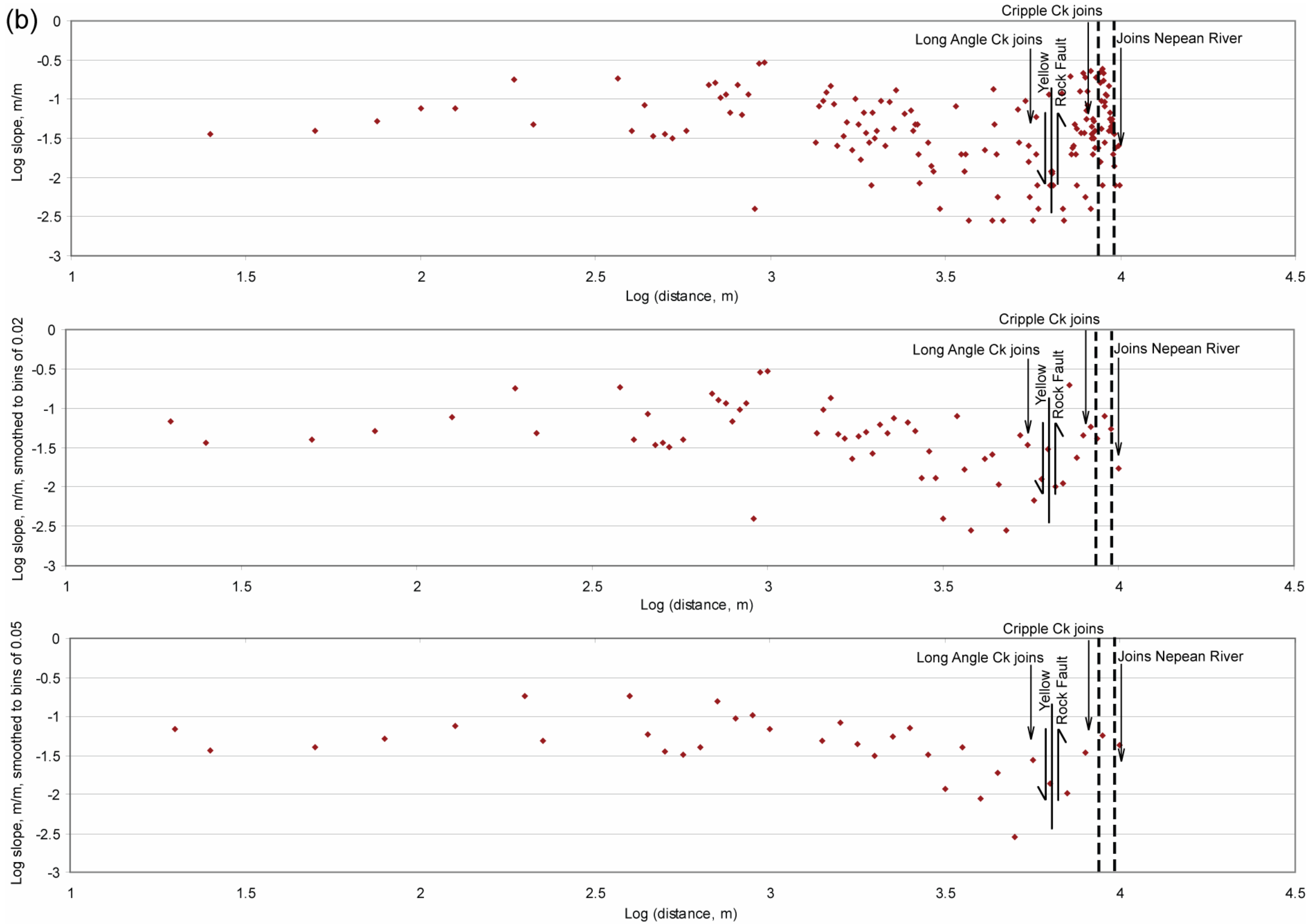


Figure 7: *DS plots for (a) the Grose River, and (b) Fitzgerald's Creek, using unsmoothed slope and slope smoothed (in log space) in bins of 0.02 and 0.05.*

Formulation for differentiating equilibrium and disequilibrium steepening

The Goldrick and Bishop (2007) formulation for distinguishing between equilibrium and disequilibrium steepening was also considered as a potential method for use in this study, however close examination of the method and Fig. 2 suggested it was inapplicable to streams crossing the LSC. In the streams that have the correct geometry for the calculation to be applicable (i.e. Springwood and Faulconbridge Creeks), oversteepened reaches occur well upstream of the faults at changes in lithology, and are interpreted directly from the long profiles as being controlled by this lithological boundary. It is unnecessary to perform calculations to show this. In the ambiguous streams, for which it is not certain whether steepening was lithologically controlled or the result of potentially tectonically-driven disequilibrium (i.e., Burralow, MacLeod's, and Burralow Tributary) the fault is located upstream of the confluence of any two of these streams, and therefore the calculation cannot be applied to these streams.

Incision rate calculations

Following the inconclusive application of the DS form to streams crossing the LSC, a second method, calculation of a proxy for local incision rates, was trialled to determine whether it could aid in distinguishing lithological and tectonically-driven disequilibrium steepening in streams crossing the LSC.

Background

Local incision rate can be calculated for stream reaches flowing through bedrock using the stream incision law (Howard and Kerby, 1983):

$$\frac{dz}{dt} = KA^m S^n \qquad (5)$$

where *dz/dt* = incision rate, *A* = upstream area, *S* = local slope, and *m*, *n* and *K* are constants.

Bishop et al. (2005) discussed the applicability of the stream incision law for representing transient (as compared to steady state) conditions. They noted that knickpoint morphology is not included in the equation, since it is assumed that the area term in the equation adequately represents discharge, which reflects stream morphology.

For streams crossing the LSC it is possible to calculate *S* from the long profiles, and *A* can be extracted from the DEM using Rivertools™ (RIVIX, LLC). Determination of *m*, *n* and *K* is less straightforward.

K is dependent on a number of factors, including lithological resistance to erosion, discharge history and climate (Stock and Montgomery, 1999). Stock and Montgomery (1999) investigated the effect of lithology and climate on the value of *K* and found that within separate investigation areas, *K* varies little with lithology. They did not find a relationship between *K* and climate.

The constant *K* is commonly determined based on incision rates, but, with the exception of one measurement in the Grose River (van der Beek *et al*., 2001), incision rates are not well known for streams in this study area. However, assuming that, as concluded by Stock and Montgomery (1999), *K* varies little with lithology within areas of similar climate, and if the exponents *m* and *n* are known, then the way in which incision rate changes along a stream profile can be determined even if absolute incision rates are unknown (Eqn. 5). Numerous studies have been published in which *m* and *n* have either been assumed or determined. From these studies it has been found that generally, *m* is less than *n*, and that *n* ranges between ~0.65 and 2.5, but is often fairly close to 1. For example, Howard and Kerby (1983) assumed incision rate to be proportional to bed shear stress, giving $m = 4/9$, $n = 2/3$. These values are comparable to $m = 0.44$ and $n = 0.68$, which they obtained from a least-squares logarithmic regression of the erosion rate versus the drainage area for rapidly eroding channels in Virginia. Seidl and Dietrich (1992) used Playfair's Law to show that the ratio $m/n \sim 1$ for streams of low gradient ($S < 0.2$) in coastal Oregon. Stock and Montgomery (1999) investigated streams in a number of areas to evaluate the stream power law, and came up with m ~0.4 and $n = 0.5$-1.0 for streams crossing the Lachlan

Fold Belt ~100 km west of the present study area. Whipple *et al*. (2000) investigated the influence of erosion process on the exponent n. They showed that erosion by plucking (i.e., the production and entrainment of loose joint blocks, involving weathering, crack propagation, and rock fracturing; common in jointed rocks) was associated with an n value of ~1, whereas erosion by abrasion (i.e., saltation of particles along the stream bed) was associated with $n > 1$.

