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Contribution to the Theory of Scarpland Development from Observations in Central Queensland, Australia

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ABSTRACT

Theories of scarpland geomorphology developed over the past century have been characterized by divergent conceptual frameworks and have been hindered by language barriers. Here, we review the main theories and assess them with reference to field evidence from central Queensland. This region provides exceptional scope for such an assessment because of the detailed K-Ar chronology available for basalt that is draped extensively over scarps and valleys. The basalt provides the key to deciphering the pattern and rate of denudation. Erosion began in the late Mesozoic and was greatly advanced when volcanism occurred during the middle Cenozoic. Postbasaltic erosion has been dominated by the incision of the basaltic caprock and by the lengthening of canyons, rather than by scarp retreat. Canyons have extended headward by 1–2 km/m.yr., widened by 150–250 m/m.yr., and deepened by 6–25 m/m.yr., while scarps between canyons have retreated by only 18–130 m/m.yr. Canyon cutting both on the scarp front and on the dip slope has been promoted by point-source seepage from networks of tubes in sandstone. These field observations support recent findings from elsewhere in Australia and from the Colorado Plateau. What is perhaps more significant, especially with regard to the way in which research in this field has developed, is that this emphasis on dip-slope erosion and solutional processes in sandstone was anticipated by research done in Germany more than 70 years ago.

Introduction

Basalt was extruded over large areas of the scarp-land and valleys of central Queensland, Australia, from about 33 to 20 Ma. K-Ar chronologies for the basalt and associated trachyte intrusions, and also for surficial alunite in prebasaltic weathering profiles, provide considerable scope for reconstructing the patterns and rates of retreat and dissection of scarps during late Mesozoic and Cenozoic times. The erosional development of this landscape was already far advanced by the time of basalt extrusion in the middle Oligocene and Early Miocene and has progressed very slowly since then. The rate of postbasaltic erosion has, however, varied greatly from one part of the region to another. This variation, and its relationship to the pattern of scarps and streams, prompts

a reassessment of the general theories of scarp-land evolution.

Theories of Scarpland Evolution

By far the most influential contribution to the understanding of the erosional development of scarp-lands was that by W. M. Davis (1895, 1899), who synthesized previous work in North America, England, and France into a worldwide general theory. Davis argued that while initial erosion is done mainly by consequent streams flowing down-dip, subsequent streams cutting back along the strike of exposures of weaker strata become increasingly the dominant agents of erosion. The headward extension of subsequent streams along the strike and the growth of small streams draining to them from adjacent scarps and dip slopes result in the transformation of the initial dendritic drainage pattern by stream capture and in its replacement by a dominantly trellis drainage. As the cycle of erosion pro-

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ceeds through maturity to old age, the terrain is lowered and scarps retreat as valley floors are widened, thereby producing an erosional surface, which truncates diverse strata (fig. 1).

In attempting to demonstrate that great changes in drainage and scarp patterns had actually occurred, Davis relied on the "underfit" channel forms of many consequent streams. He argued that the great contrast in size between the small meanders on these streams and the much larger bends of the confining valley walls recorded major reductions in discharge that must be overwhelmingly due to loss of drainage area resulting from river capture. During the 1950s, however, Dury demonstrated that underfit channels are very much the result of climatic change rather than of river capture (Dury 1954). While Dury's contribution to fluvial geomorphology was acclaimed, its implications for the theory of scarplands were not recognized. Thus, while Davis's terminology has become largely obsolete, his evolutionary scheme still provides the basic conceptual framework among English-speaking geomorphologists.

Most subsequent contributions published in English focused on aspects of scarpland geomorphology, especially those of slope processes, glossed over by the broad sweep of Davis's synthesis. On the Colorado Plateau, for example, Schumm and Chorley (1966) drew attention to the effect of the variable breakdown of protective talus mantles on rates of scarp retreat. In that same region, however, emphasis was again placed on stream action by R. A. Young (1985), who attributed accelerated undercutting and retreat of scarps to lateral planation by streams at times of baselevel stability.

Davis's approach to scarplands was at first enthusiastically applied by French geomorphologists to the Paris Basin but later severely criticized by Tricart and Cailleux (1965) who argued that the morphology of that region was greatly affected by periglacial processes. Davis's influence was nonetheless still obvious in the emphasis given by his French critics (e.g., Tricart 1968) to the action of streams at the foot of scarps. Indeed, erosion by subsequent streams like the Meuse and Moselle has been repeatedly seen as the key to the shaping of the eastern part of the Paris Basin. However, the recent review by Battiau-Queney (1993) demonstrates a significant development in French research. She argues that the incision of streams into a broad undulating surface following regional uplift during the late Cenozoic unleashed a "morphological revolution" in which the differential resistance of strata to a more dynamic erosional regime produced the scarps and cuestas. Moreover, she em-

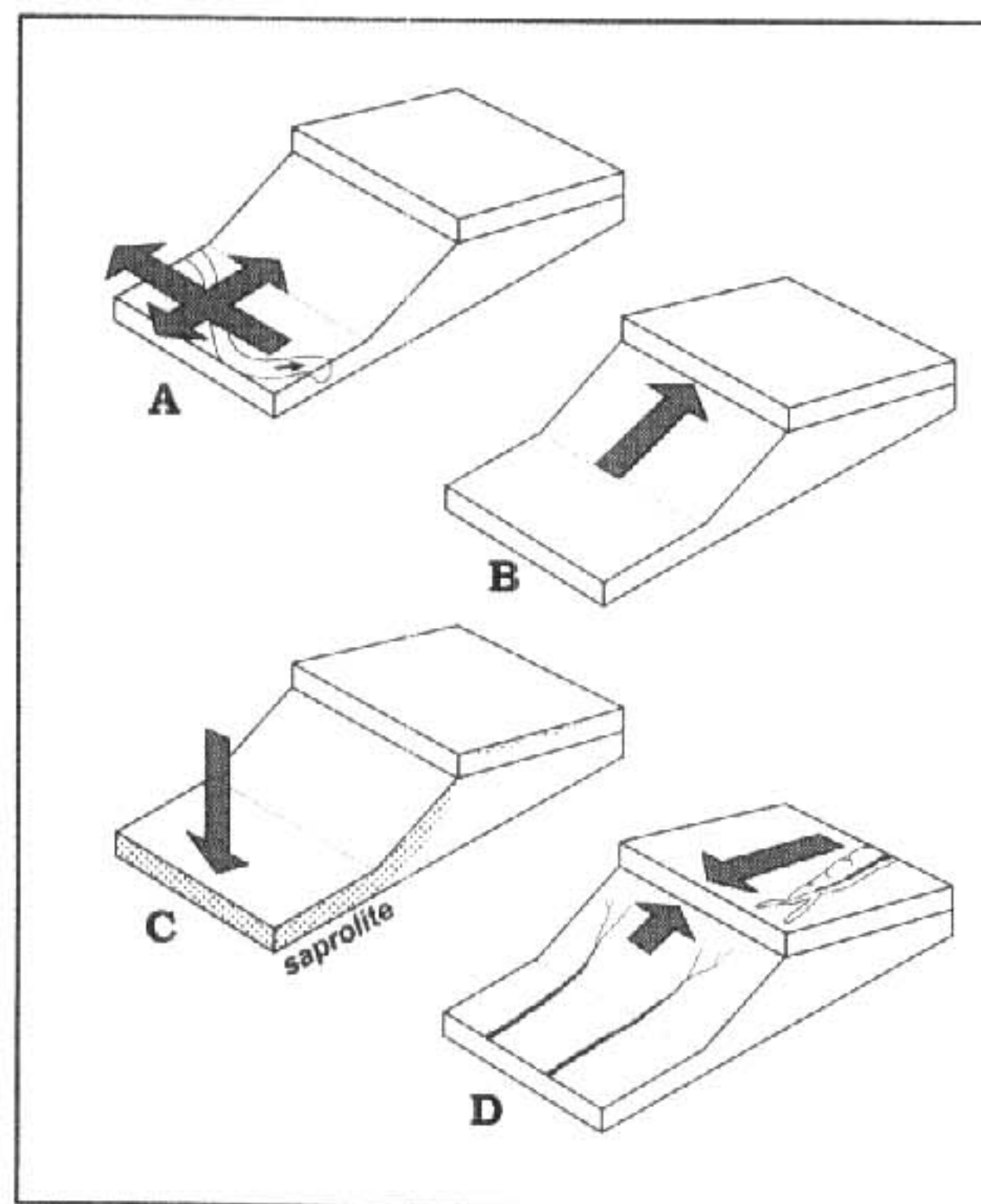


Figure 1. Postulated dominant forms of scarpland evolution in gently dipping strata. Arrows indicate main direction of erosion. *A*, Davis: headward extension and widening of subsequent valleys by stream erosion along the strike of weaker rocks. *B*, King: retreat of the scarp face and pediment expansion on footslopes independent of drainage lines. *C*, Büdel: downwearing by the erosion of deep saprolite weathered under tropical climates. *D*, Schmitthenner: headward erosion and deepening of dip-slope valleys and seepage hollows, together with erosion of streams draining the scarp face.

phasizes that the stripping of weaker strata from the dip slopes, rather than erosion on the scarp faces, was decisive in shaping this landscape.

