13th Australia New Zealand Conference on Geomechanics – Acosta-Martínez & Lehane (Eds.)

Massive landsliding in Narrabeen sandstones in the Watagan region

S.G. Fityus
The University of Newcastle, Australia

P. Flentje
The University of Wollongong, Australia

R. Rigby
Newcastle, Australia

ABSTRACT: The Narrabeen Group is a thick sequence of bedded Triassic sandstones which occupies the stratigraphic interval between the Permian Coal Measures and the Hawkesbury Sandstone in the Sydney Basin. In the northern Sydney Basin it is laterally extensive, extending throughout the southern Hunter Valley from the Central Coast to beyond the Great Divide. In the Watagan region, a unique situation arises where a disconformity causes the Narrabeen group to be underlain directly by Permian upper marine sediments. The result is a dramatic occurrence of ancient massive landsliding, leading to steep sandstone slopes that break to an elevated detrital plane, of considerable lateral extent. This paper describes the unusual geomorphic features associated with the landslide mass and interprets a variety of individual mass-movement and rockfall mechanisms which have contributed to these impressive features in the various stages of its development.

1 INTRODUCTION

The Permian Coal Measures of the Sydney Basin are succeeded by widespread thickly-bedded Triassic sandstones generally referred to as the Narrabeen Group. Narrabeen Group sandstones have the ability to stand as steep cliff lines, and these form extensively within the basin where they are undercut by preferential erosion of the weaker underlying Permian Coal Measures.

Steep cliffs are well known in the Narrabeen group sandstones in the Watagan mountains and Broken-back ranges adjacent to the northern coalfield; the Widden-Goulburn valley adjacent to the northern western coalfield; the Wollemi to the west, the Blue Mountains adjacent to the southern western coalfield; and the Illawara escarpment in the southern coalfield. Although the cliff forming tendencies are common to all of these areas, the heights and styles of the cliffs vary, as do the styles of cliff line instability that occur in these areas. Slope failures have been studied in the Illawarra escarpment (Flentje et al. 2017) and Blue Mountains (Cunningham, 1988) regions, but little has been written about cliff stability in the Watagans.

The Watagans are relatively poorly mapped compared to the rest of the Lower Hunter area, due in part to the rugged topography, and in part to the absence of economic targets for drilling due to absence of the Newcastle and Tomago Coal Measures on the Lochinvar Anticline and the greater depth (800-1200m+) to the Greta Coal Measures

This paper presents a preliminary study of massive slope instability at the northern margin, around 7km due south of the townships of Ellalong and Quorrobolong. It utilises high quality LIDAR data, and sev-eral days of field investigations as the basis for a de-tailed ground surface model from which geomorphological interpretations can be made.

2 GEOLOGICAL SETTING

A geological map of the region is presented in Figure 1. The Narrabeen group comprises 5 to 7 formations of massive sandstone units and fine grained units, depending on where it outcrops around the Sydney Basin (Bembrick 1980; Ward 1980). In the north-eastern part, the basal units of the Narrabeen group are the Clifton sub-group (Uren 1980) which can comprise several hundred metres of conglomerates shales and claystones, but in the Watagans, the Clifton sub-group appear to be poorly developed. The Clifton sub-group is overlain by massive cliff-forming sand-stones with thin intervening shale beds, which unlike elsewhere, are un-differentiated in the Watagans.

In the Lake Macquarie region, on the Sugarloaf Range, the Narrabeen group appears to conformably overlie the Permian Newcastle Coal Measures. Similarly, further to the west, the contact with the Permian Wollombi Coal Measures also appears conformable. However, where the Narrabeen group overlies the