Methods

For this study the exponent n was set to 1, since in the Hawkesbury Sandstone and Narrabeen rocks (the dominant lithologies exposed on the LSC) jointing is common, and therefore, following the reasoning of Whipple *et al*. (2000), plucking may be expected to be the dominant erosion process, consistent with $n = 1$ (Whipple *et al*., 2000). Erosion by plucking was observed directly in Wheeny and Flat Rock Creeks, lending further support to the application of this value. A constant value of $n = 1$ is also similar to results obtained by Stock and Montgomery (1999) for Tumbarumba Creek and the Tumut River, located ~350 km southeast of the present study area, which flow through granitoids and metasediments of the Paleozoic Lachlan Fold Belt.

The m/n ratio was then calculated using Playfair's Law in a similar way to Seidl and Dietrich (1992). Playfair's law is derived from the stream incision law, and relates the ratio of the slopes of a trunk stream and its tributary as follows:

$$\frac{S_t}{S_p} = \left(\frac{A_p}{A_t}\right)^{\frac{m}{n}} \qquad (6)$$

where S_t and S_p are the slopes of the tributary and principal streams respectively at their confluence, and A_t and A_p are their respective catchment areas. Therefore, a plot of log (S_t/S_p) versus log (A_p/A_t) should be linear with a slope equal to m/n.

A plot of log (S_t/S_p) versus log (A_p/A_t) (Fig. 8) was generated for 20 principal/tributary stream reach combinations upstream of the KFS. The plot gives an m/n ratio of 0.43, similar to the average m/n ratio of 0.4 obtained by Stock and Montgomery (1999).

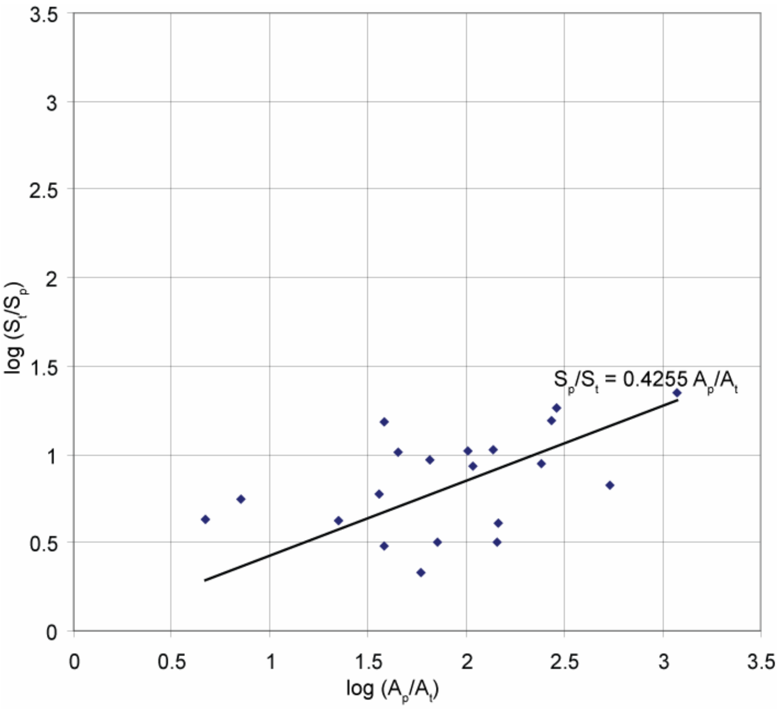


Figure 8: *log (S_t/S_p) vs log (A_p/A_t) for streams upstream of the Kurrajong Fault System in the Blue Mountains, NSW. S_t = slope of a tributary stream and S_p = slope of a principal stream, at their confluence, and A_p and A_t are the respective areas of the principal and tributary streams.*

Using the exponents $n = 1$ and $m = 0.4$, $A^m S^n$ (i.e., dz/dt / K) was calculated at each point along the long profiles for streams crossing the LSC (Figs. 9a-r). To give an indication of equivalent incision rates, a second axis has been provided. The values for this axis were obtained using an estimate of a regional K value in the stream incision equation. The regional K value was calculated by dividing the average erosion rate from the compilation of Tomkins *et al*. (2007) (21.5 ± 7 m/Ma; see Section 2.1) by the overall average $A^{0.4}S$ value across all analysed streams (0.073). This gives a K value of 296. Notably, this second axis gives an average incision rate of 40 ± 11 m/Ma over the Lapstone Monocline in the Grose River (Fig. 9g), similar to the figure of 40 m/Ma obtained by van der Beek *et al*. (2001) for the same area.