Davis's ideas were also initially accepted in Germany, but his great German critic, Alfred Hettner, recognized the difficulty of matching theoretical and actual patterns of drainage and thereby laid the foundations of a very different interpretation of scarpland evolution (in German "Schichtstufenlandschaft"). In his opinion, "Longitudinal valleys are in fact exceptional; and when they do occur the fact that they are juxtaposed with scarps is either fortuitous, or they have been established subsequently as a result of scarp formation" (Hettner 1928, p. 64). He also rejected the claim that such streams are the primary agents in forming wide benches at the foot of scarps: "Such a view is not

supported by observation; moreover, it is theoretically unlikely that rivers could form a valley floor wide enough" (Hettner 1928, p. 63). Two decades earlier, Hettner (1903) had already argued that the critical process in this type of terrain is not erosion by streams at the foot of scarps but undermining by seepage along bedding planes, especially at the contact of less permeable strata. He rejected the then-current idea that truncation of strata on the crests of *cuestas* was necessarily indicative of widespread planation followed by uplift and incision. Moreover, Hettner argued that Davis's scheme replaced real geological time with a hypothetical sequence of development that exaggerated the rates of change involved. Geological evidence, he insisted, suggested a much greater antiquity: "Oligocene and Pliocene gravels and clays on the surface point to their (*cuestas*) advanced development in the Tertiary period" (Hettner 1928, p. 66).

Hettner's ideas were developed into a comprehensive theory by Schmitthenner (1920, 1926, 1956; see also Blume 1958), who emphasized the central role of geological constraints: "Die Schichtstufenlandschaft ist ein Ausdruck des inneren Baues"—the scarp landscape is an expression of inner structures (Schmitthenner 1956, p. 66). Among these constraints, he included not only the variable strength of rocks, expressed mainly in the form of the scarp, but also their variable permeability, which controlled seepage and denudation on the dip slope. Indeed, Schmitthenner's theory not only emphasizes scarp retreat but also focuses on the denudation of dip slopes by linear stream erosion and, especially, the formation of numerous seepage hollows, or *dells* (fig. 1). "The rivers and their mechanism of general erosion can be compared with the spring in a clock, *dells* perhaps with the pendulum which is just as important in the action. The old thesis: 'the step landscape is the work of the rivers' is only tenable in as much as the rivers give impulse and acceleration to the denudation process" (translated from Schmitthenner 1926, p. 23).

The language barrier precluded any widespread influence of Schmitthenner's work outside Germany, but recent work in sandstone scarplands on the Colorado Plateau and in Australia has confirmed the importance of seepage as a denudational factor. The recognition by Laity and Malin (1985; see also Laity 1988) of the critical role of groundwater sapping in sculpting dip-slope canyons in parts of the Colorado Plateau has been strongly supported by the study of *cuesta* landform assemblages in that region by Howard and Kochel (1988). Howard and Kochel also demonstrated the importance of surface solutional processes, and their observa-

tions have been extended by the recognition of giant weathering pits many meters deep (Netoff et al. 1995).

Whereas these observations from the Colorado Plateau have been on arkosic sandstones, numerous solutional landforms caused by etching of siliceous cement and quartz grains have been observed in highly quartzose sandstones in Australia (R. W. Young 1986, 1987; Wray 1997a, 1997b). Solutional weathering of sandstone near Sydney has produced numerous seepage hollows, similar to Schmitthenner's *dells* (A. R. M. Young 1986). Young's recognition of the significant denudational role of *dells*, far beyond the limits of Pleistocene cold climates, and her observation that *dells* may undergo repeated cycles of filling and flushing are important because Schmitthenner's critics in Europe had dismissed such features as periglacial phenomena postdating scarps and *cuestas*.

Ironically, while research overseas has lent support to Schmitthenner's idea, it has fallen from favor among many influential German geomorphologists who have expounded climatic explanations of scarplands. First advocated by Mortensen (1949), these explanations have been elaborated into a systematic theory (*Klimagenetische Geomorphologie*) by Büdel (1977) and Bremer (1989a, 1989b). In this theory, rock control, scarp retreat, valley excavation, and sapping are replaced as the dominant factors by sequential deep weathering and stripping of regolith. Instead of being formed by scarp retreat and fluvial erosion, scarplands are thus claimed to be sculpted "predominantly by areal downwearing" (Bremer 1989b). Indeed, Büdel (1977) dismissed the structural influences so clearly expressed in many scarplands in central Europe as only an "arabesque" in the general two-phased morphological development of deep weathering followed by erosion (fig. 1). Moreover, his major theoretical synthesis (Büdel 1977) dealt with scarplands under the heading "Etchplain Escarpment and Cuesta. Etchplain Stairways," thereby invoking previous tropical weathering regimes to account for such terrain in midlatitudes: "Most of the long *cuestas* (*Schichtstufen*) of S.W. Germany were formed under a tropicoid climate in the same way as etchplain escarpments" (Büdel 1977, p. 169). In that synthesis, he again dismissed structural control as being the product of recent climate cooling.

Although Büdel's theory has been very influential, it has not been accepted by all German geomorphologists. Geological influences, seepage, and dip-slope erosion continue to be emphasized by Blume (1976; see also Blume and Remmele 1989). Louis and Fischer (1979) also sought a more bal-

anced approach to the relative influence of climate and structure. And Stengel and Garleff (1987) have regarded structurally controlled scarps and cuestas as a transitional stage in the course of pediment expansion, similar to the early and late stages of Davis's cycle. Their conclusions, however, seem to have more in common with ideas of L. C. King than with those of Davis.

According to King (1953), most landscapes are shaped by the expansion of pediments at the base of retreating scarps (fig. 1), the key processes being mass failure and gullying operating on the scarp, together with sheet wash that planes the surface of the pediment. Although King's emphasis on wearing back rather than wearing down of slopes is often considered to be only a variation on the cyclical theme, in one critical aspect it is the very antithesis of Davis's theory. Whereas Davis argued that scarps, as well as the valley floors below them, are essentially shaped by streams, King maintained that scarps evolve independently of streams: "The scarps retreat virtually as fast as nick-point advance up rivers so that the distribution of successive erosion cycles bears no relationship to the drainage pattern whatsoever" (King 1953, p. 742).

Assessing which of these rival theories best explains a particular region is no simple task, and Blume (1976) has warned that none of them may be entirely satisfactory. On the contrary, he argued that a comprehensive theory of scarpland evolution would require considerably more quantitative, as well as qualitative, research. This study in central Queensland attempts such a contribution.

Climate, Geology, and Drainage

This region lies between the Tropic of Capricorn and 27°S, 300–600 km inland from the Australian east coast. The climate is subhumid and subtropical, with rainfall concentrated in summer. Annual average rainfall varies from about 620 to 700 mm. The mean annual maximum temperature is 30°C and the mean annual minimum is 16°C. The vegetation is dominantly savanna woodland, with riverine forests along streams in sheltered canyons. Until mid-Tertiary times, however, this region, together with the other now semiarid parts of the continent, received much higher rainfall, which supported substantial areas of rainforest (Martin 1994).

This scarpland lies in the southern part of the sedimentary, mainly Permo-Triassic Bowen Basin and the northern part of the overlapping Jurassic-Cretaceous Surat Basin. Large parts of the region are mantled by Oligocene and Miocene volcanics.

Since the regional dip of the strata is southward, the general alignment of the scarps is east-west; but locally they deviate along a series of folds that have a north-south strike (fig. 2). The Jurassic Precipice Sandstone crops out on the major scarp that dominates the northern part of the region. The Triassic Clematis Sandstone also forms prominent scarps, especially in the northeast where it is thickest. Other scarp-forming rocks are the Permian Colinslea Sandstone, the Jurassic Boxvale Sandstone and Jurassic Hutton Sandstone, and the sandy units of the Cretaceous Bungil Formation (Jensen 1975; Exon 1976). Basalt and trachyte also form scarps, especially in the vicinity of Springsure.

