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The Lapstone Structural Complex, New South Wales

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The Lapstone Structural Complex forms the most prominent topographic feature in the Sydney region. The complex consists of a number of related folds and faults, trending generally north–south, which together form a large south-plunging structure between Kurrajong Heights and Lapstone. The east-facing escarpment of the Blue Mountains, formerly called the Lapstone Monocline, varies in its character, being sometimes a single monocline, sometimes a double monocline and sometimes a normal or high-angle reverse fault. Faulting west of Kurrajong and at Glenbrook is part of a series of overlapping *en echelon* faults, west-side down, and sometimes overturned, rather than a single fault. This fault system forms the west side of the complex. Significant minor structures associated with major features include thrusts, minor folds, joint systems, tectonic breccias, sedimentary injections and igneous dykes. Many of the minor structures show a marked parallelism with the major structures.

The main period of deformation forming the complex is believed to have taken place in the Early Tertiary, but the overall structure has a long and complex history. Field evidence suggests that sinistral strike–slip faulting played a part in the deformation, particularly of the near-surface rocks. Basement block faulting was also significant, producing the Cumberland Basin and associated structures when the main Lapstone structures were formed. Basement structural control is believed to consist of the northerly extension of the western edge of the Eden–Comerong–Yalwal Rift intersected by elements of the east-trending Lachlan Lineament.

Key words: basement lineaments, block-faulting, minor structures, monocline, normal and high-angle reverse faults, structural complex, strike–slip.

INTRODUCTION

The Lapstone Structural Complex, 60 km west of Sydney, consists of a number of structures (generally elongated north–south) between Warragamba in the south and the Colo River, a distance of some 50 km (Figs 1, 2). One of these structures forms the Lapstone–Kurrajong escarpment, the most prominent topographic feature in the Sydney region. The escarpment marks the abrupt eastern edge of the Blue Mountains Plateau where it abuts against the Cumberland Plain (Fig. 3). Work by Branagan (1969, 1975) and Herbert (*in* Smith 1979), demonstrated that the Kurrajong and Glenbrook Faults were separate members of a series of *en echelon* faults, west-side down, situated west of the main escarpment, and generally parallel with it (Fig. 4).

Intimately associated with the major structures is a variety of small-scale structures. These have received little attention previously, but their study has proved important in elucidating the deformational history of the region.

Branagan and Pedram (1982) presented a preliminary account of the findings reported in this paper, and detailed discussion of some aspects was given by Pedram (1983). Some conceptual ideas on the faulting were presented by Branagan (1983).

STRATIGRAPHY

The Lapstone Structural Complex consists mainly of sedimentary rocks of Triassic age, relicts of Tertiary gravel, and minor occurrences of igneous rocks (mainly dykes and necks) and Quaternary sediments.

Triassic rocks

The Hawkesbury Sandstone, the major unit exposed along the complex, is characteristically cross-bedded. It is overlain in places by up to 6 m of Mittagong Formation, consisting largely of laminated siltstone. This unit is overlain occasionally by Ashfield Shale. When the Mittagong Formation is absent, the Ashfield Shale rests disconformably on the Hawkesbury Sandstone.

Post-Triassic Sediments

Post-Triassic sediments are limited in extent, patches of gravel disconformably overlying the

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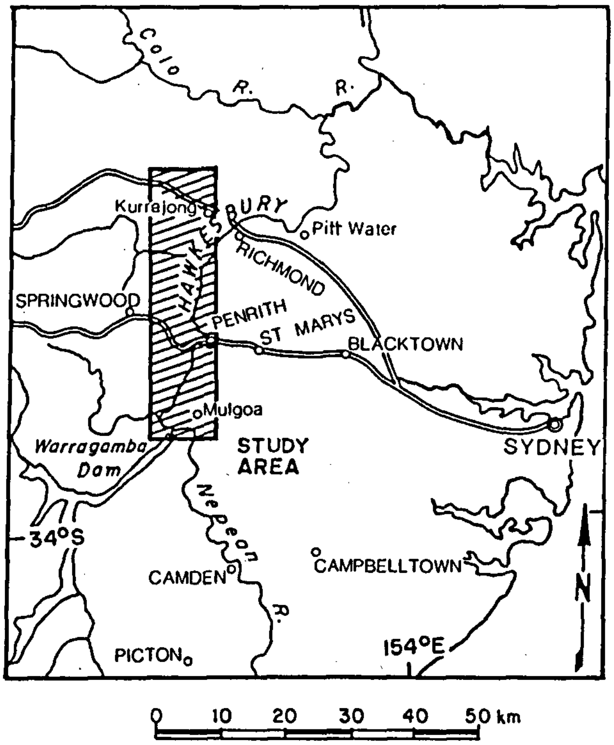

Fig. 1 Locality map.

Triassic rocks (Fig. 4). Despite their sporadic distribution, these deposits give important clues to the history of tectonism.

Generally the gravels can be divided into four groups based on their topographic occurrences: (1) on the Blue Mountains Plateau; (2) on the limb of the South Lapstone Monocline (see below); (3) on the high-level surface of the Cumberland Plain; and (4) in the present Nepean–Hawkesbury River drainage system. Gobert (1976) named the third of these the Rickaby's Creek Formation, and the fourth the Cranebrook Formation. Gobert (1978) included the first two with the Rickaby's Creek Formation as did Pedram (1983) and Bishop (1986), but they may be older. The first three groups of gravels have a varying degree of cementation and those on the plateau and monocline are lateritized.

All four groups contain pebbles derived essentially from the same locations — the drainage basins of the Cox and Wollondilly Rivers to the southwest — and the main source may be the thick Permian fluvioglacial gravels in that region. Bishop