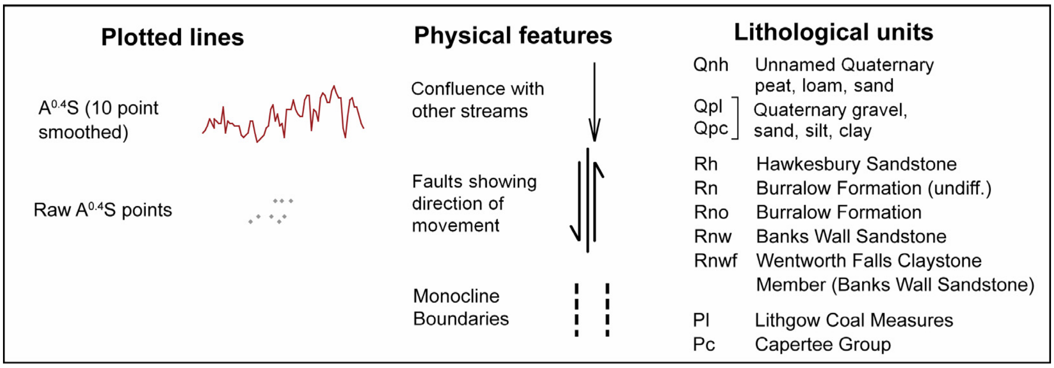


Figure 9: *Key to symbols used in $A^{0.4}S$ plots.*

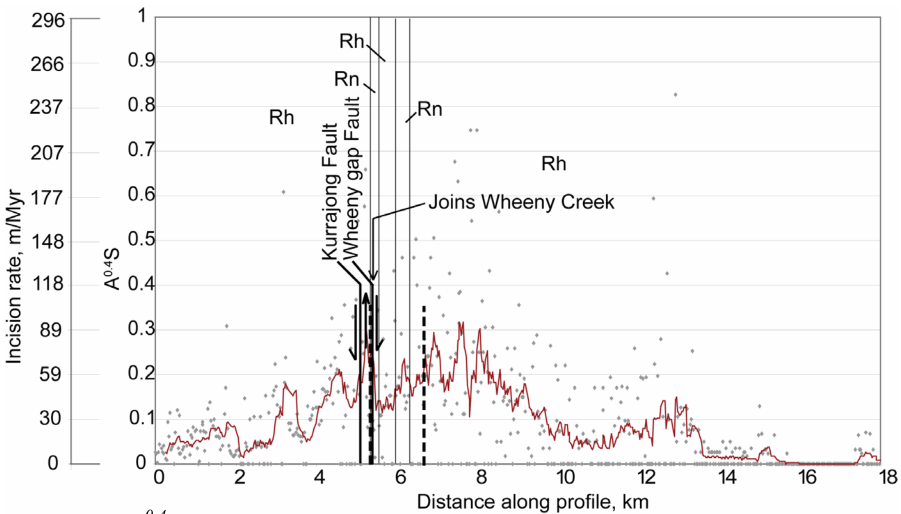


Figure 9a: *$A^{0.4}S$ vs. distance plot for Flat Rock Creek.*

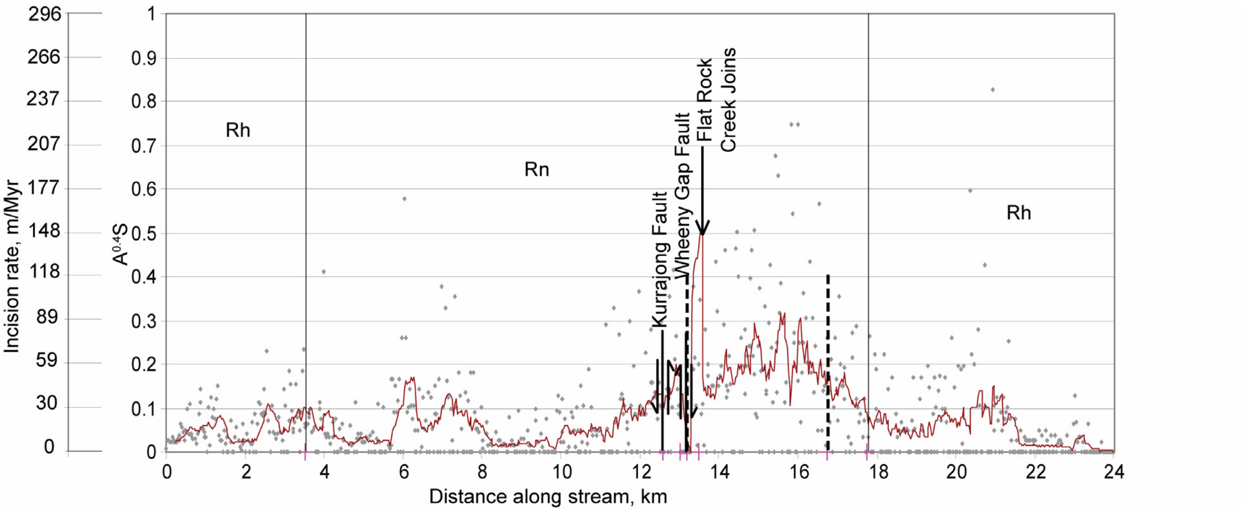


Figure 9b: *$A^{0.4}S$ vs. distance plot for Wheeny Creek.*

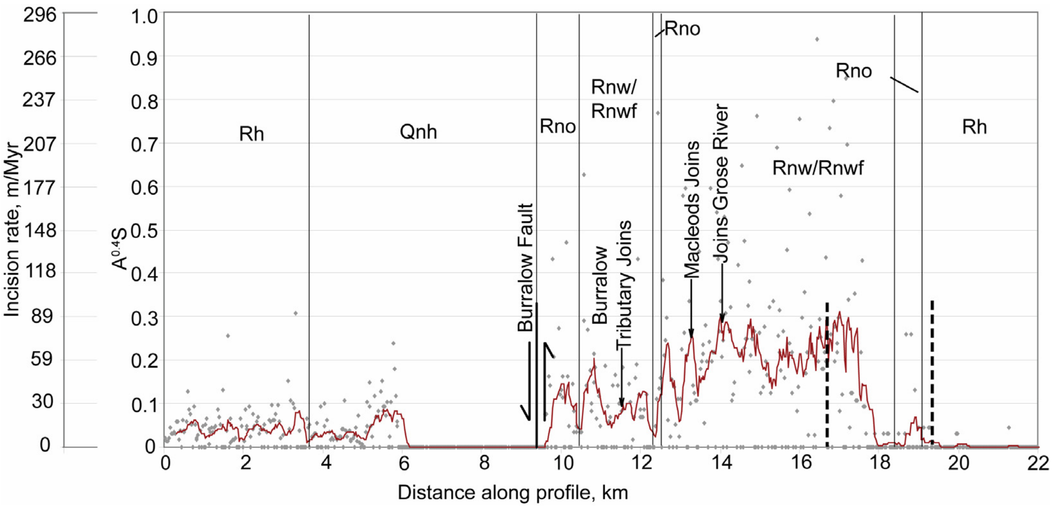


Figure 9c: $A^{0.4}S$ *vs. distance plot for Burralow Creek.*

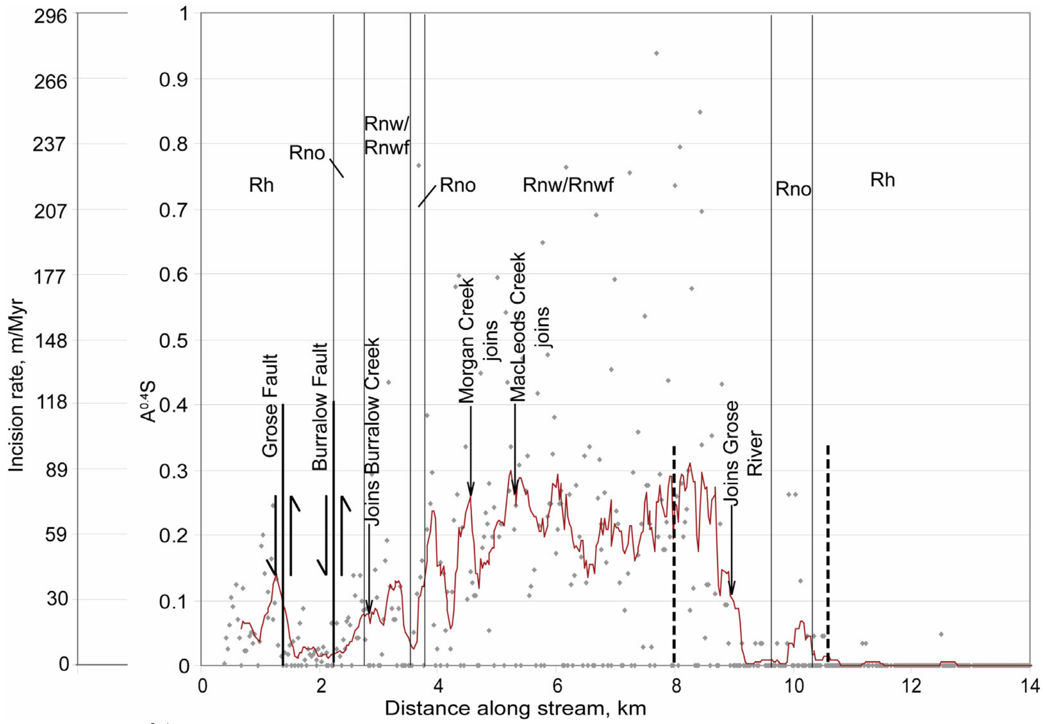