Variations in rock resistance have produced variable scarp morphologies (Galloway 1967*a*, 1967*b*, 1974). For example, a very abrupt scarp occurs where shale is exposed beneath the Precipice Sandstone (fig. 3). Exposures along the Carnarvon Gorge show that brittle failure in the shale causes collapse of the overlying sandstone either by the tilting of joint-bounded blocks or by the generation of fractures through intact blocks. Behind the main scarp, where the shale dips below the land surface, cliffs give way to irregular pyramidal sandstone hills and towers with dominantly convex "slickrock" slopes where there is strong cross-bedding in the sandstone (fig. 4). This change in morphology is linked to a change in process, for block failure is replaced as the dominant mode of breakdown by solution and granular disintegration. The terrain is thus very reminiscent of Gregory's description of the landscapes of the Navajo Sandstone on the Colorado Plateau where "cliffs are straight or undercut at the base and rounded at the top, and surfaces between canyons weather into domes, haystacks and teepees" (Gregory 1938, p. 96).

The drainage of the region is dominantly dendritic, rather than the trellis pattern characteristic of scarplands. Lateral (subsequent) streams, which are crucial to Davis's theory, are poorly developed here. Several major streams, notably the Maranoa and Warrego Rivers, flow down-dip to the south and southwest to join the Murray-Darling River system. A second main group of streams, especially the Comet and Nogoa Rivers, flow northward off the edge of the tilted strata, then turn eastward to join the Dawson River. The upper and middle reaches of the Dawson River are aligned eastward, obliquely to the regional dip, but even these are not subsequent in the Davisian sense, for instead of being aligned along the strike of weaker rocks, they cut across a wide range of rocks and structures (fig. 2).

Although the regional southerly dip has con-

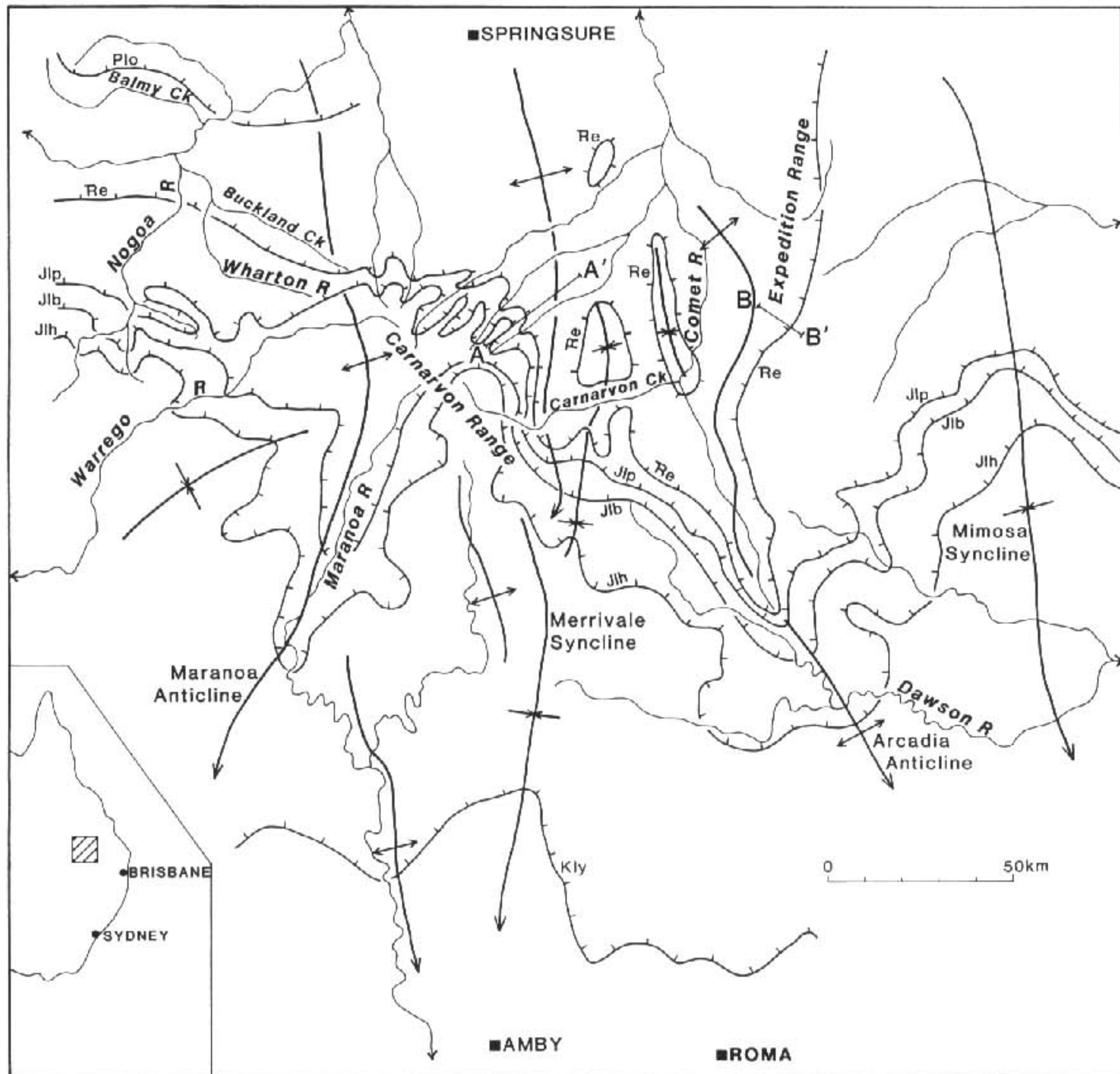


Figure 2. Scarps, structure, and drainage in central Queensland. The Mesozoic strata have a regional southerly dip, but stream alignment is controlled largely by secondary folds that strike north-south. Note the prominence of anticlinal valleys and synclinal mesas. The main scarp-forming rocks: *Plo*, Permian Colinlea Sandstone; *Re*, Triassic Clematis Sandstone; *Jlp*, Jurassic Precipice Sandstone; *Jlb*, Jurassic Boxvale Sandstone; *Jlh*, Jurassic Hutton Sandstone; *Kly*, Cretaceous Bungil Formation. For sections A-A', B-B', see figure 6.

trolled the direction of drainage, the positions of the major streams flowing southward have been largely determined by the secondary folds striking north-south. In several instances, ancestral valleys are preserved beneath basalt along synclines, most notably on the Merrivale Syncline where the basalt now forms the summit of a major synclinal ridge. However, the major streams flowing southward down the regional dip are, for much of their courses, aligned along the secondary anticlines (fig. 2). This

is also the case on major streams, like the Comet River, that flow north from the edge of the tilted sedimentary sequence.

Although many of these streams have incised deeply into weaker rocks in the cores of the anticlines, they typically display dendritic rather than trellis drainage. Trellis drainage is significant only in the middle and upper reaches of the Nogoa River catchment in the northwest part of the region, where secondary warping of the strata is less prom-