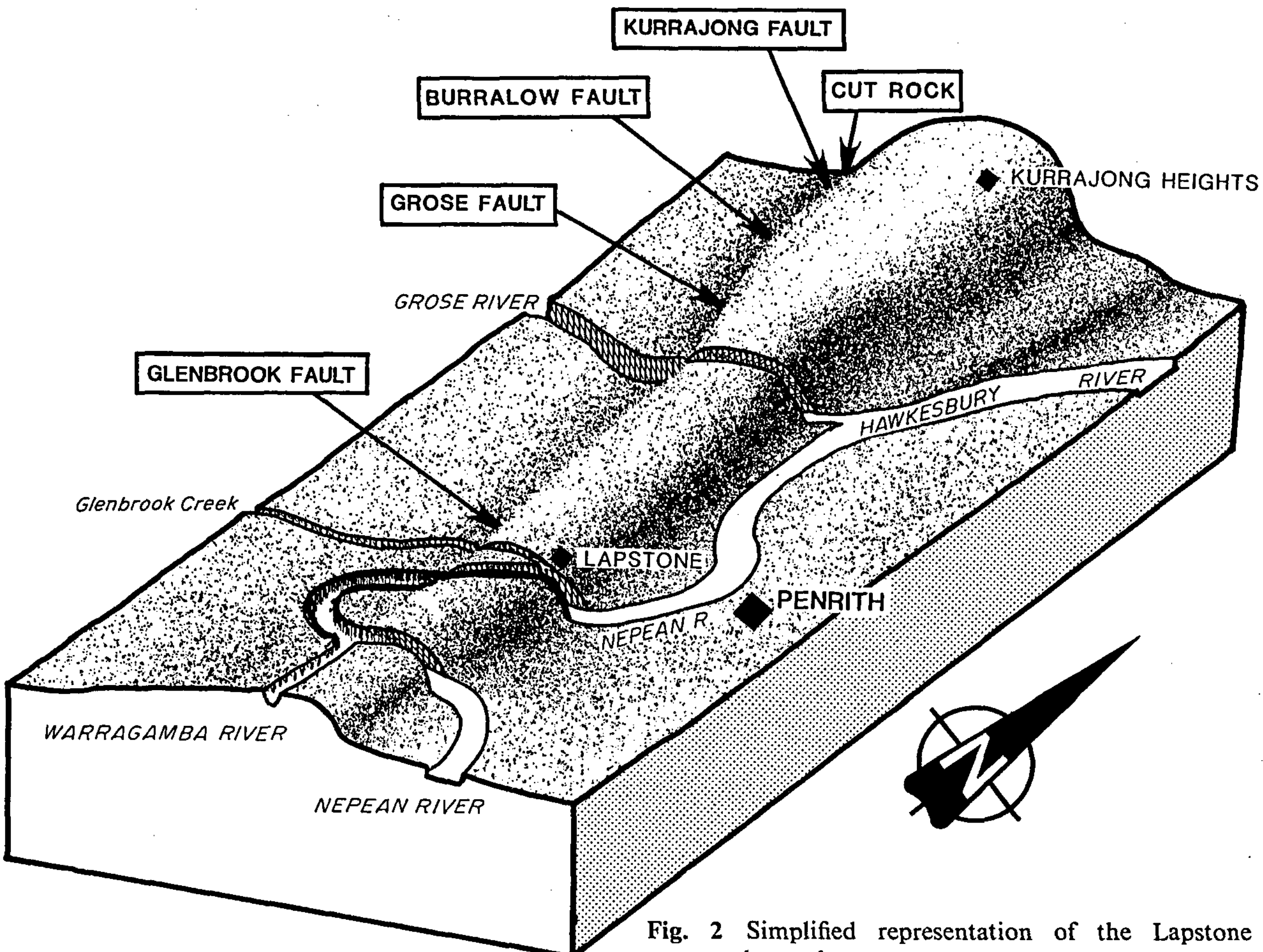

Fig. 2 Simplified representation of the Lapstone structural complex.

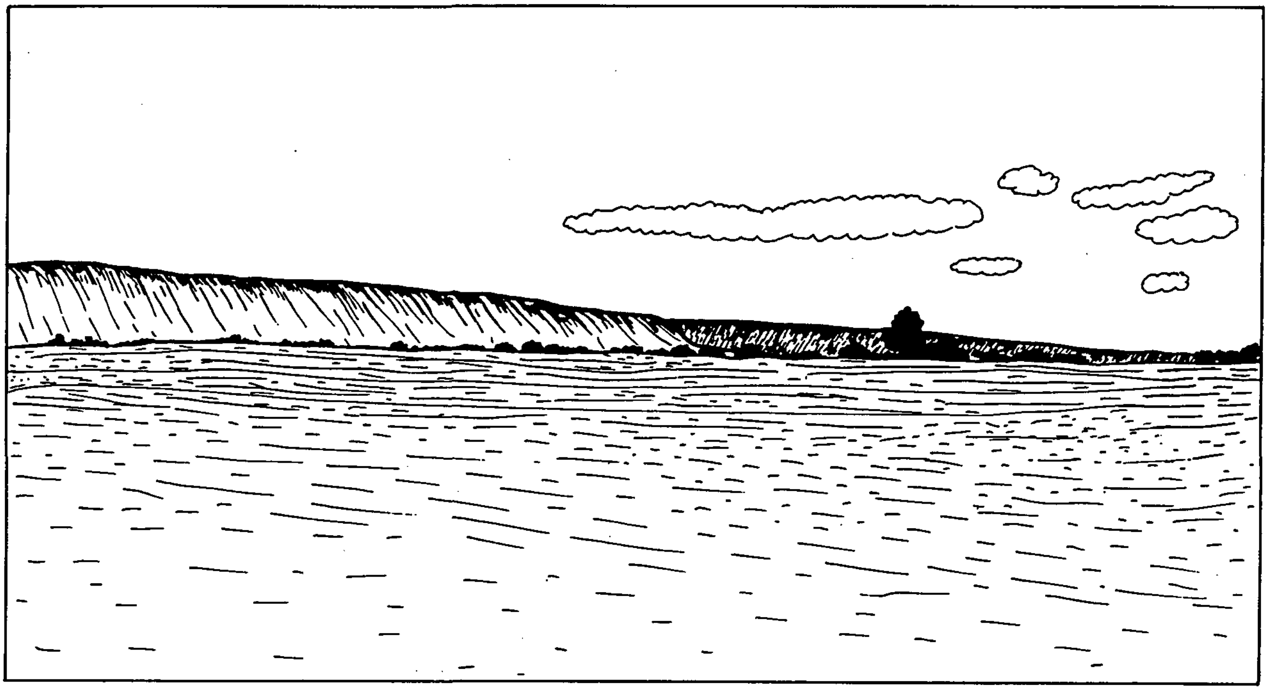

Fig. 3 Lapstone structure. View towards the north from Cranebrook showing Mount Riverview Fault and 'step back' west at Grose River.

(1986), after studying imbricated structures within the Lapstone gravels, thought there had been no significant change in the direction of flow of the Nepean River system transporting the gravels during its long history.

Although the age of the gravels on the monocline is not well defined, all the authors who have studied them, for example Branagan and Packham (1967), Taylor (1970), Gobert (1978), Bishop *et al* (1982) and Bishop (1986), suggest a Tertiary age of Miocene or possibly older. Gravels of the present Nepean–Hawkesbury river system at Cranebrook north of Penrith (GR 862270) have been dated at 45 000 years BP (Nanson *et al* 1987).

Igneous rocks

Igneous rocks in the area are confined to a few volcanic dykes and necks. They are mainly basaltic and are now largely altered to clay. A west-trending dyke is exposed at Bellbird Hill, Kurrajong-Heights (GR 803862), and one trending 350° is present at Glenbrook (GR 812608). In the Grose Valley there are three vertical and almost parallel dykes trending north–northwest. These dykes follow the trend of the nearby Grose Fault.

Basaltic breccia necks exist at Diamond Hill near Kurrajong (GR 833874), at Norton's (GR 798508) and Bent's (GR 810427) Basins adjacent to the main eastern monocline–fault structure. The Green Scrub Basalt north of the area (GR 798942) appears to be cut by the Kurrajong Fault and rests on the Ashfield Shale. Wellman and McDougall (1974) determined the age of this basalt as 18.8 Ma.