Figure 9d: $A^{0.4}S$ *vs. distance plot for Burralow Creek Tributary.*

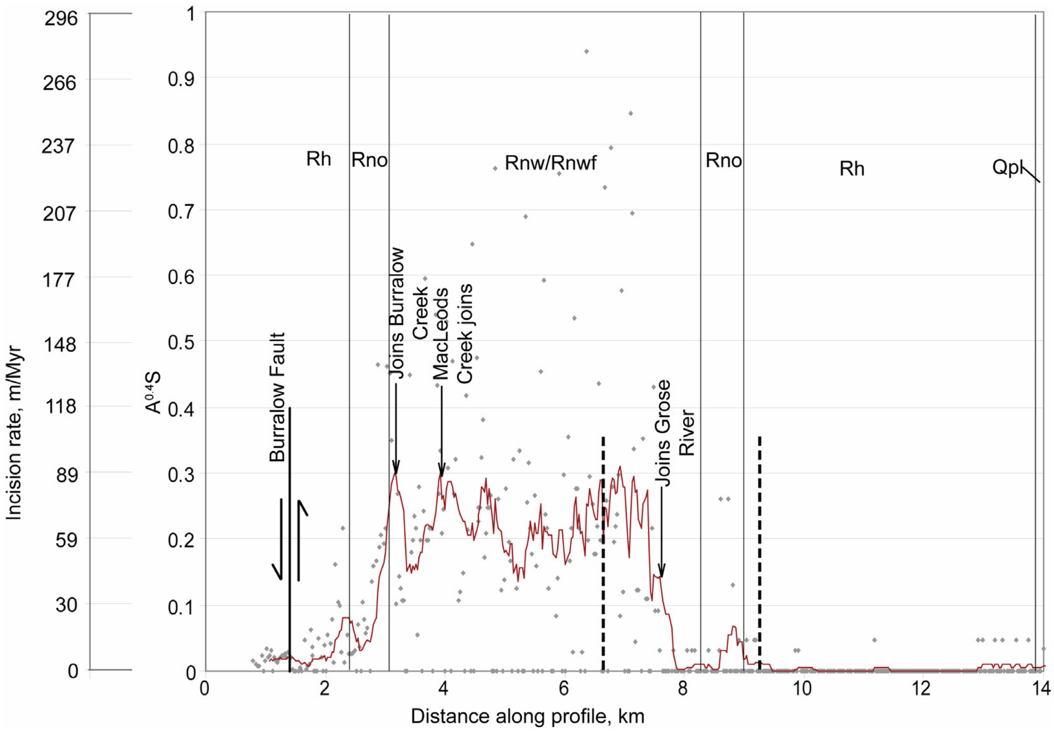


Figure 9e: *$A^{0.4}S$ vs. distance plot for Morgan Creek.*

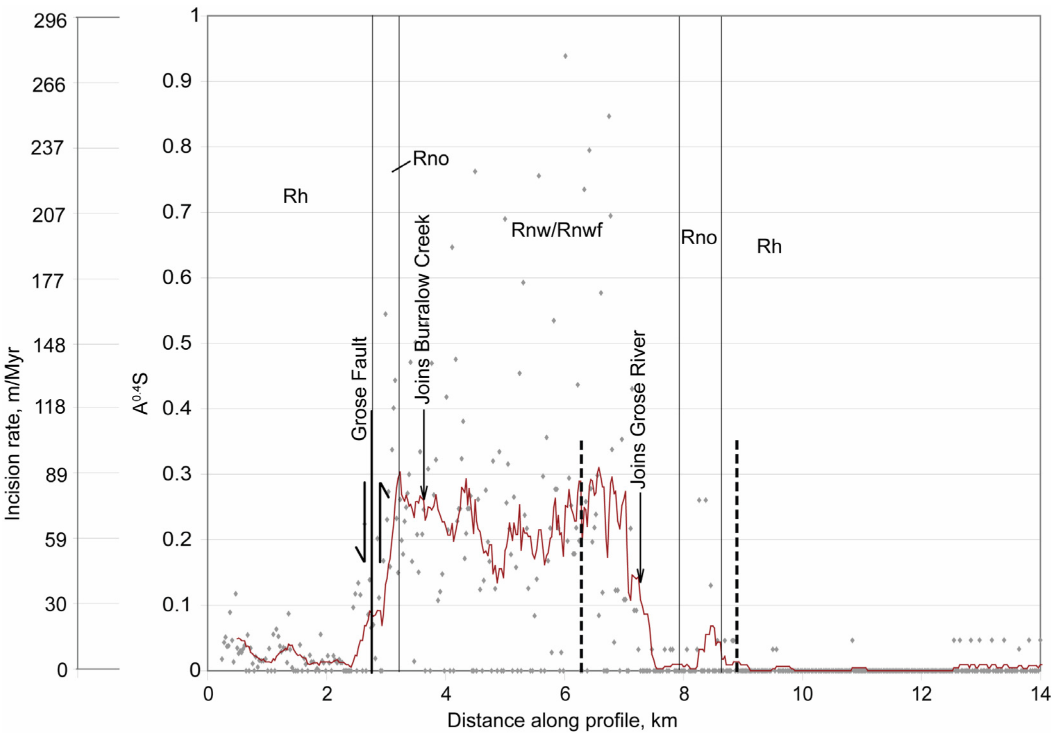


Figure 9f: *$A^{0.4}S$ vs. distance plot for McLeod's Creek.*

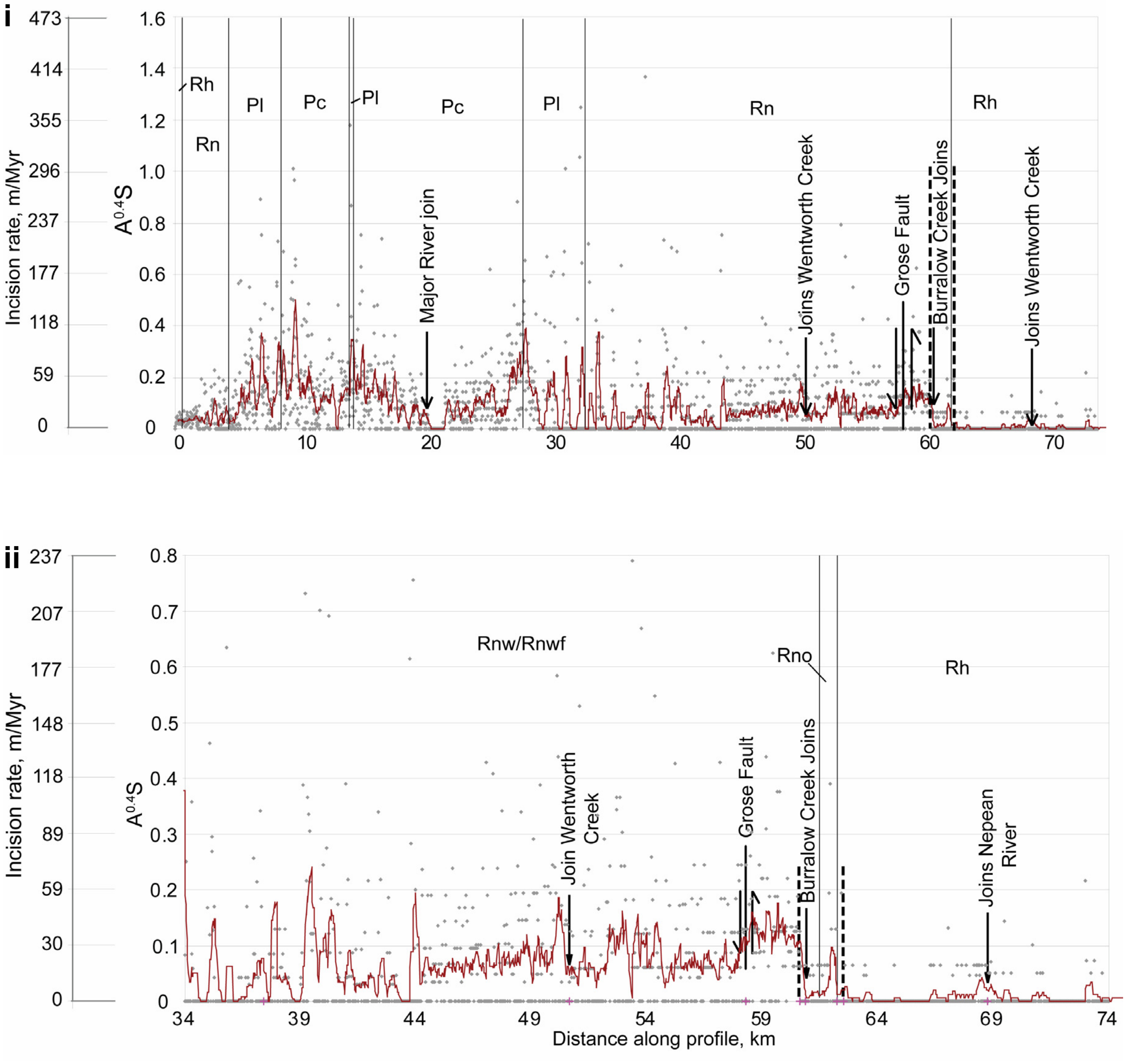


Figure 9g: *$A^{0.4}S$ vs. distance plots for the Grose River, i) the whole catchment, ii) the catchment from 34km downstream of the headwaters.*