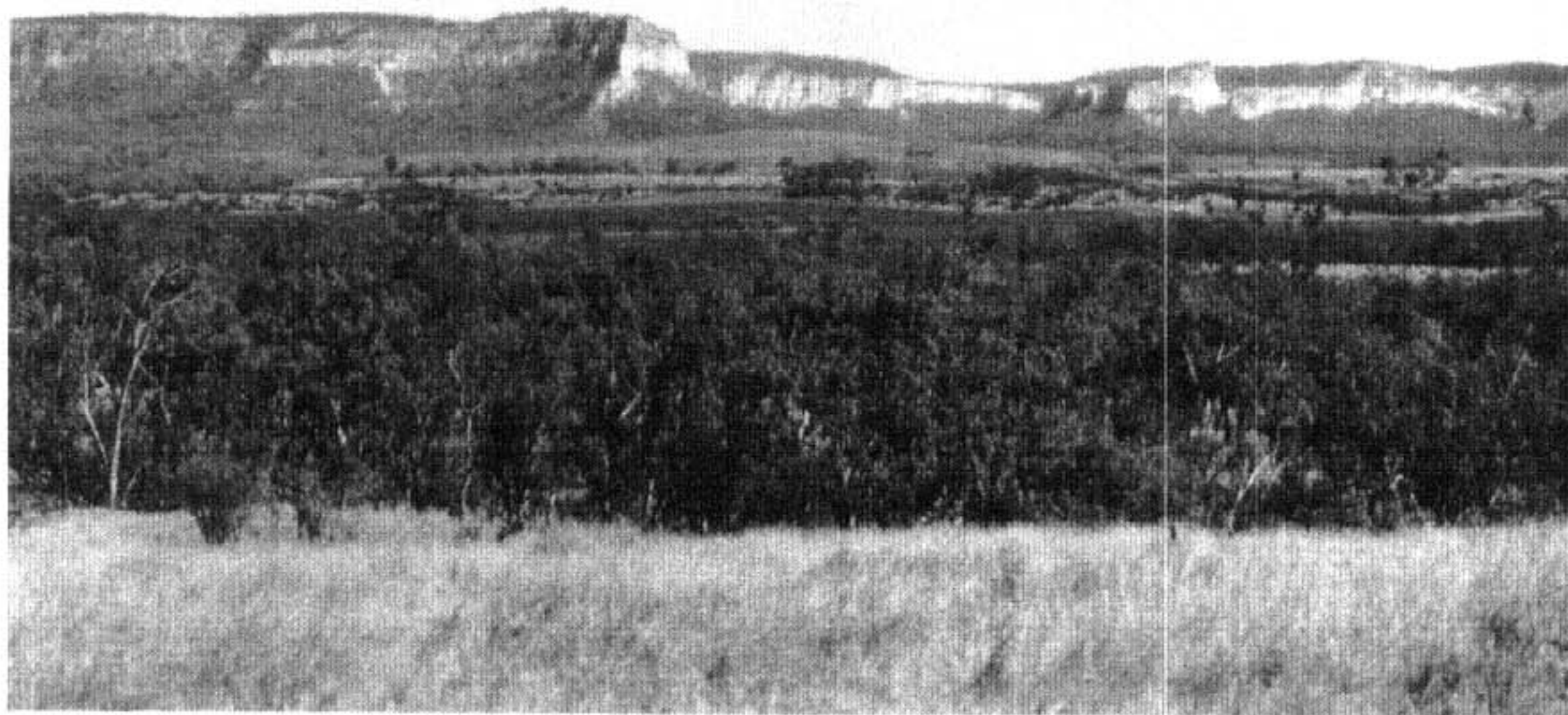


Figure 3. Main 150-m-high escarpment in the upper Nogoia River Valley. The cliffs are cut in the Precipice Sandstone and the lower slopes in the shaley Moolayember Formation.

inent. Even there, however, few streams have cut back along the strike of weaker rocks. The most notable example is Buckland Creek, which flows along the strike of the shales of the Rewan Formation (fig. 2). But several other lateral tributaries of the Nogoia River run along the strike of some of the most resistant rocks in the catchment. For example, Balmy Creek is incised into the Colinlea Sandstone rather than in adjacent shale, and several headwater tributaries have incised into the Precipice Sandstone behind the main scarp, their courses apparently being determined by a prominent set of joints in that sandstone (fig. 2).

There is also little reliable evidence of stream capture, which figures so prominently in Davis's theory of scarplands. Galloway (1967*b*) claimed that there had been a southerly migration of the drainage divide by some 50 km owing to the headward expansion of the Comet River and the capture of streams once draining to the Dawson River. But this claim, based mainly on the fact that Carnarvon Creek runs to the southeast before turning abruptly to the north to join the Comet (fig. 2), is difficult to sustain. Structural control seems more likely than river capture, since the alignment of the upper sections of Carnarvon Creek and of its tributaries is strongly constrained by major fractures. The only unequivocal change in drainage was a westward

shift of the drainage divide when the valley along the Merrivale Syncline was filled by basalt. Elsewhere the flow of basalt down the main valleys points strongly to continuity of drainage since at least Oligocene times.

Age and Distribution of Volcanic Rocks

The age of volcanic activity in the region has been well documented by repeated K-Ar dating (ages prior to 1977 have been recalculated using new constants). Webb and McDougall (1967) initially analyzed three whole-rock samples from a basal sequence of basalt near Springsure (fig. 5), which gave ages ranging from 28 to 35 Ma, but because these rocks show evidence of deuteritic alteration, these determinations must be regarded as minimum ages. Six whole-rock samples from the overlying sequence of basalt and pyroclastics gave ages from 24 to 28 Ma. The middle to late Oligocene age for the volcanic activity was supported by the approximately 28-Ma age for trachyte that intruded the extrusive basaltic sheets. Subsequent research has confirmed the work of Webb and McDougall. Bird et al. (1990) obtained an age of 28 Ma from basalt east of Springsure, and Sutherland (1985) obtained ages of 27 Ma from basalt at Springsure, 25–27 Ma from basalt southwest of Springsure, and 26 Ma

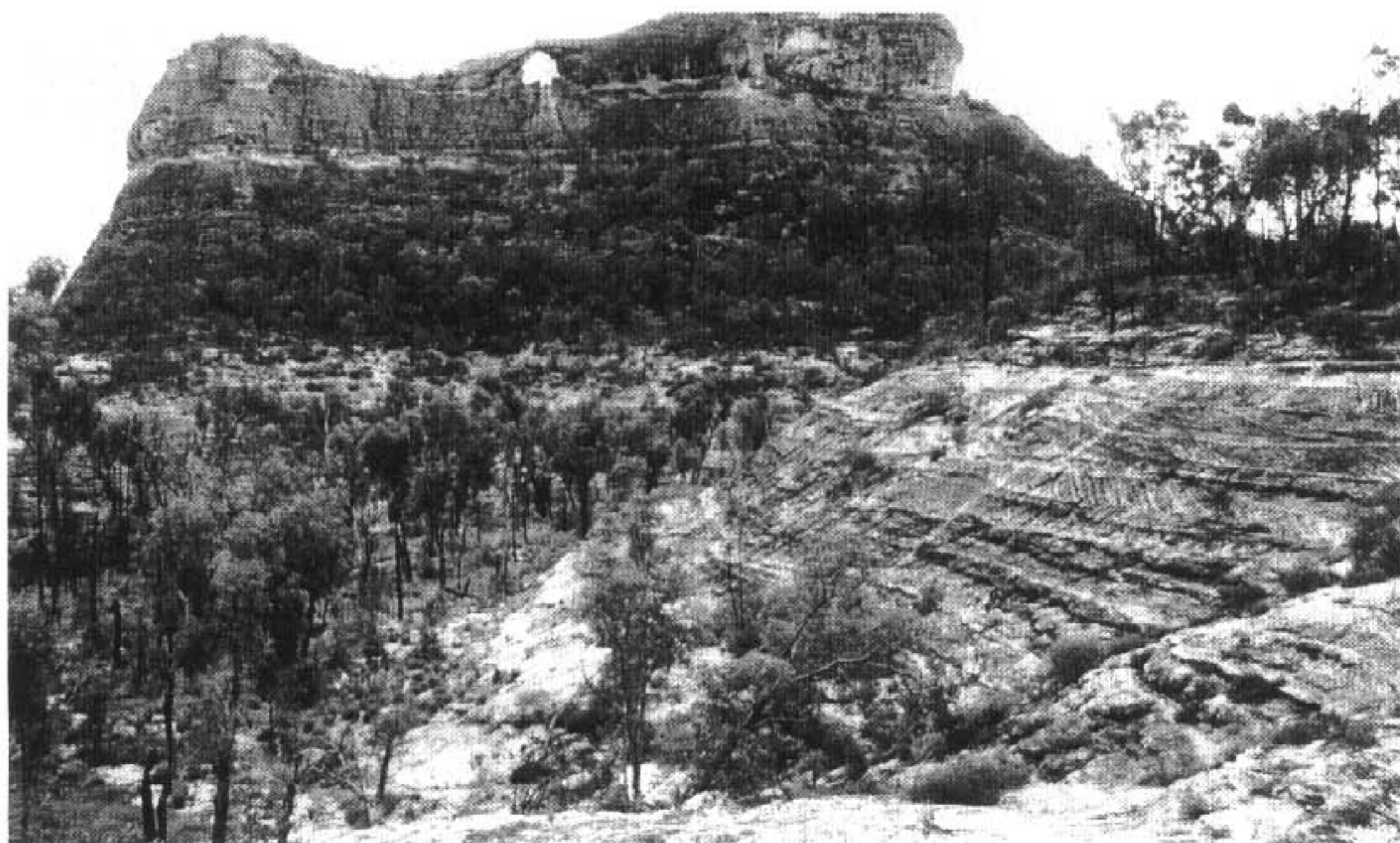


Figure 4. Dissected slickrock slopes in the Precipice Sandstone at Spyglass Hill, 3 km south of the main scarp on the upper Nogoia River. The prominent hole through the summit of the hill was initiated as a solution tube and subsequently enlarged by mass collapse and granular disintegration. Note the contrast between this site, where granular disintegration is dominant, and the main scarp, where block failure is dominant (cf. fig. 3).

from basalt in the eastern part of the region. However, volcanism in the southern part of the region near Amby and Roma (fig. 5) was distinctly later. K-Ar determinations on nine samples of basalt from this area gave ages at only 20–23 Ma, demonstrating that extrusion did not begin there until Early Miocene times (Exon et al. 1971).