MAJOR STRUCTURES

The Lapstone–Kurrajong escarpment can be divided from south to north into four structural zones: the Nepean Fault, South Lapstone Monocline, Mount Riverview Fault, and North Lapstone Monocline (Fig. 4).

The Nepean Fault

This feature is the dominant structure south of Mulgoa. The fault is well-exposed at Bent's Basin where a zone of sandstone overlain by shale, some 80 m wide, dips mainly easterly at 80°, but there is one exposure of overturned beds dipping 85° to the west. The dipping beds abut in the west against almost horizontal sandstone. Although there is topographic expression of the fault scarp for some kilometres to the south, the fault is poorly exposed elsewhere and has been only cursorily examined in this study. Sherwin and Holmes (1986) indicated that it is sometimes a monocline. From field

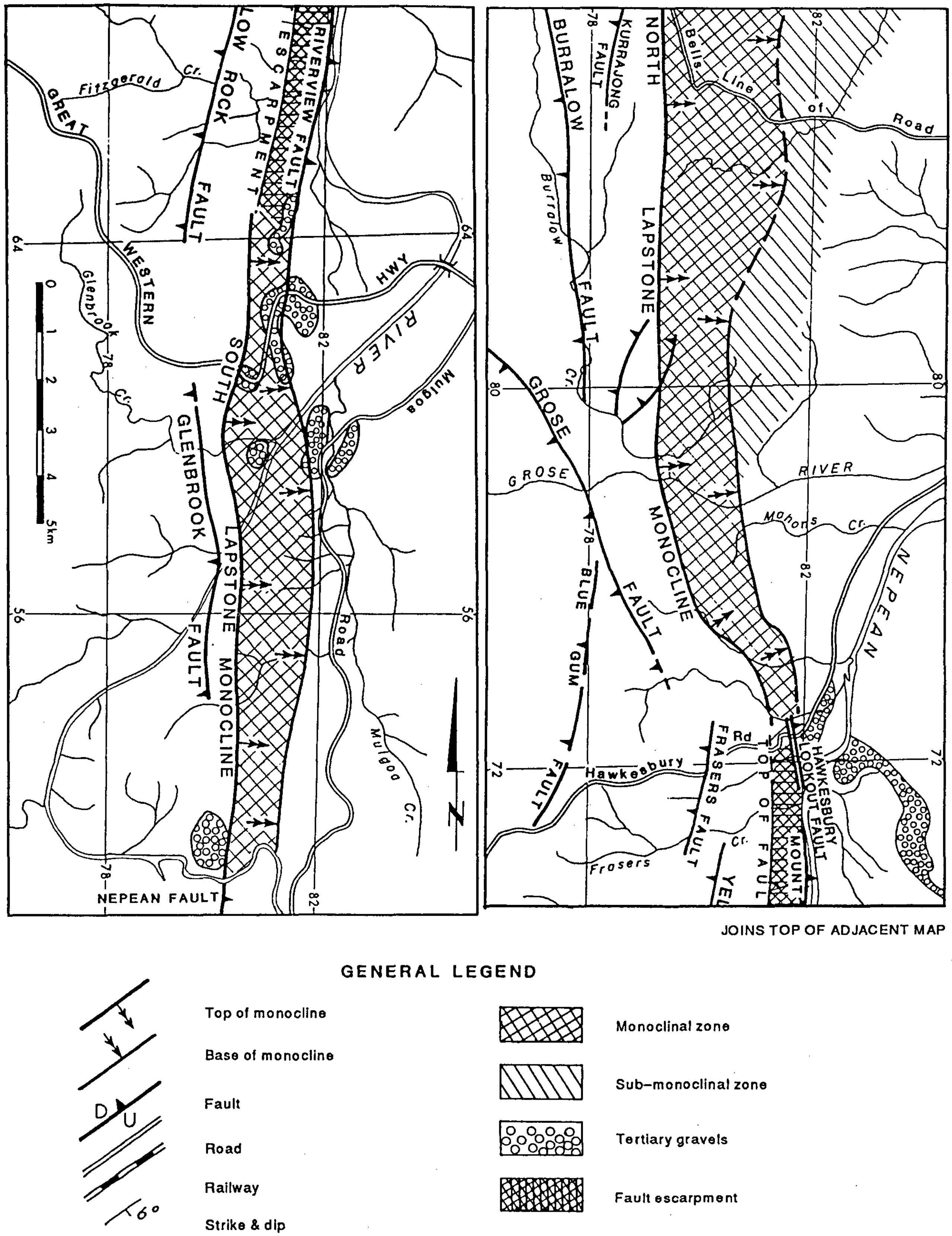

Fig. 4 Map of Lapstone Structural Complex.

evidence the fault appears to dip nearly vertically or steeply east, and the displacement is east-side down.

Interpretation of seismic surveys south of Bent's Basin by Herbert (1989) indicates a complex system of faults. These are mainly in two separate zones: the Nepean Fault system; and, 7 km to the west, the Oakdale Fault system. The Nepean Fault appears to be a high-angle reverse fault dipping steeply west.

South Lapstone Monocline

From Mulgoa north to the Old Bathurst Road the escarpment follows the South Lapstone Monocline, an elongate north–south structure. Its extreme southern point lies east of the Warragamba River where its dip gradually decreases and its topographic position is taken by the Nepean Fault. The general dip of the structure in the area west of Mulgoa and Wallacia is approximately 8° towards the east. In this region the structure is 1–1.7 km wide.

Farther north, the Monocline transects the Nepean River and Glenbrook Creek. Near Glenbrook Creek the structure consists of two parallel and north–south-trending flexures separated by a short section of horizontal beds (Fig. 5). The more westerly of the two flexures is present north of Mount Portal (GR 808596) where the dip is about 10° eastwards. Within a short distance both south and north of Glenbrook Creek these two flexures merge and form one monoclinal structure.

On Mitchell's Pass Road (Fig. 6) two monoclinal flexures are again exposed. The smaller of the two flexures, between Lennox Bridge (GR 808626) and Elizabeth Lookout, has a maximum dip of 14° towards the southeast. The main structural feature lies east of Elizabeth Lookout (GR 813626). The Hawkesbury Sandstone north of the lookout is almost flat-lying, but becomes gently tilted (5°) towards the southeast. Over a horizontal distance of 300 m the dip gradually increases to 42° and the monoclinal structure abruptly becomes strongly shattered. The shattered zone lies along the strike of the Mount Riverview Fault (see below), and is most likely related to it. The shattered zone is present in a deformed sequence of alternating shale and sandstone overlain by lateritized gravel. The dipping beds are broadly curved to form a sub-monocline, and have a maximum dip of 87°. Within a short distance eastwards the curved beds regain their horizontal position.

Thus the character of the South Lapstone Monocline changes (Figs 5, 6), having considerable variation in the flexuring and amount of easterly dip of the monoclinal beds, and also in the width and amplitude of the monoclinal zone.