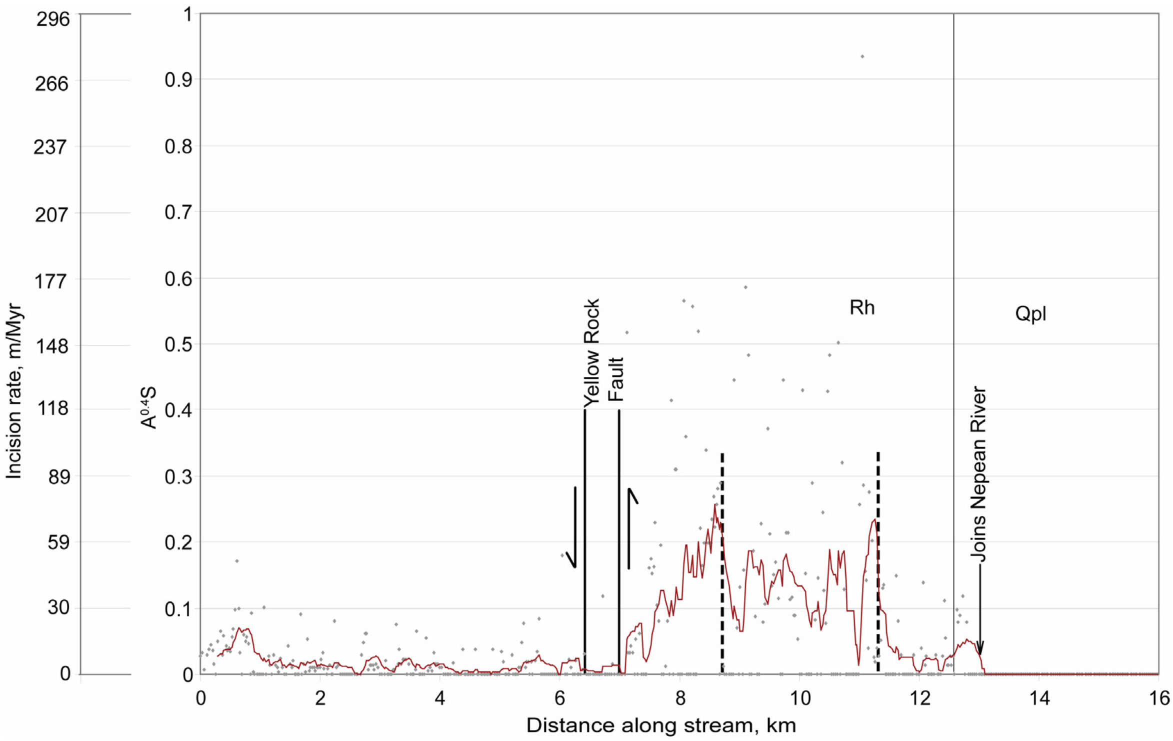


Figure 9h: *$A^{0.4}S$ vs. distance plot for Blue Gum Swamp.*

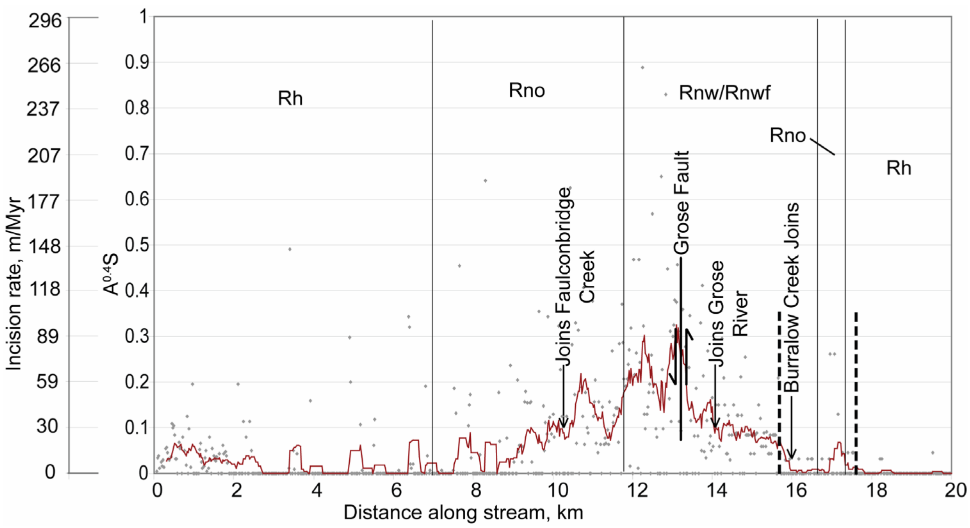


Figure 9i: *$A^{0.4}S$ vs. distance plot for Springwood Creek.*

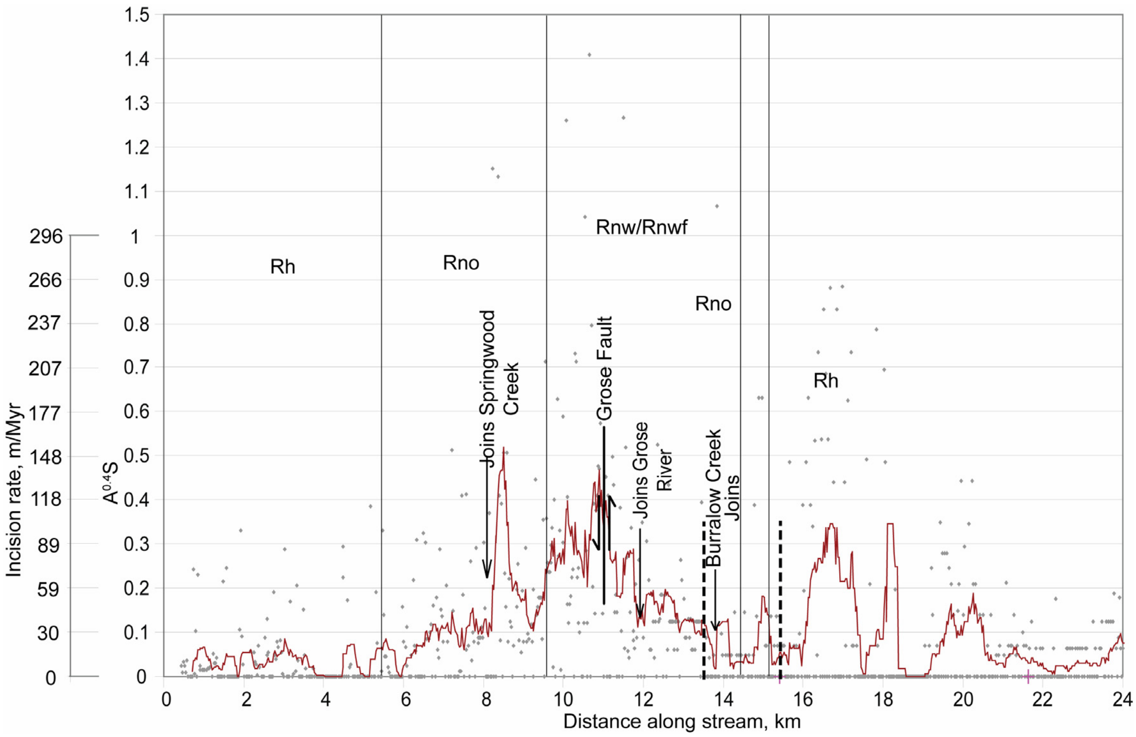


Figure 9j: *$A^{0.4}S$ vs. distance plot for Faulconbridge Creek.*

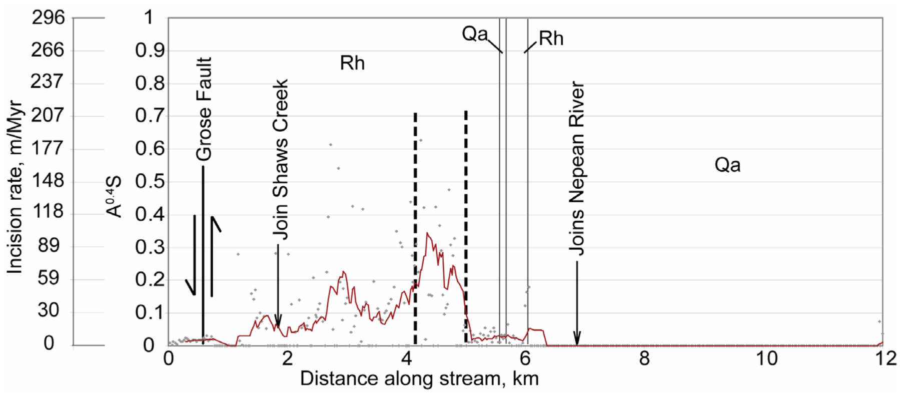


Figure 9k: *$A^{0.4}S$ vs. distance plot for Shaw's Ridge Creek.*

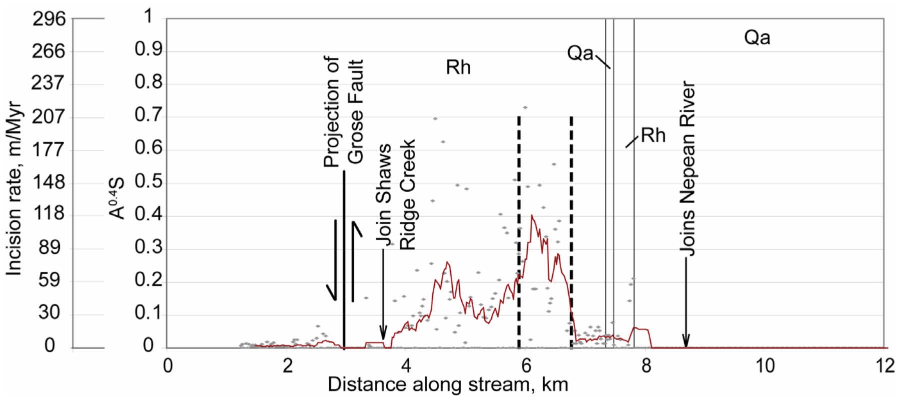


Figure 9l: *$A^{0.4}S$ vs. distance plot for Shaw's Creek.*

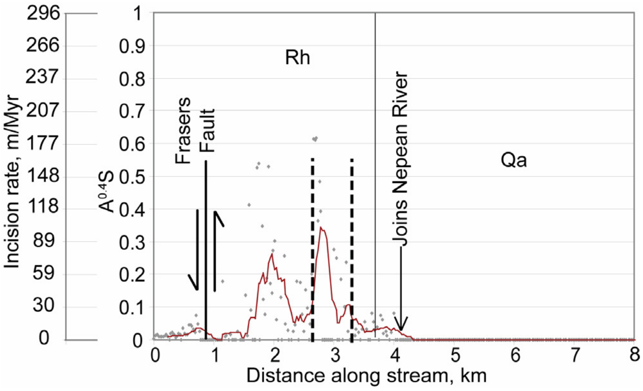


Figure 9m: *$A^{0.4}S$ vs. distance plot for Winmalee Creek.*

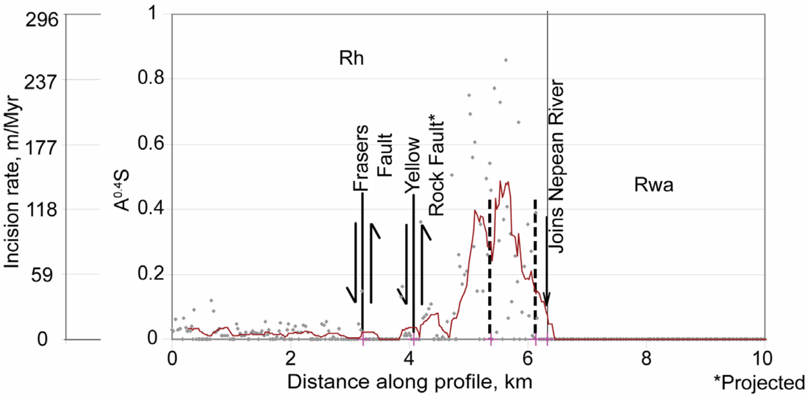


Figure 9n: *$A^{0.4}S$ vs. distance plot for Fraser's Creek.*

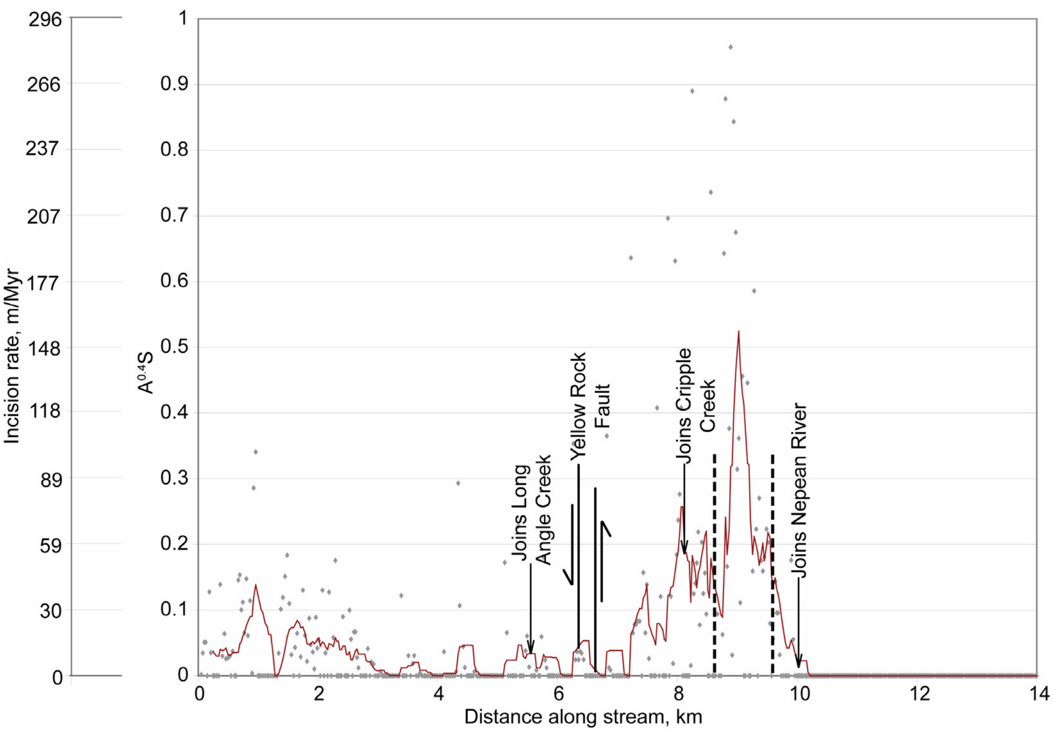


Figure 9o: *$A^{0.4}S$ vs. distance plot for Fitzgerald's Creek.*

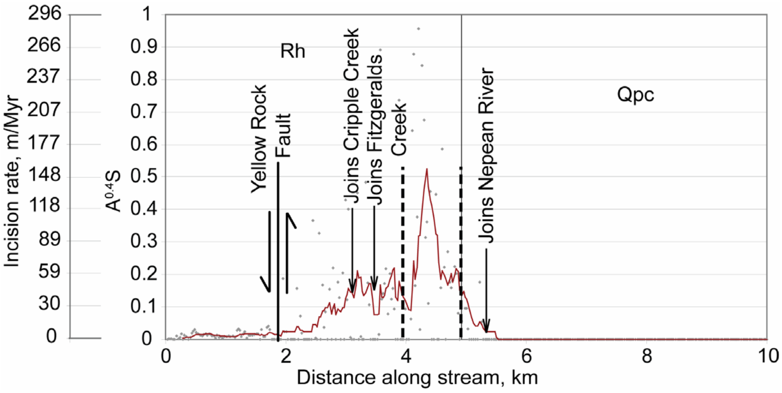


Figure 9p: *$A^{0.4}S$ vs. distance plot for Warrimoo Creek.*

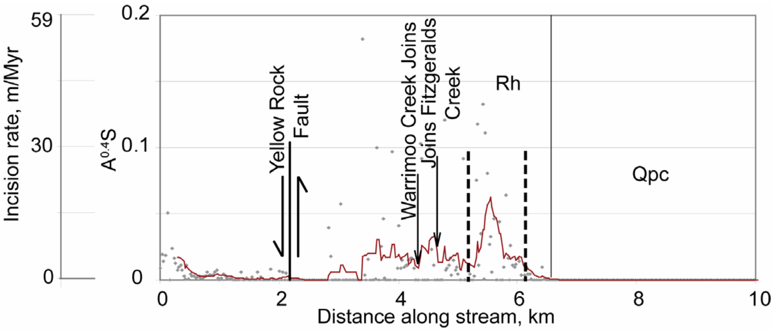


Figure 9q: *$A^{0.4}S$ vs. distance plot for Cripple Creek.*

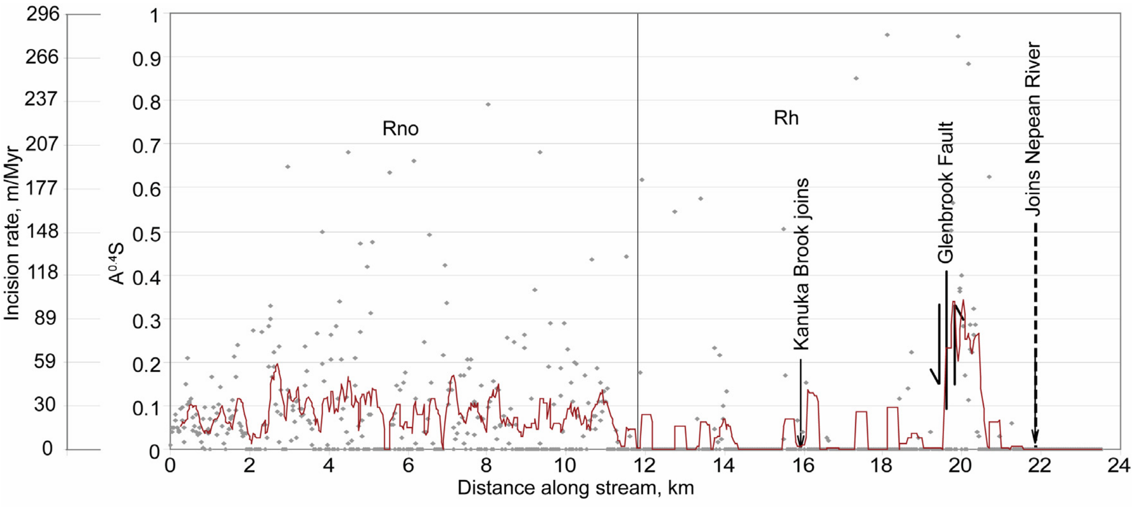


Figure 9r: *$A^{0.4}S$ vs. distance plot for Glenbrook Creek.*

Results

The most striking observation that can be made about the $A^{0.4}S$ versus distance plots is the similarity between them. In all streams except Springwood and Faulconbridge Creeks, $A^{0.4}S$ values increase between faults of the KFS and the eastern boundary of the monocline, regardless of whether there is a lithological change at the faults. This is particularly apparent in Glenbrook Creek (Fig. 9r), where the $A^{0.4}S$ values show a sharp increase at Glenbrook Fault, with the $A^{0.4}S$ value immediately downstream of the fault being about three times higher than anywhere else in the plot. That the $A^{0.4}S$ value peaks downstream of the fault suggests that incision rates peak downstream of the fault, as might be expected for a disequilibrium reach downstream of an east-dipping fault.