Figure 5 shows the generalized distribution of the basalt. The basalt crops out at a wide range of elevations. In the north it forms the highest summits at about 1200 m on the Carnarvon Range and can be traced almost continuously to elevations of only about 150 m in the valley of the Comet River. It also caps the summit of the Expedition Range at about 700 m and can be traced eastward down to about 150 m. In the south it caps the summit of Mt. Hutton at 890 m and descends discontinuously downvalley to about 370 m near Amby. The total elevation range of the basalt in the region thus exceeds 1000 m.

Prebasaltic Topography

The generalized pattern of the contact of the basalt with the underlying strata is shown in figure 5 by subbasaltic contours derived from the geological

sheets and 1 : 100,000 topographic maps, supported by field checking along major roads. For cartographic clarity these contours are drawn at 200-m intervals. The pattern is relatively simple and shows that the base of the basalt descends from several high points both northward and southward along major drainage lines. Although localized deformation of the basalt cannot be ruled out, its relationship to the underlying Mesozoic rocks displays no sign of significant post-eruptive warping or faulting. The main fall of the basalt northward from the Carnarvon Range is counter to the southerly regional dip of the underlying sediments. Moreover, this 1000-m fall is not only topographic but also stratigraphic; the highest parts of the basalt overlie Jurassic strata, and the lower sections in the valleys to the north overlie Triassic and Permian strata (fig. 6). A similar relationship occurs on the Expedition Range where basalt caps the Clematis Sandstone, whereas basalt at the foot of that range lies on the Rewan Formation, which underlies the Clematis Sandstone (fig. 6). Furthermore, the east-west folding in the sedimentary sequence is not paralleled by the subbasaltic contours. On the contrary, much of the basalt descends from synclinal summits into anticlinal valleys (fig. 5), thereby demonstrating

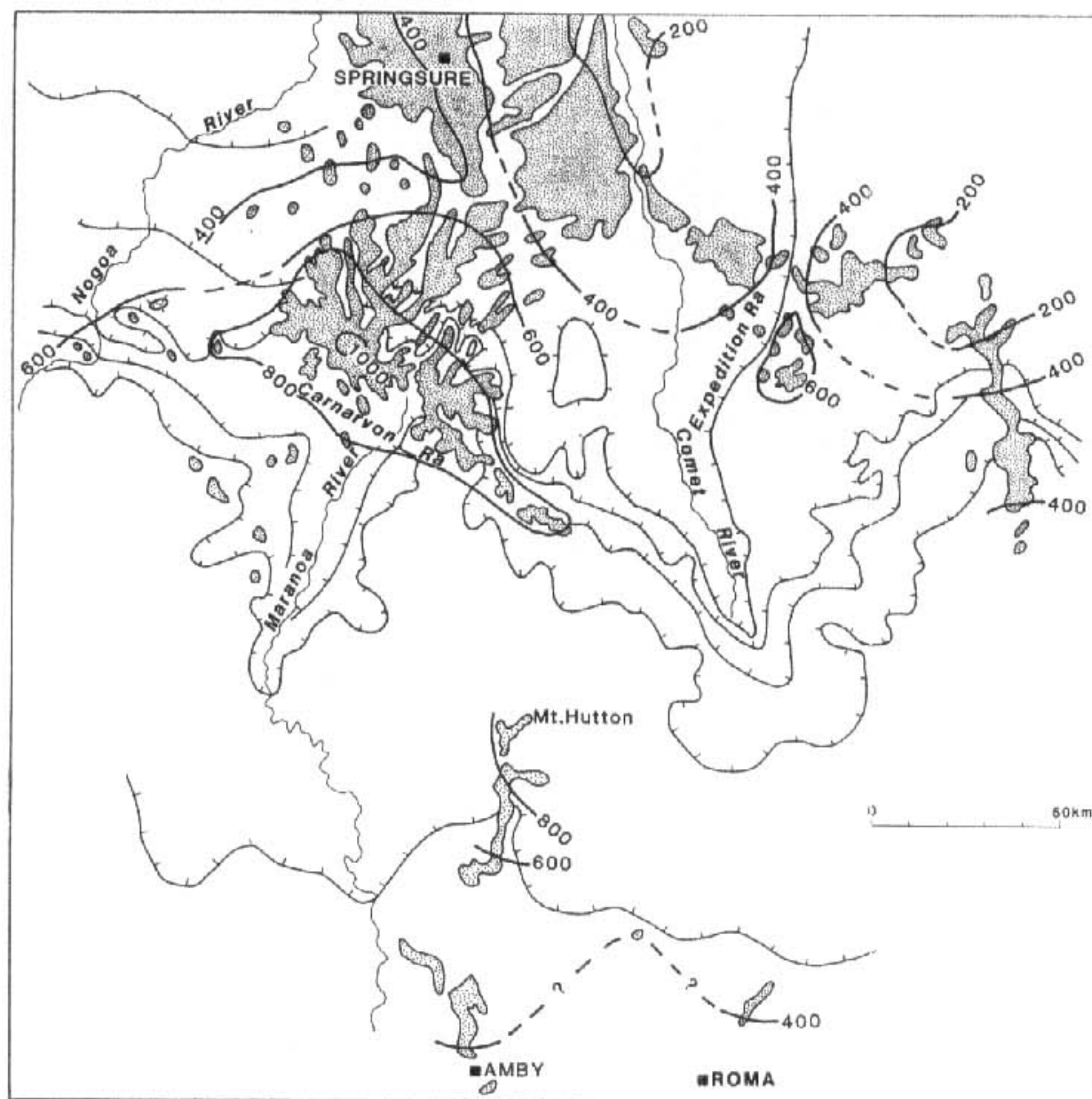


Figure 5. Relationship between the main scarps and the Late Oligocene and Early Miocene basalt. The basalt extends over almost the entire range of relief and the generalized subbasaltic contours drawn at 200-m intervals show no evidence of postvolcanic tectonics.

that the folding was followed by substantial erosion and, in places, topographic inversion prior to volcanism.

Extensive prebasaltic erosion also occurred on dip slopes south of the Carnarvon Range and in the Mt. Hutton and Amby areas. The base of the basalt again cuts across the Mesozoic strata. On the dip slope of the Carnarvon Range, the basalt flowed down valleys incised into the Precipice Sandstone and then onto a broad surface, 35 km wide, formed by the stripping of Late Jurassic sediments from atop the Precipice Sandstone. Farther south, basalt flowed down a shallow valley that extended down the plunge of the Merrivale Syncline from Late Jurassic rocks at Mt. Hutton onto Cretaceous rocks near Amby.

Since the present-day relief exceeds the subbas-

altic relief by only about 250 m and basalt on the valley floors is within a few kilometers of major scarps, the greater part of the erosional development of this landscape occurred prior to volcanism. Indeed, dating of prebasaltic weathering profiles east of Springsure (see below) indicates that, apart from the excavation of canyons into the basalt sheets and the rocks below them, the landscape had taken on essentially its present form by early in Tertiary times (see also Galloway 1967b).

Postbasaltic Erosion

The basalt provides an excellent spatial and chronological datum from which quantitative estimates of the various types of erosion can be made. Although the original thickness is often difficult to