Mount Riverview Fault

On the Old Bathurst Road (GR 810636) the dip of the monocline decreases substantially (15° to the east), but the slope of the scarp remains high (up to 50°). Slab failure along the foresets in the cross-bedded Hawkesbury Sandstone is generally responsible for the slope of the scarp. North of the Old Bathurst Road as far as the Hawkesbury Lookout (GR 822723) the escarpment is formed by a steep to vertical fault, named by Pedram (1983) the Mount Riverview Fault, which has an east-side down displacement of some 200 m. As for the Nepean Fault, Herbert (1989) suggests this is a high-angle reverse fault, but his very steep structure is placed some distance west of the escarpment and his interpretation may be complicated by bifurcation of the fault. Pedram (1983) postulated such bifurcation south of Hawkesbury Lookout, naming the separate Hawkesbury Lookout Fault. This fault is exposed on the Hawkesbury Lookout Road (GR 821724), sandstones and shales dipping steeply east to overturned (80° to the west) in a zone nearly 100 m wide. The nearly vertical west side of this zone is well-defined but the eastern edge is not exposed (Fig. 7).

North Lapstone Monocline

Immediately north of Hawkesbury Lookout the escarpment swings northwestwards for some 2 km to the Grose River (Figs 3, 4).

The Grose Valley, Burralow Creek valley and Paterson Hill areas (GR 795780) are tectonically more disturbed than other parts of the complex and contain a series of monoclines, warps, faults and anticlinal structures. Whilst all these structures are probably the direct result of tectonism, the Paterson Hill Anticline (GR 795780) could have formed by valley bulging (Bryan *et al* 1966). The amount of dip of the monoclinal structure varies in different localities in the Grose Valley, attaining a maximum dip of 45° towards the north at the junction of the Grose River and Burralow Creek; the average dip of the monocline in this area is 12° towards 070°.

At the Grose River, the escarpment swings north (Figs 3, 4, 8) and continues in this direction to beyond the Colo River. In the Grose Vale–Kurrajong area the monocline is 1.6 km wide. Exposures of Ashfield Shale along the monocline are sporadic, but dips up to 15° towards the east are

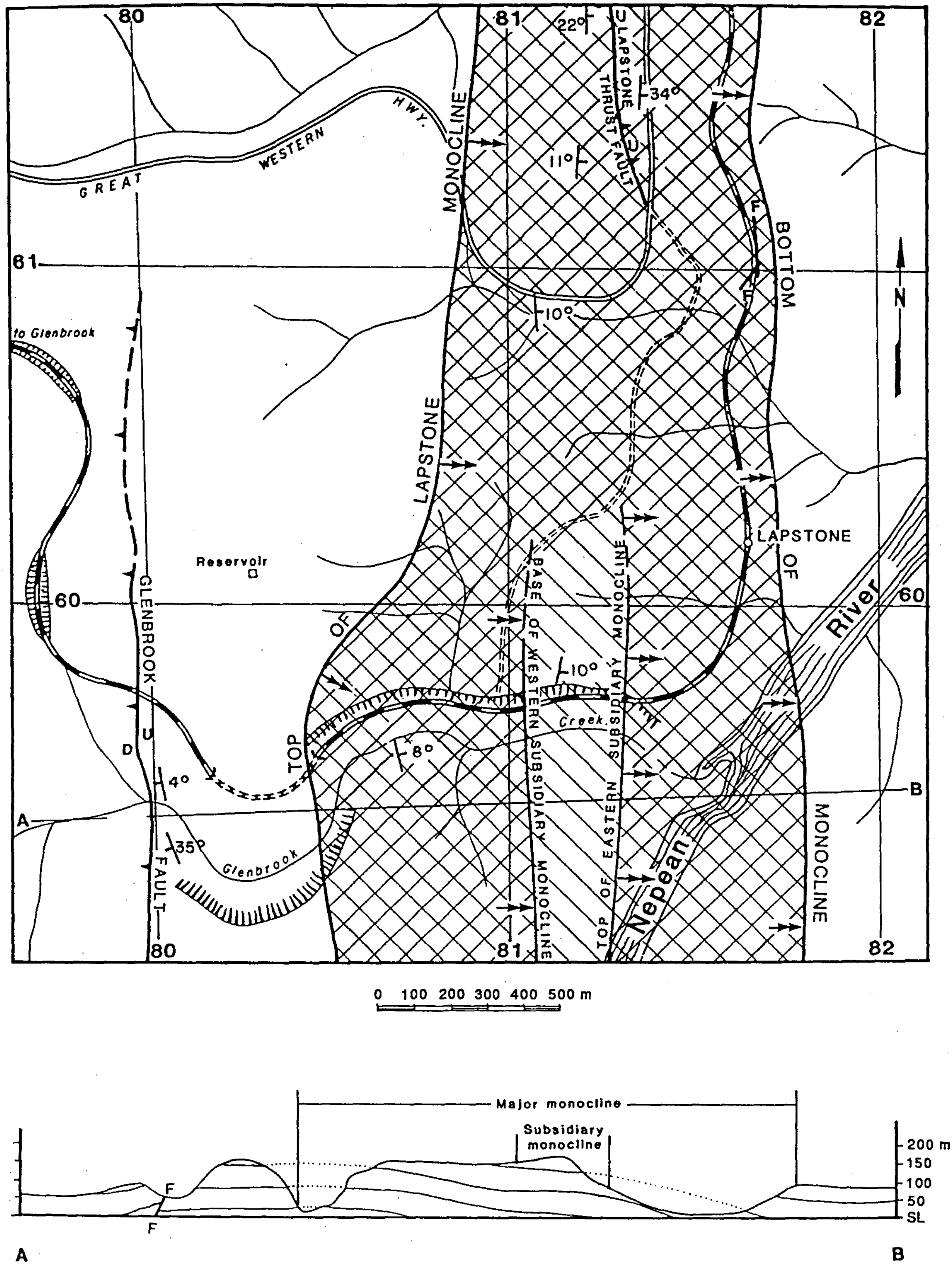

Fig. 5 Structure of Glenbrook–Lapstone district.