The plots also suggest that $A^{0.4}S$ (and therefore, potentially, the constant *K*) is moderately to strongly affected by lithology. Glenbrook Creek and the Grose River, two of the few streams that are disrupted by faulting and lithological changes at different points along their reaches, are good examples of this. The plots show $A^{0.4}S$ is higher in Narrabeen Group rocks than it is in Hawkesbury Sandstone by a factor of about two ( ). However, the plot for Glenbrook Creek also suggests that the effect of lithology is minor compared to the apparent influence of the fault.

The apparent magnitude of the incision rates may have significance for the evolution of the LSC. $A^{0.4}S$ is typically ~ 0.2 m over the monocline. This is equivalent to dz/dt = 59 ± 23 m/Ma assuming the average denudation rate from the Blue Mountains Plateau is representative of average incision rates in the analysed streams. If incision rate was constant it would take about 2.8 Ma to vertically incise 200 m (the approximate relief offset of a knickpoint in the study area).

In reality, knickpoint evolution will vary through time. A basic model of knickpoint evolution for streams crossing the LSC could be generated based on the incision rate calculations outlined above. However, this model would be most effective if constrained by measured current incision rates in streams crossing the LSC.

An interesting comparison can be made between streams crossing the Lapstone Structural Complex and the Shifting Walsh stream in a semi-arid environment; the Canyonlands National Park, Central Utah. Exposed at the surface over much of the Canyonlands National Park are Carboniferous – Permian metasediments underlain by evaporates, black shales and carbonate (Shultz-Ela and Walsh, 2002). The Shifting Walsh stream is disrupted along its reach by normal faults