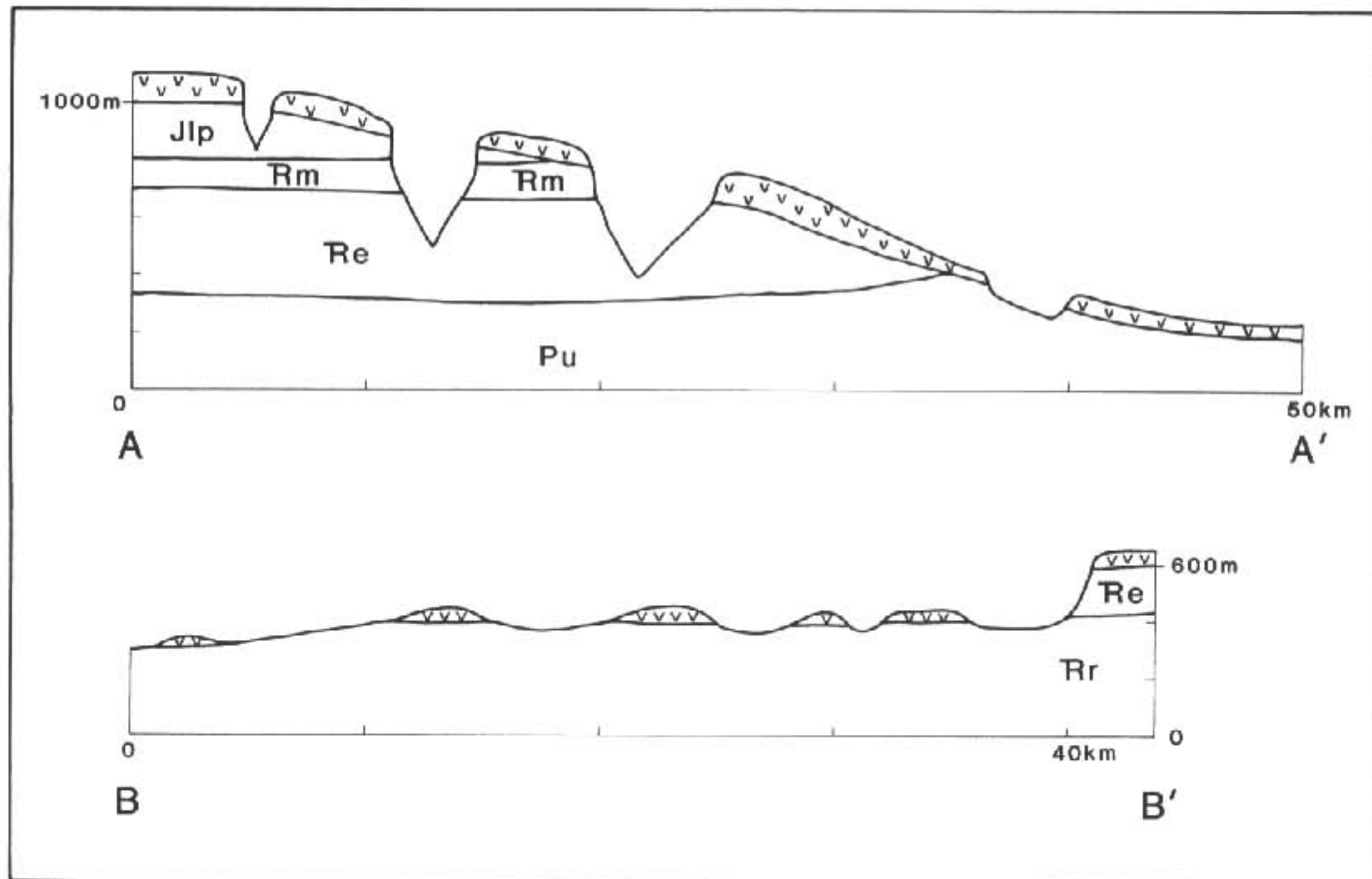


Figure 6. Sections showing the relationship between the Oligocene basalt (shown by V symbol) and the Mesozoic strata (locations on fig. 2). A-A' section from Carnarvon Range to the western side of the Comet River Valley adjacent to Rocky Creek; B-B' section from the Expedition Range to the eastern side of the Comet River valley. *Jlp*, Jurassic Precipice Sandstone; *Rm*, Triassic Moolayember Formation; *Re*, Triassic Clematis Sandstone; *Rr*, Triassic Rewan Formation; *Pu*, Permian Blackwater Group.

estimate, the flat tops of many basalt-capped summits indicate that there has been little stripping from them. Relative erosional stability is also indicated by the preservation of lateritic weathering on many gently inclined basalt outcrops, since the last phase of such weathering probably is no younger than Late Miocene (Coventry et al. 1985). Furthermore, although the postbasaltic sedimentary sheets in the major valleys are extensive, they are dominantly siliceous, derived primarily from the Mesozoic strata rather than from the basalt; nor have they significantly masked the extent of the basalt. Therefore, while the estimates given here are strictly minimum rates of erosion, they probably do provide reasonable indicators of actual post-basaltic rates.

Canyons cut back from the floors of the Nogoia and Comet Valleys into the basalt-clad escarpment vary from about 30 to 60 km in length. Postbasaltic extension of the canyons thus occurred at rates averaging 1–2 km/m.yr. and was more rapid on streams draining northeast that cut through more shale than streams draining farther west. The distance to which the canyons have penetrated beyond

their Oligocene limits can be estimated from the location of the Precipice Sandstone buried under basalt. The variable resistance of the Mesozoic rocks has again been significant, for canyons in the northeast have extended 14–20 km beyond their apparent Oligocene limits, while those farther west have extended only 3–5 km. The width of these canyons has also been geologically controlled, for those draining to the northeast are 6–7 km wide, whereas those farther west are only about 3–4 km wide.

The depths of postbasaltic incision by streams varies greatly throughout the region. The stream channels on the wide valley floors to the north, close to regional baselevel, have incised only about 50 m below the adjacent basalt, at an average rate of about 2 m/m.yr. (see also Galloway 1987). Canyons on the north side of the Carnarvon Range have cut deeply below the summits of the basalt, but there is considerable depth variation within the canyon tract. Estimates of rates of incision were therefore obtained by sampling at 830 points on the 1-km grid of the 1 : 100,000 topographic sheets. The maximum depth is 670 m and the mean depth is

365 m; the corresponding rates of incision are 25 and 13 m/m.yr.

Substantial postbasaltic erosion also occurred on streams draining southward down-dip on the southern side of the Carnarvon Range. Sampling of 100 points on the 1:100,000 topographic sheets indicates that they incised to a maximum depth of 450 m (17 m/m.yr.) and to a mean depth of 270 m (10 m/m.yr.) through the basalt and into the Precipice Sandstone. Similar erosion depths occur as far south as the fossil valley near Mt. Hutton, where Early Miocene basalt lies about 450 m (20 m/m.yr.) above the adjacent lowland. The topographic potential for erosion decreases farther south toward the regional base, and near Amby the present floor of the Maranoa Valley is only 15–20 m below adjacent basalt and silcrete (Exon et al. 1971), giving an incision rate of about 1 m/m.yr. Nevertheless, the depths and rates of erosion on the dip-slope streams are not much less than those of streams that have cut back into the main northern escarpment.

Valley extension rather than scarp retreat has been the dominant form of erosion in the shaping of this landscape. The distance between basalt and the foot of adjacent scarps varies from only 0.5 km to about 4 km. Thus, in a range of geological settings throughout the region, the rates of postbasaltic scarp retreat ranged from about 18 m/m.yr. to about 130 m/m.yr. Comparison with the estimated rates of postbasaltic headward valley extension shows that the latter has been at least an order of magnitude greater. This difference is due to the much greater concentration of erosive energy in the discharge through stream channels than in the mass movement, sheetwash, and gullying operating on the scarp faces.

The dominance of headward extension of canyons, as opposed to scarp retreat, has also been demonstrated by studies from southeastern Australia published previously in this journal (Young 1983; Bishop et al. 1985; Young and MacDougall 1993; Nott et al. 1996). In that region, canyon extension ranged 1–2 km/m.yr., whereas scarp retreat generally ranged from only 10 to 170 m/m.yr. and at one site it has been only 0.3 m/m.yr.

Although these rates of erosion are extremely low when compared with general worldwide rates (Summerfield and Hulton 1994), similar rates have been reported for some continental settings. For example, Ward and Carter (1999) estimated that rates of incision on the Arkansas River since the late Tertiary ranged from about 6 to 97 m/m.yr. R. A. Young (1985) demonstrated that scarp retreat on the Colorado Plateau since Miocene times has averaged

only about 160 m/m.yr. Young also demonstrated that during and immediately after the Laramide uplift, scarp retreat averaged between 1.5 km and 3.8 km/m.yr. and suggested that the dramatic reduction in rates of retreat during the Late Miocene–Pliocene coincided with the incision of streams on the plateau; the slower rates may indicate that rapid cliff recession in cuestaform landscapes is favored only by stable or rising baselevels, whereas drainage incision causes irregular scarp dissection by random headward growth of scarp-face tributaries (R. A. Young 1985). A corollary of this hypothesis is that erosion surfaces form rapidly, but their destruction by stream incision takes place at rates an order of magnitude slower. Young's idea is highly significant because it reverses the assumption of the classical cycle of erosion that erosion surfaces develop slowly and that the destruction of such surfaces by stream incision is much more rapid.

The scarplands of central Queensland, where the canyon tracts have undergone major postbasaltic incision but the lower valley tracts have been essentially stable for at least 30 m.yr., provide an interesting comparison to R. A. Young's observations. The average amount of retreat of the canyon walls varies from about 1.5 to 3.5 km. When allowance is made for the delay in postbasaltic knickpoints migrating from the broad valley floors to the main canyon tracts, the canyon walls retreated at an average rate of 150–250 m/m.yr., closely comparable to that of scarp retreat associated with stream incision on the Colorado. However, the rates of postbasaltic scarp retreat on the valley floors, where there has been negligible incision, have been approximately an order of magnitude less than the rates of canyon wall retreat. In contrast to R. A. Young's suggestion for the Colorado Plateau, scarp retreat in this region seems to have been more rapid during incision and to have slowed down as relatively stable baselevels were achieved. Since most of the widening of the main valleys in this region occurred before 30 Ma, indeed about 90% of it on the eastern flank of the Comet River Valley, rates of scarp retreat were probably enhanced under the much wetter climates during the Early Tertiary.