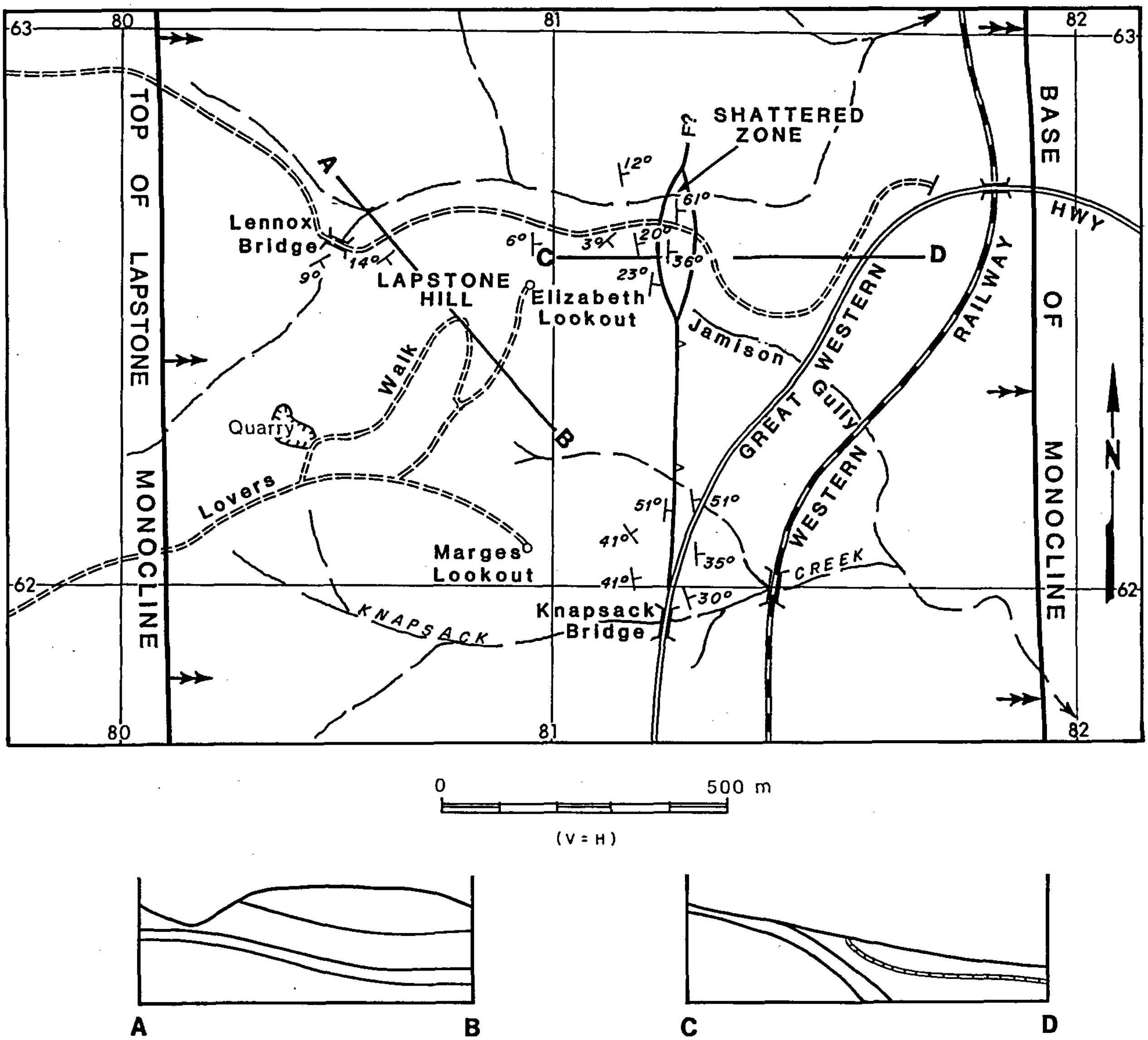

Fig. 6 Structure of Mitchells Pass Road area.

present. Within this area, topographic evidence, such as a noticeable break in slope (Fig. 8), indicates a sudden localized increase in dip of part of the structure, suggesting the formation of several monoclinal flexures. North of the Grose River a progressively larger area is incorporated in the warping, which also has a greater vertical extent than to the south.

In this study the monocline has only been examined in detail as far as the Mountain Lagoon Fire Trail road (GR 800950), some 7 km north of Kurrajong Heights (Fig. 1): information on the structure farther north has been given by Galloway (1965), Branagan (1969) and Henry (1987). Detailed mapping of this area is still required.

The *En Echelon* Faults

Pedram (1983) referred the series of west-side down *en echelon* faults west of the main escarpment collectively to the Kurrajong Fault System. The system runs north–south, nearly parallel with the Lapstone Monocline–Fault System. Work by Herbert (*in* Smith 1979) and the present authors established the position of seven faults, named by Herbert the Kurrajong, Burralow, Grose, Blue Gum, Fraser, Yellow Rock and Glenbrook Faults (Fig. 4). In the absence of key horizons the amount of displacement on these faults cannot be measured accurately. At Cut Rock, David (1902) assessed the throw of the Kurrajong Fault as 423 feet (130 m).