known to be active, and these are expressed in its long profile as oversteepened reaches (Phillips et al., 2003). The rate of knickpoint retreat along the profile was measured directly using cosmogenic radionuclide dating of surfaces, which showed that while vertical incision upstream of the knickpoints is low (15.0 – 20.7 m/Ma), the rate within oversteepened reaches (i.e. immediately downstream of knickpoints) is 4 – 5 times higher (77 m/Ma) (Phillips et al., 2003). These measured rates are remarkably similar to those calculated for streams crossing the LSC: for most streams, average $A^{0.4}S$ values upstream of the faults range from about 0.03 – 0.05, equivalent to incision rates of ~ 10 ± 3 to 17 ± 6 m/Ma, or ~ 4 – 7 times less than those on oversteepened reaches.

Neotectonic Indicators: Fault angle depressions

It was noted by Rawson (1990) in his analysis of stream long profiles crossing the KFS that drainage modification is evident in all streams with catchment sizes less than or equal to that of Glenbrook Creek. The results from the present study are consistent with those from the Rawson (1990) study, i.e. in all streams that cross the KFS, stream gradients are markedly reduced upstream of the fault. This study also reveals that drainage modification is evident along the larger streams - Wheeny Creek and the Grose River.

In streams with catchment areas smaller that of Glenbrook Creek, the reduced gradient reaches coincide with swamp/lake features observed in the field (Rawson, 1990). Rawson (1990) argued that these swamps owe their existence to damming or partial damming by the fault as a result of recent uplift. This would require that the thickness of sedimentary fill behind the fault be consistent with the local throw of the fault at the dams minus the erosion rate, and that uplift on the fault occurs faster than (or at a broadly consistent rate with) erosion in the stream.