Relict Weathering

Relict kaolinitic weathering is preserved under basalt east of Springsure. K–Ar determinations on alunite in these profiles indicate two periods of weathering: the first at 62 Ma and the second at 49–47 Ma (Bird et al. 1990). An even greater age was indicated by the similarity of the oxygen iso-

tope signatures of kaolin on the Staircase Range to those of weathering dated as pre-late Mesozoic elsewhere in eastern Australia (Bird and Chivas 1989). However, as reworking of kaolin from Permian rocks cannot be ruled out at this site, the weathering may be younger than isotopic signature indicates.

The Early Tertiary profiles appear to have been stripped from the southern part of the region (Exon et al. 1971), where the oxygen isotope signature of kaolin indicates only a maximum Late Oligocene–Early Miocene age for weathering (Bird and Chivas 1989). This later weathering event is also recorded both in the north and in the south by extensive silcretes, many of which underlie basalt (Gunn and Galloway 1978; R. W. Young 1985). And as noted previously, comparisons with findings farther north in Queensland (Coventry et al. 1985) suggest that the lateritic profiles developed both on the basalt and on postbasaltic sediments are of at least Late Miocene age.

The preservation of relict deep weathering prompts serious consideration of Büdel's theory of scarpland evolution, but it cannot automatically be assumed that the landscape as a whole is the product of deep chemical etching and downward stripping of regolith. On the contrary, Büdel's theory encounters major difficulties here. First, there was a great span of time (ca. 50 m.yr.) between the close of sedimentation and the weathering of the oldest relict profile, during which at least 600 m of rock were stripped. Second, since the thickest relict profile is only about 15 m deep, and most are <5 m, it is difficult to see how stripping of such intensely weathered material can account even for the 250 m of subsequent lowering of the valley floors. Third, the subbasaltic silcretes, together with the sands and gravels incorporated in postbasaltic laterites, show that coarse debris, and not just kaolinitic regolith, was being formed on the hillsides and transported onto valley floors during the main weathering events. Fourth, as demonstrated previously, the dominant form of denudation, both before and after volcanism, has been the cutting of valleys, not the forming of etchplains. Finally, Büdel's and Bremer's insistence that scarplands are sculpted by downwearing, and that horizontal retreat of outcrop is negligible, is very much at odds with field evidence here, where the Precipice Sandstone has been pushed back 80 km and the Hutton Sandstone has been pushed back 100 km from their northernmost outcrops (fig. 2).

Seepage and Solution

Since the Precipice Sandstone is a major aquifer, there is considerable groundwater seepage along the scarps and on the dip slopes. However, the seepage is not primarily from bedding or joint planes but rather is concentrated at point sources because it moves mainly through integrated networks of tubes. These networks of tubes are very numerous and range in diameter from a few centimeters to several meters (R. A. L. Wray, unpub. data) (fig. 7). Many of them, now perched high on cliff faces, are inactive or discharge only after prolonged rain, but those feeding directly into major streams have substantial discharges and flow all year. For example, the estimated discharges from springs along Louisa Creek, a headwater tributary of the Nogoa River, range from about 600 m³/d to about 19,000 m³/d (Finlayson and Brizga 1993), and the springs flow strongly even in the middle of the dry season. While seepage facilitates the sapping of cliffs, the concentration of flow from point sources promotes linear erosion by streams, both on the scarps and on the dip slopes. Seepage and linear stream erosion have resulted in very active denudation on the dip slopes. Consequently, the dominance of erosion on scarp faces and along the strike of weaker strata necessary for large-scale retreat of drainage divides has not occurred here.

At some places, scarps have been breached from the rear by dip-slope valleys, in a fashion similar to that observed on the Colorado Plateau by Howard and Kochel (1988) and in the Black Forest by Blume and Remmele (1989). Probably the best example in this region is the breaching of the Colinlea Sandstone scarp by the northern tributaries of Balmy Creek (fig. 8). These tributaries, which run southward down the dip, have incised through the sandstone into shale. Erosion of these weaker rocks at the head of the dip-slope valleys has resulted in the sapping and removal of sandstone along 27 km of the scarp crest. The dominant role of the tributaries of Balmy Creek in the stripping of the scarp crest is demonstrably the lack of any southward indentation in the drainage divide that would result from a gain of ground by streams draining northward from the scarp face (fig. 8).

Large swampy dells occur on the southern side of the Carnarvon Range, but this type of landform is not common on such permeable sandstone. Nonetheless, numerous towers and pinnacles show that interfluvic surfaces on the Precipice Sandstone have been lowered by as much as 50 m. These protuberances are similar to the sandstone tower karst reported from various parts of Australia (Twidale

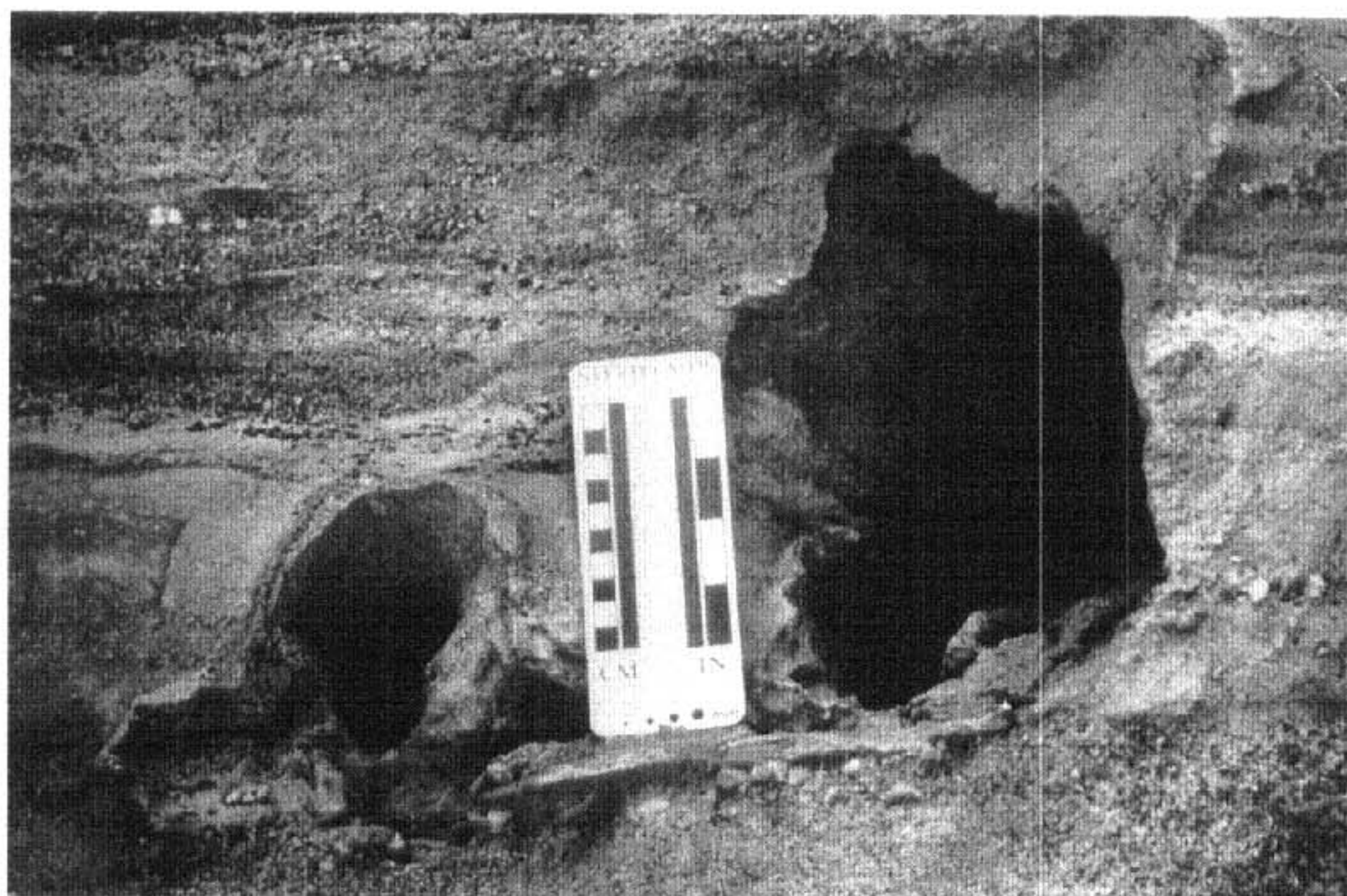


Figure 7. Seepage through the Precipice Sandstone occurs mainly through integrated networks of tubes, rather than along bedding planes. The walls of the tubes are indurated with precipitated silica.