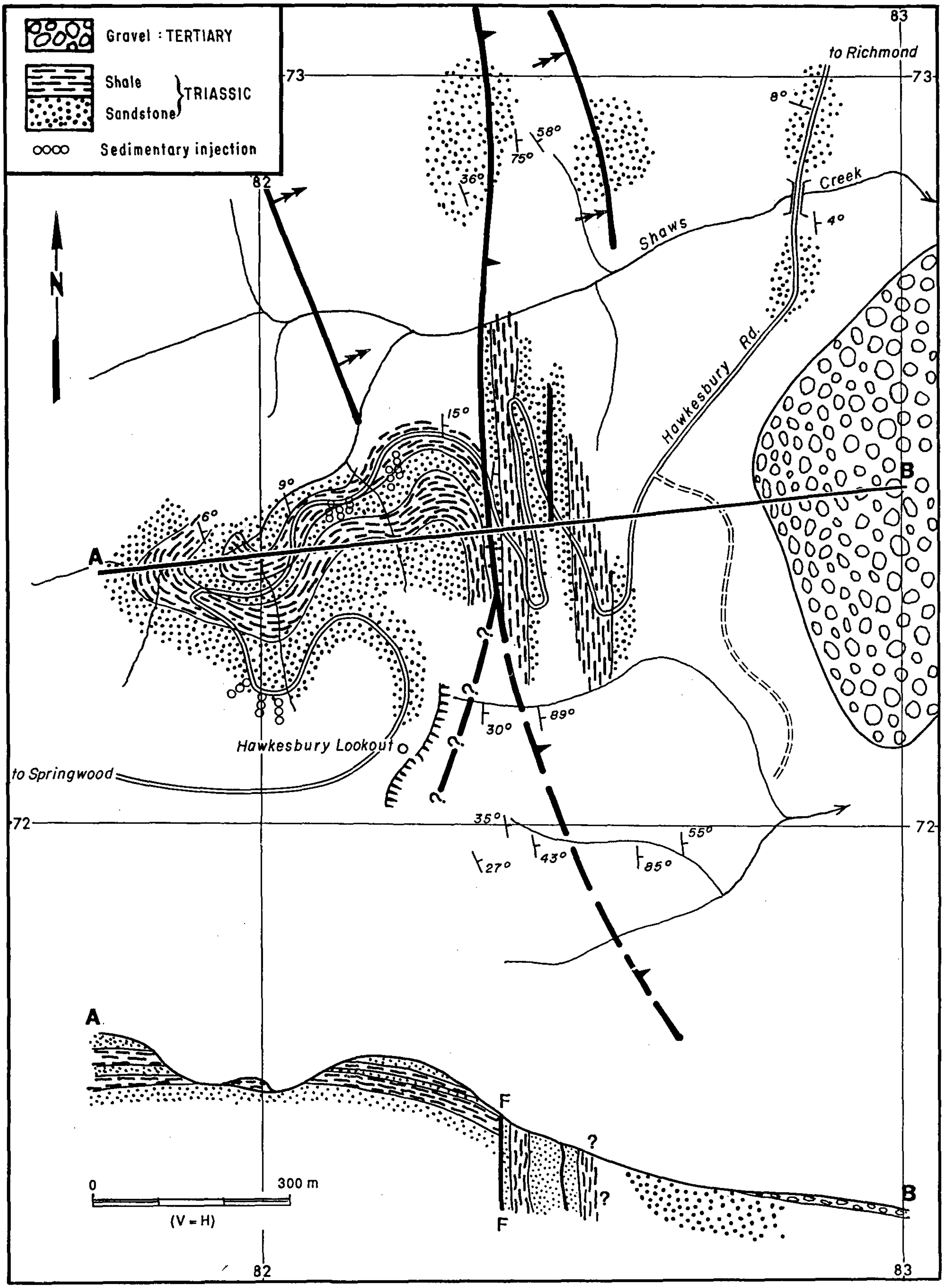

Fig. 7 Geology of Hawkesbury Lookout road section.

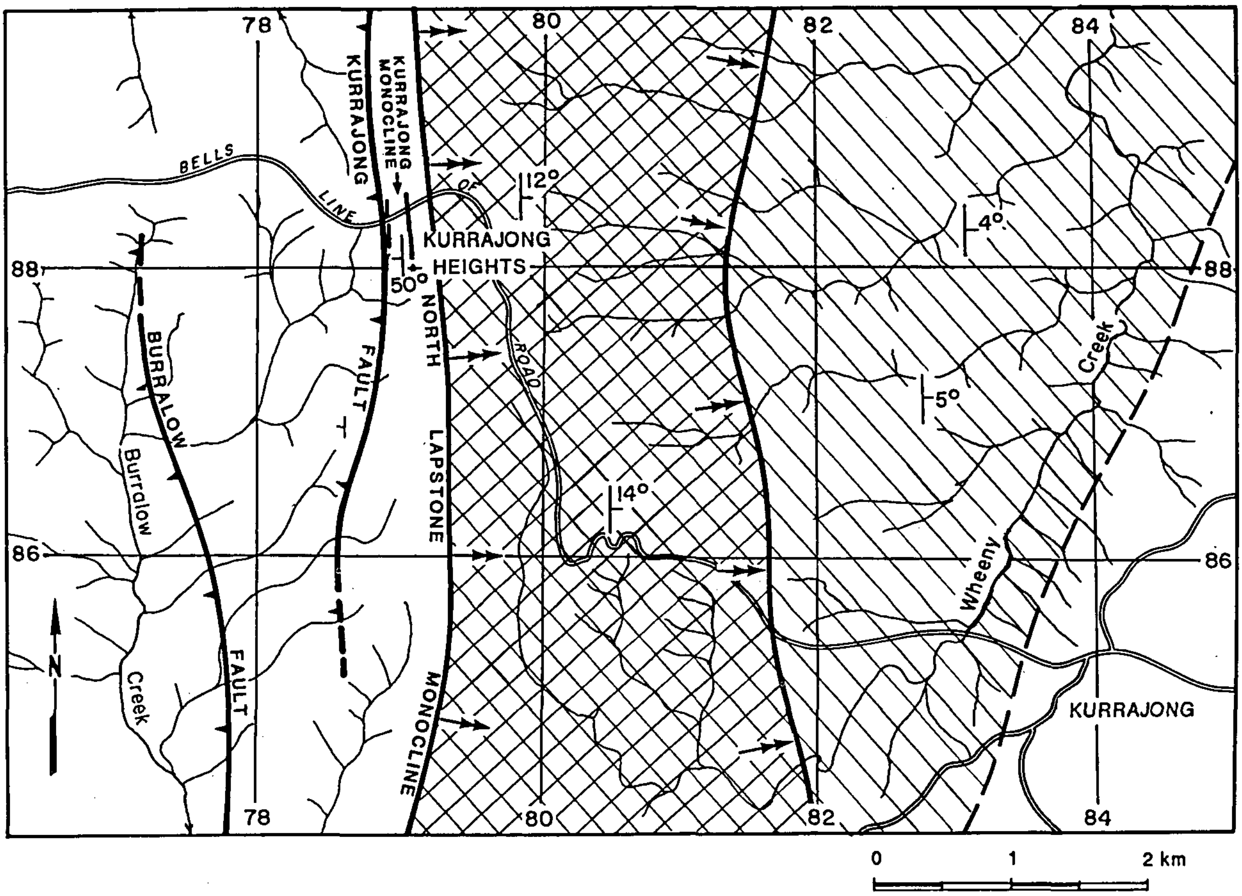

Fig. 8 Structure of Kurrajong Heights area.

However the throw of the Grose Fault does not exceed 100 m, while the downthrow on the Glenbrook Fault is approximately 70 m; that is, the amount of vertical displacement of the system decreases southwards.

The Kurrajong Fault is well-exposed on Bell's Line of Road at Cut Rock (GR 787884). The downthrow is to the west but the beds in the fault zone (3–4 m wide) are overturned and dip 80° to the east. West of the fault zone the beds gradually attain a westerly dip and then eventually become horizontal. This fault forms a well defined scarp north from Cut Rock to Mountain Lagoon, but then swings slightly northeasterly and gradually dies out. It has not yet been studied at its northern extremity. South of Cut Rock the fault edges towards the west, being traced to GR 785852 where it dies out (Fig. 8).

One hundred and fifty metres east of the Kurrajong Fault at Cut Rock the almost horizontal Hawkesbury Sandstone changes its attitude and dips west, increasing to a maximum of 50° immediately adjacent to the fault. This change is the direct result of drag on the fault. Although this small monocline seems of local extent (Fig. 8), a similar feature is present on the Mountain Lagoon Fire Trail some 7 km to the north. Minor faulting associated with this drag is discussed below.

The Burralow Fault is present about 1 km west of the Kurrajong Fault and nearly parallel to it (Fig. 8). Displacement of about 80 m (west-side down) has produced the Burralow Swamp valley west of the scarp. Outcrops of this fault occur in Burralow Creek and at GR 777829. The fault zone consists of parallel vertical cleavage planes cutting through quartz-pebble conglomerate. Inclined slickenlines on some surfaces indicate an element of strike-slip movement.

At GR 779776 the northwest-southeast-trending Grose Fault crosses the Grose River (Fig. 4). This fault forms a prominent westerly facing scarp on both sides of the river, but its displacement declines markedly towards its southeastern extremity and the fault dies out 2 km west of Hawkesbury Lookout. At its northerly end it is the locus of the dyke swarm, previously mentioned, which extends several kilometres northwest (Crook 1956). The spatial relationship between the Kurrajong, Burralow and Grose Faults is clearly visible from the south-southwest, from Warrimoo on the Great Western Highway (GR 778659).