To test the hypothesis that the swamp/lake features in the smaller streams crossing the Lapstone Structural Complex are the result of damming by the Kurrajong Fault, Rawson (1990) investigated the depth and nature of the sediments infilling the swamps/lakes, and any evidence for fault damming. A number of the smaller streams were investigated revealing that, with the exception of Blue Gum Creek, Burralow, and Shaw's Creek swamps, there was minimal (≤ 3.5 m) sediment accumulation behind the fault. It was noted, however, that at Morgan Creek, Winmalee Creek, and Warrimoo Creek swamps, the fault bar downstream of the swamps was at a level higher than bedrock within the swamps, consistent with the fault damming hypothesis.

The most extensive swamp/lake feature associated with the KFS is Burralow Swamp. Rawson (1990) investigated Burralow Swamp in detail to determine the depth, stratigraphy and age of sediments in the swamp. Hand and power augering was carried out down to a maximum depth of 14 m (not reaching bedrock), revealing that, while the main sediments present are gravels, sands and silts, in some locations a heavy organic clay layer (the 'Tarabaga Unit') was identified (Rawson, 1990). The clay layer was interpreted as resulting from previous lacustrine conditions. That this layer occurs below the present level of Burralow Creek suggests that base level was lower during its deposition than it is currently. Furthermore, the layer was found to occur below the level of bedrock downstream of the fault, suggesting that the base level elevation is a result of movement on the fault over time.

Dating and pollen analysis of the organic layer revealed that the organic clay is probably Pleistocene in age. Carbon dating was problematic – two dates were obtained (28,200 +900/-800 B.P. at 12.9 m and 35,400 +2,400/-1,990 B.P. at 8.8 m depth). That their relative ages are inverted compared to their stratigraphic positions, and that both dates are near the upper age limit of carbon dating, casts doubt on their reliability. Nonetheless, pollen analysis has revealed the occurrence of Late Pleistocene pollen within the layer, suggesting that the dates are broadly accurate (Rawson, 1990).

As part of the present study, the swamps associated with Burralow and Blue Gum Creeks were revisited and hand augered to:

- Identify the occurrence of the Tarabaga Unit in Burralow Swamp, confirm the field observations of Rawson (1990), and identify potential sites for drilling and sediment sampling for OSL dating;
- Determine if the Tarabaga Unit occurs in Blue Gum Swamp, and if so, identify potential drilling sites, and;
- At all swamps, confirm whether any sediments indicative of swamp/lake conditions occur at an elevation lower than bedrock bars corresponding to faults.

At Burralow Swamp, four hand auger holes were drilled near the location of borehole BC3 of Rawson (1990), which intersected the Tarabaga Unit at 4 m depth, below fluvial sands. None of these holes intersected the Tarabaga Unit, instead reaching the water table and losing recovery at ~2.5 - 3.0 m depth. The bedrock bar identified by Rawson (1990) downstream of Burralow Fault could not be found; instead fluvial sands and landslide deposits formed the stream bed for some distance downstream of the fault. This suggests that the bedrock bar of Rawson (1990) has been covered by block fall and sands since his investigation, or alternatively that bedrock was misidentified.

In Blue Gum Creek Swamp, a ~1.2 m thick heavy organic clay layer very similar to the Tarabaga Unit was intersected at 3.1 m depth. The elevation of this layer, based on the topographic map of the area, is ~210-220 m. Downstream of the fault, bedrock was found exposed at ~210 m elevation, broadly consistent with the elevation from the topographic map. It is therefore possible that bedrock occurs at a higher elevation than the clay unit intersected at Blue Gum Swamp, and the sediments intersected at Blue Gum Swamp may be materials trapped by the Grose Fault.

Conclusions and further study

This study has used observation and analysis of the geomorphology of the Lapstone Structural Complex, including a detailed analysis of 18 streams crossing the LSC, to investigate the possible timing of uplift on this structure, in particular its most recent significant movement.

Conclusions from stream long profile analysis

In all but two streams, oversteepening by ~2-5 times occurs immediately downstream of the faults of the KFS. The oversteepening occurs regardless of whether there is a change in lithology mapped at the faults. Oversteepening occurs to a greater extent in streams with smaller catchment areas and those to the northern end of the LSC. Analyses were carried out to determine whether the oversteepening is due to tectonically induced disequilibrium, and if so, how long it would take for equilibrium to be restored.

Attempts to use DS plots and analysis techniques of Goldrick and Bishop (2007) to distinguish between equilibrium and disequilibrium steepening in each stream crossing the LSC proved inconclusive, at least based on the 25 m resolution elevation data used in this study.

The stream incision law was used to calculate along stream variations in the product A^mS^n which, in an area of near constant lithology and climate, is approximately proportional to incision rate. The exponents m and n were approximated to 0.4 and 1 based on the results of previous studies, and Playfair's Law applied to reaches upstream of the KFS. K was estimated to give incision rate by equating the average $A^{0.4}S$ value to the average denudation rate from sites on the Blue Mountains Plateau of 21.5 m/Ma.

The main conclusions from the application of this analysis to streams crossing the LSC were that:

- Calculated incision rate reaches a maximum between faults of the Kurrajong Fault System and the eastern margin of the monocline; and
- $A^{0.4}S$ varies with lithology, although the lithological effect appears to be less pronounced than the apparent effect of the LSC structures.

Springwood and Faulconbridge Creeks were an exception to the trend, showing no jump in incision rate, and in the long profiles showing a concave downward profile extending from several kilometres upstream of the faults to immediately downstream from the faults. It is not known why these streams have a different expression to the other analysed streams, but it is suggested that there may be unmapped structures upstream of the mapped Grose Fault that are causing the unusual profile form.

The incision rate calculation technique appears to have been successful in showing disequilibrium in that it has demonstrated that incision rates in the streams increase markedly over the Lapstone Monocline, as would be expected for streams not in equilibrium. The results of long profile analysis therefore suggest that uplift of the LSC is ongoing.

Conclusions from investigation of swamps/lakes at the faults

Swamp/lake features upstream of faults of the KFS were identified by Rawson (1990) as further potential evidence for ongoing uplift of the LSC. Augering of these features has been carried out at Burralow and Blue Gum Creek Swamps. Augering identified a clay layer in Blue Gum Swamp, similar to the Tarabaga Unit identified by Rawson (1990) in Burralow Swamp. The layer occurs at ~3 m depth, an elevation similar to that of bedrock coinciding with the fault. The Tarabaga Unit is believed to be of Pleistocene age (Rawson, 1990). Therefore, the interpretation of the swamps as fault-dammed sediment traps, as proposed by Rawson (1990), is still plausible, and this study has identified that Blue Gum Creek Swamp is a potential target for future studies.

Further research

The following points could provide useful directions for further research:

- Application of the DS form of the long profile to higher resolution data than used in this study.

While this study has shown that 25 m DEM data is inadequate for study of the LSC using the methods of Goldrick and Bishop (2007), higher resolution elevation data (e.g., LIDAR) may be more successful.

- Direct measurement of incision rates to calibrate the $A^{0.4}S$ versus distance plots.

Incision rates at various points along some of the streams analysed in this study could be assessed using the Cosmogenic Radionuclide dating technique. Rates at specific points could be plotted against appropriate $A^{0.4}S$ values from the same points to determine K for Hawkesbury Sandstone, Banks Wall Formation and Burralow Formation, and subsequently be used to predict incision rates for all streams crossing the LSC. Once incision rates are known, profile evolution from the current form could be modelled to constrain the age of the LSC. Dating would also be useful in assessing the effectiveness of the $A^{0.4}S$ versus distance plots in approximating the along stream variation in incision rate.

- Further investigation and dating of sediments in Blue Gum Creek and Burralow swamps.

Optically Stimulated Luminescence (OSL) dating of sediments in Blue Gum Creek and Burralow Swamps could be used to constrain their age of deposition. Assuming the fault-damming hypothesis is correct, then the age of the sediments could constrain the minimum age of movement on the LSC. The sediment ages could also be compared to the ages determined from incision rates in the long profiles as described in above.

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