1956; Jennings 1983; R. W. Young 1986; Young and Young 1992; Wray 1997a). As in those cases, the towers in this region have been substantially shaped by groundwater seepage. Most of them display solutional flutes, most have flanges associated with footslope weathering (Twidale 1962), and most are pierced by inactive networks of tubes. Some have vertical sides, whereas others have predominantly rounded "slickrock" slopes. Moreover, microscopic thin sections show extensive etching of quartz grains (R. A. L. Wray, unpub. data).

Conclusions

The development of the theory of cuestas and scarplands has not been an orderly, cumulative process of testing, modifying, or discarding hypotheses. On the contrary, it has been characterized by research couched within different conceptual frameworks that have had a lasting, though often unrecognized, influence. Thus, while increasing attention has been given to scarp processes, Davis's emphasis on planation by streams extending along the strike of weak rocks is still widely accepted as typical of scarplands. This is true not only of many works published in English but also of most of

those published in French, despite their rejection of Davis's terminology. And it must be said that Davis's conclusions do fit the field evidence in many places. Indeed, the initial challenge from German geomorphologists was directed not primarily at Davis's interpretation of particular sites but rather at what was perceived to be his expansion of a special case into a general rule. Detailed studies in the German scarplands led to very different conclusions, emphasizing the critical role of seepage and solution, rather than lateral planation, both in scarp retreat and the denudation of dip slopes. But because of the language barriers, this research had little influence overseas so that when the critical role of seepage on the Colorado Plateau was recognized 60 yr later, it was quite independent of the German work. Moreover, while the role of seepage in scarplands was being increasingly demonstrated overseas, it had been largely superseded in Germany, where advocates of climatic geomorphology sought to explain the modern landscape in terms of etchplains formed under past tropical weathering regimes.

The extent to which these divergent theories explain the development of the scarplands of central Queensland can be assessed primarily from the dis-

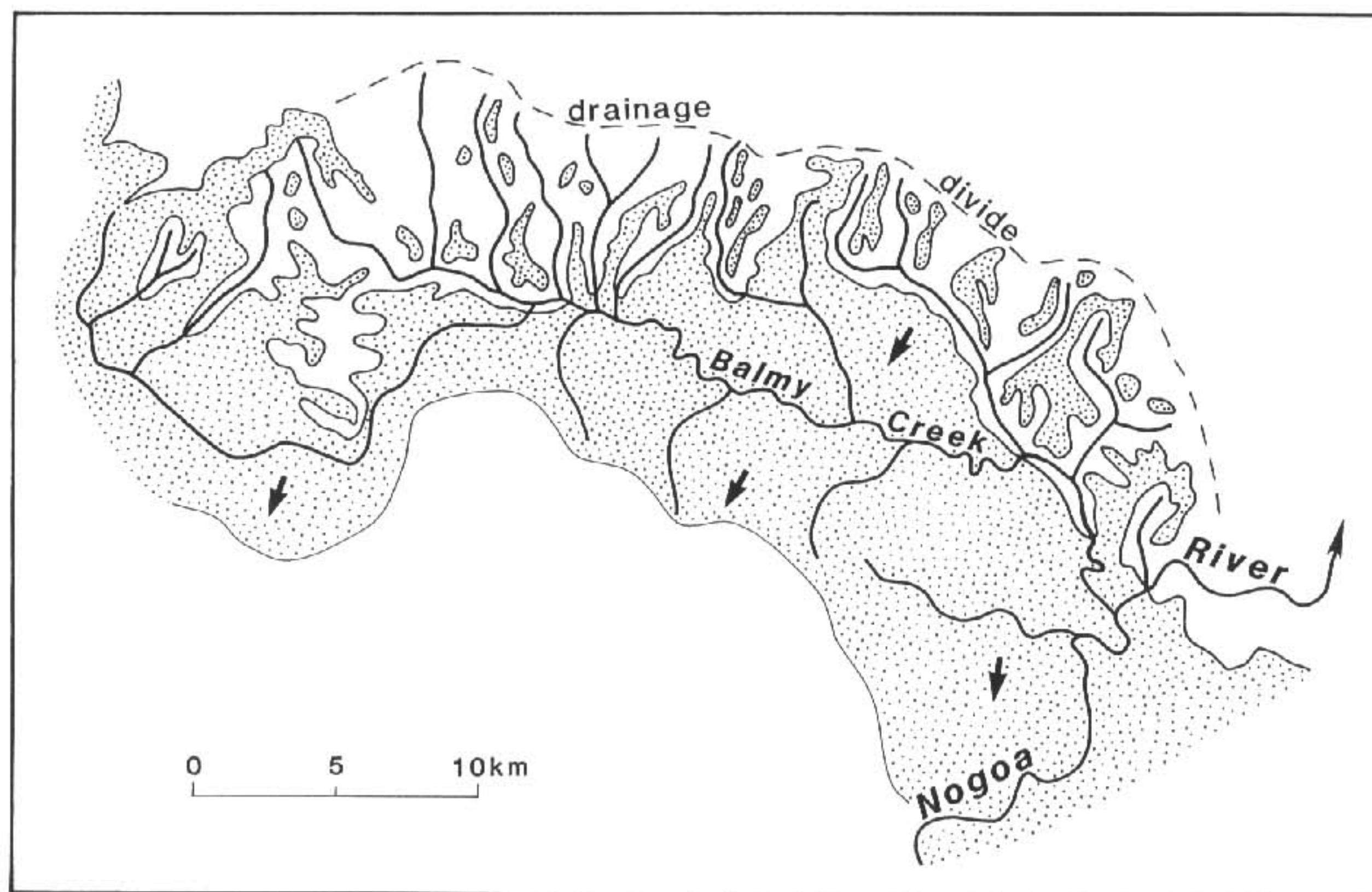


Figure 8. Colinlea Sandstone (*shaded*) is dissected and the scarp breached from the rear by dip-slope tributaries of Balmy Creek (arrows indicate the dip). The position of drainage divide near the foot of the scarp shows the dominance of erosion by dip-slope streams rather than scarp-front streams.

tribution of the extensive mid-Tertiary basalt. The shaping of this landscape has been slow by general world standards. Denudation began in the late Mesozoic, and much of the landscape had attained essentially its modern form when volcanism occurred during the Late Oligocene and Early Miocene. The dominant form of postbasaltic erosion has been the headward extension and deepening of canyons. The rate of retreat of scarps between the main streams has been an order of magnitude less than that of the canyon heads. Thus, the concept of the retreat of scarps independently of the drainage lines, advocated so vigorously by King (1953), does not hold here.

Because of the slow rates of denudation, relic weathering profiles dating from Cenozoic times are preserved over substantial areas of this region. But the landscape cannot be primarily attributed to the stripping of deeply rotted rock and formation of etchplains following a major shift in climate. The weathering profiles are too shallow; the sedimentary record shows the dominance of quartzose rather than kaolinitic debris throughout the Ce-

nozoic; and extensive valleys were cut into hard rock.

Observations here support Davis's contention that scarplands are the product of the variable resistance of rocks to the distribution of erosive energy, which is concentrated along major streams. But subsequent streams, which are the dominant erosive agents according to Davis, are poorly developed here. Instead of a progressive transformation of the drainage pattern, as predicted by Davis's model, the major features of this pattern were already established prior to basaltic extrusion in the Oligocene and Early Miocene. Continuity of drainage has been the general rule here during much of the Cenozoic.

Seepage through the sandstone has played a major role in promoting erosion by streams. However, unlike parts of the Colorado Plateau where seepage greatly favored the extension of canyons on streams draining down-dip, seepage here has not been controlled by the dip of particularly porous rocks. Instead of the seepage being diffuse, it is concentrated in networks of tubes. These networks are subsur-

face tributaries of the main drainage systems and are thus largely independent of regional dip. Surface solutional features are also well developed here. However, unlike those observed in arkosic sandstones on the Colorado Plateau, these are in quartz arenites and were formed mainly by the etching and removal of quartz grains.

The development of the scarplands in central Queensland has been controlled by the concentration of erosive energy along major streams, the overall continuity of the drainage pattern, the effects of seepage, and the variable resistance of rock to these and other denudational factors. Our conclusions are thus an extension and justification of

ideas first outlined in the pioneering research of Hettner and Schmitthenner during the early decades of the past century.

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