The Blue Gum, Fraser and Yellow Rock faults are similar in character to the above faults but have smaller throws and more limited lateral extent (Fig. 4).

In the Glenbrook Gorge area there are two separate faults: the more easterly and minor unnamed fault has tilted the strata to dip 29–293°, while the larger Glenbrook Fault has dragged the beds so that they dip 50–251°. This fault forms a prominent scarp across Glenbrook Creek. North of the gorge the scarp swings slightly west and rapidly becomes less prominent south of the Great Western Highway (Fig. 5).

The Glenbrook Fault is exposed south of Glenbrook Creek at GR 800586, the rocks being nearly vertical over a width of several metres. The fault also cuts across the deep gorge of the Nepean River at its junction with Euroka Creek (GR 803572), where there is a breccia zone, in places recemented by a network of quartz veins. The considerable degree of local disturbance suggests there were possibly several or more separate movements on the fault. Crossing the Nepean at Euroka Creek the fault shows lessening displacement to the south, as indicated by a diminishing west-facing scarp, and dies out north of the junction of the Nepean and Warragamba rivers.

MINOR STRUCTURES

The minor structures are those which have a limited extent (up to 50 m) in individual outcrop. These consist of folds, a variety of faults, joints, igneous dykes and sedimentary injections. Some of these structures are believed to have formed during a period of westerly directed compression. The folds have small amplitudes but comparatively high dips. The axes are parallel to the principal structures of the area and have generally been formed in the vicinity of the main structures. These can be examined near Lapstone Railway Station (GR 816605 and 815615) and near Glenbrook (GR 815588). At the first site a bed of consolidated bouldery gravel, up to 8 m thick, overlying Triassic sandstone, appears to have been involved in the regional folding, and is also deformed by several steeply dipping faults.

Numerous high- and low-angle normal faults, thrusts and shatter zones are present. At Cut Rock (within the Kurrajong 'Monocline') a series of seven small steep easterly dipping normal faults crops out, immediately east of the Kurrajong Fault (Fig. 9). The amount of displacement does not exceed 0.6 m and in all faults the eastern blocks are downthrown, that is, in the opposite sense to the nearby major fault. The direction of movement suggests that rebounding has followed the deformation which caused the major faulting.

Small-scale low-angle thrust faults are common throughout the region, particularly on the Hawkesbury Lookout Road (GR 823725), and are present within or in the vicinity of major folds or faults. Their strikes remain parallel with major structures except in Burralow Creek (GR 798782) where thrusts within the North Lapstone Monocline have a tendency to strike east rather than north, possibly because of the nearby Paterson Hill Anticline.

Overturned beds have been mentioned earlier. A tectonic origin is supported by the geophysical profiles identifying high-angle reverse faults (Herbert 1989). However in some localities overturning may have been caused by slumping.

Zones of intense shattering are present in massive sandstones in the old Lapstone Zig-Zag cutting, just west of the Great Western Highway (GR 813613), and on Mitchell's Pass Road, where the South Lapstone Monocline attains its maximum dip (Figs 5, 6). These may be part of a single zone extending some 1.5 km. Such zones have been recorded at a number of localities in the Sydney region (Branagan 1977, 1985; Norman 1986; Branagan *et al* 1988; Mills *et al* 1989) and are believed to be mainly caused by strike–slip shearing.

Joint planes are common throughout the region and several domains can be recognized. Stereographic projections of poles to jointing are given in Pedram (1983) and Norman (1986). Data from the Blue Mountains, adjacent to or removed from the complex, for example Woodford and Katoomba–Blackheath, were given by Mauger *et al* (1984). Common to all the regions is a northwest-trending set. These joints appear to have formed early, perhaps by shearing, and are the foci for intrusion of dykes at Bellbird Hill, Grose River and at Luddenham (south-southeast of Penrith) during a later tensional period. East–west- and north–south-trending joints, apparently induced by tension during formation of a broad north–south-trending fold, are restricted to the complex.

At Bellbird Hill, northeast iron-filled joints (Norman 1986), are apparently radial tension structures caused by monoclinal folding. Planar but tight north–northeast- to northeast-trending conjugate joints cut across the northeast master joints and apparently formed subsequent to the main folding events.

In summary, there were probably four periods of joint formation: one (by shearing) prior to the main

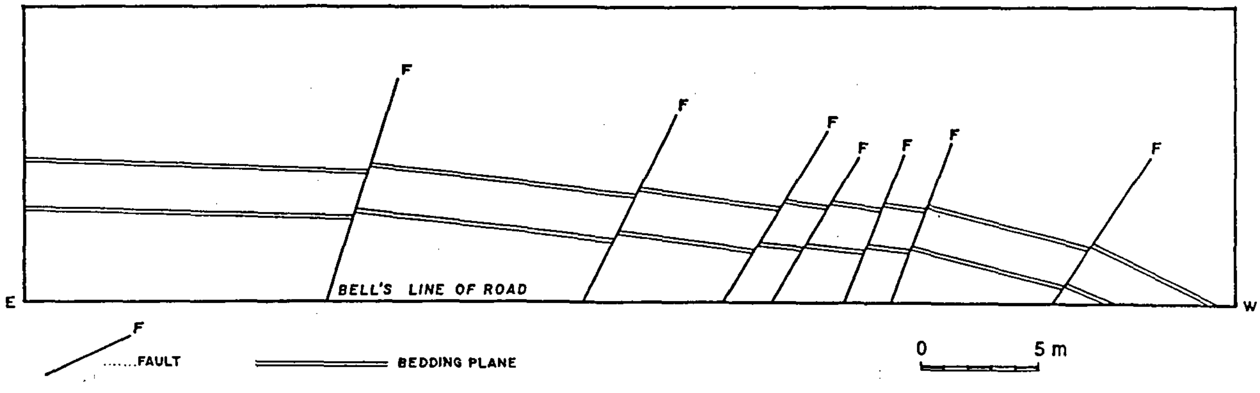

Fig. 9 Small-scale normal faults at Cut Rock (within the Kurrajong Monocline).

period of deformation; two (mainly tensional) associated with that event; and a more recent period (possibly shear).

Clastic dykes are abundant and are mainly offshoots of shale beds or lenses associated with joint systems; in all cases the shale has been injected into overlying sandstone. Thickness of these dykes varies from 10 mm to more than 1 m, for example at Lapstone Railway Station (GR 817603) and in the Hawkesbury Lookout area (GR 822725; Fig. 7). On Mitchell's Pass Road (GR 810625) sedimentary dykes form an interconnected network. The injections are consistent with a sudden release of pressure after slow deformation. The shaly material became plastic under load but was restrained. Following brittle failure of the sandstones, the plastic shale penetrated recently formed joint openings and other available spaces.

DISCUSSION

The general north–south orientation of the major structures and many of the minor ones suggests that the major stress directions were generally the same during periods of deformation, even though there may have been change from tension to compression. However, asymmetries in the regional pattern indicate that the deformation history was not simple. The Kurrajong portion of the complex is topographically nearly three times higher than the Lapstone part and the width of the disturbed area is greater in the north. Furthermore, deformation is generally greater on the eastern side.

Whilst much of the present configuration can be attributed to relatively recent movements (probably Tertiary) it is believed that some features of the complex were inherited from earlier events. Broadly, the history of the complex is in three parts: (1) tectonism prior to formation of the Sydney Basin (i.e. pre-Permian); (2) movements during Sydney Basin sedimentation (Permian and Triassic); and (3) movements well after sedimentation ceased.

A deep-seated basement structure is believed to be present below the complex (Qureshi 1984; Harrington & Korsch 1985). If the boundaries of the 'Eden–Comerong–Yalwal' Rift (McIlveen 1974) are extended north from the Shoalhaven River beneath the Sydney Basin rocks, the western edge runs beneath the Lapstone region (Fig. 10). The

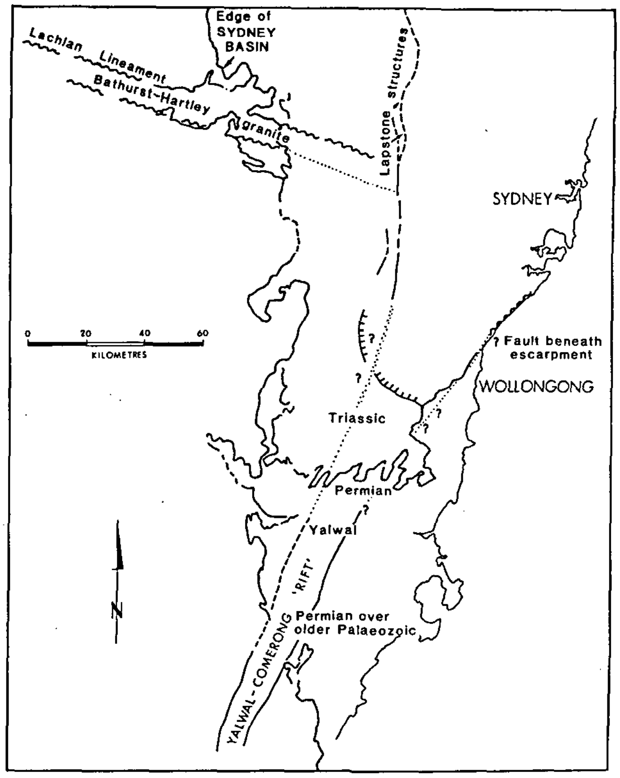

Fig. 10 Conjectural relations between basement structures and Lapstone Structural Complex.

lowest part of the Lapstone complex and the adjacent Cumberland Plain are in an area where an eastern extension of the Bathurst Batholith and the Lachlan Lineament (Scheibner 1974) would intersect the north-trending structure (Fig. 10). Such an intersection could well be the locus for episodic movements during and after basin sedimentation.

During the sedimentary history of the Sydney Basin there was certainly structural control of sedimentation, due to basement deformation and contemporaneous tectonism (Raggatt 1938; Branagan & Johnson 1970). Adjustments in the basement during the Early Triassic may have initiated the Cumberland Basin and caused the restricted area of deposition of the Mittagong Formation and the overlying Ashfield Shale (Branagan 1969; Herbert 1979). After sedimentation ceased, uplift possibly accentuated topographic variation by adjustment along structural weaknesses echoing those in the basement. Compressive forces continued to act from the northeast in Late Triassic times (Branagan *et al* 1988; Moelle & Branagan 1988; Mills *et al* 1989). Herbert (1989) believes this was the time of major development of the structural complex.

With the onset of sea-floor spreading in the Late Cretaceous, basement weaknesses were reactivated. Ollier (1982) implied that the Lapstone structures formed at this time as part of his Great Escarpment. Norman (1986) fixed the date of formation as about the same time. It is believed that adjustments at this time gave the complex its present form.

Deformation (relative uplift) of the Lapstone Complex continued through the mid-Tertiary but was uneven and probably slow, producing the southerly plunging, flat-topped anticline with a larger east flank (Fig. 2). Uplift may have been initiated in the north and proceeded southwards, explaining the southerly courses taken by the Grose River and Glenbrook Creek which cut through the barrier. Movements at this time may have caused features such as Thirlmere Lakes (GR 735100), suggested by Fanning (1983) as pre-Miocene, and Howes Swamp (GR 820490) which has an enigmatic history (Henry 1987). However, Rawson (1989) postulates continuing slow movements of the whole complex throughout the Cainozoic, as did Cotton (1921).

At some time the stress pattern changed and brittle deformation produced the major faults on both sides of the complex. A left-lateral deforming couple (i.e. west-side south) could have produced the present fault pattern, together with the flexure in the North Lapstone Monocline in the Grose Valley area, as supported by the slickenlines on faults surfaces, shatter zones and jointing at Bellbird Hill.

The gravels on the monocline are suggested as Miocene in age by Gobert (1978) and Bishop (1986), who believed that they predate deformation. They are not preserved on the steeper fault faces and it is believed that they may have a wider spread of age through the Tertiary, and were reworked down the monocline during several periods of deformation.

Iron-filled joints formed during tensional deformation of the eastern monoclinal structure (Norman 1986), and the lateritization of some of the gravels (Bishop *et al* 1982) may be attributed to the same period of iron migration (?Early Miocene), which supports the idea that the gravels may be, in part at least, Early Tertiary, and that the main deformation may date from that epoch.

Earthquakes in the region in 1801, 1886 and 1919 (Cotton 1921) indicate that the structure is still mildly active.

To gain a better understanding of the formation of the Lapstone Structural Complex the total extent of the structure must be mapped in detail and the relation between various named structures at the southern end of the complex needs to be clarified. There is presently no agreement about the nature, location, or age of formation of these structures (Bunny 1972; Scheibner 1974; Mullard *et al* 1983; Sherwin & Holmes 1986).

The overall pattern does not fit the strike–slip pattern in which a divergent wrench fault is accompanied by a component of extension (Harding *et al* 1985). Rather there is no evidence of major extension of the area for the past 40 Ma. Osborne (1948) suggested two periods of deformation, mainly of compression and shear, with minor tension. He believed the main movements forming the complex took place early in the Tertiary. This suggestion is supported by Willan (1923), Norman (1986) and the present work.

SUMMARY

In summary the structure is the result of three major events:

(i) Permian and Triassic sediments were draped over a well-developed north-trending structure intersected by easterly trending structures — an extensional event.

(ii) Compression (mainly from the northeast) and uplift of both basement and basin sediments took place during and immediately following cessation of sedimentation. This 'thin-skin' type adjustment formed a broad warp.

(iii) Early Tertiary adjustments to the near-surface rocks, caused by compressional strike–slip, formed the elements of the complex visible today.

(iv) Later minor adjustments took place.

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