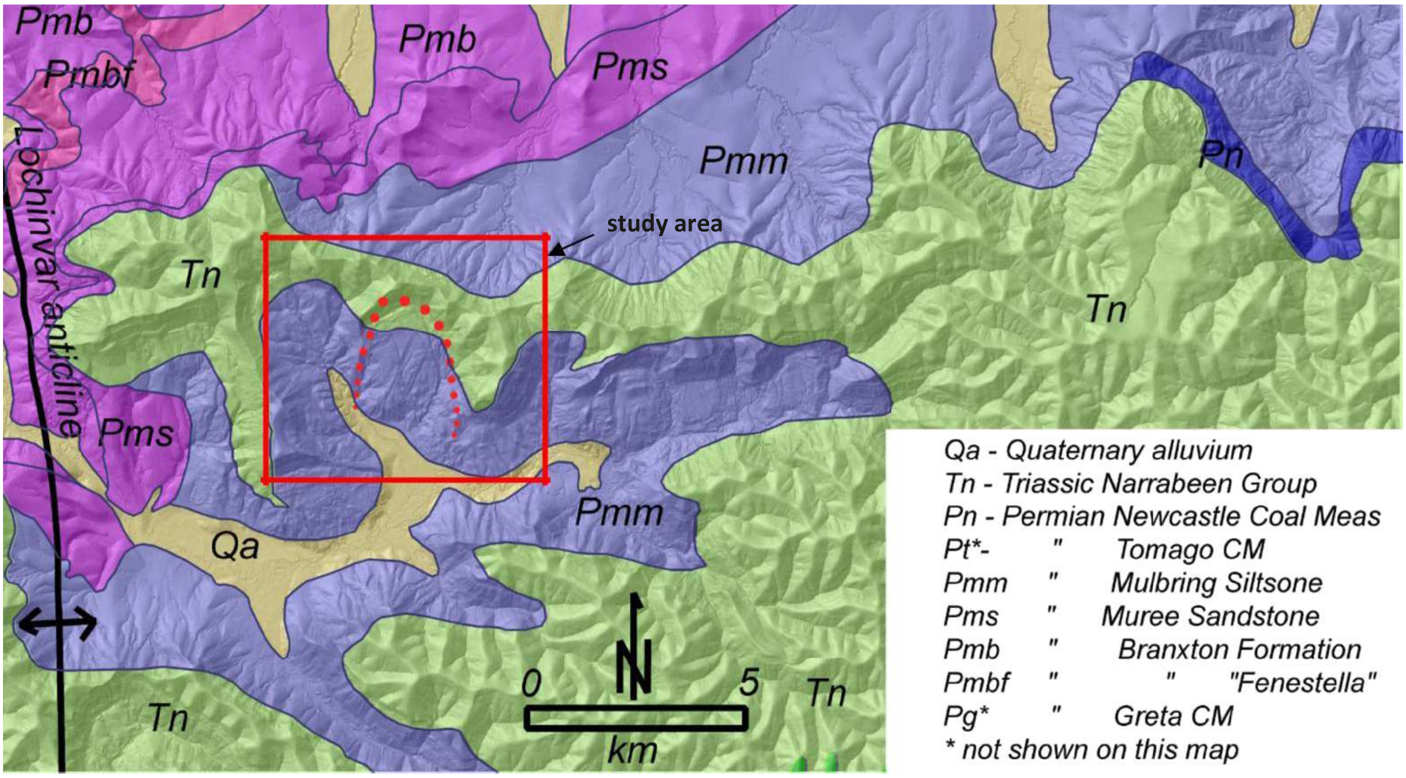

Figure 1. Geological setting of the study region with the study site (Figure 2) highlighted in red.

southern end of the Lochinvar anticline in the Quorrobolong area, the contact is not conformable (strictly an angular unconformity) where Newcastle and Tomago Coal measures are absent, and the Narrabeen group directly overlies the Mulbring siltstone and Muree sandstones of the marine Maitland Group (Uren, 1980).

3 EVIDENCE OF MASSIVE SLIDING

A lidar hillshade with 10m contours of the area is presented in Figure 2. It is evident from Figure 2 that site can be partitioned into three areas of different broad scale surface morphology: well-defined steep ridges to the north and east; a flat, smooth plain to the south; and an extensive zone of hummocky ground in the centre, extending from the northwest to the south east.

On the basis of its morphology, one subject landslide has been identified outlined by the red dashed line, with the obvious interpretation that much of the hummocky mass is a runout fan, resulting from the collapse of slopes to the north. Two distinct styles of instability are evident: in the centre, massive collapse has occurred to form a southward facing valley, and to the east, additional landslides have produced blocks A to D radiating out from the south trending spur, and along the western margin of the map, additional blocks F and E have also failed as part of an-other valley feature further west. Landslide block G in the southwestern corner of Figure 2 has truncated a large spur and moved out onto the valley floor. Smaller areas of slide and flow instability of have occurred within all of these features.

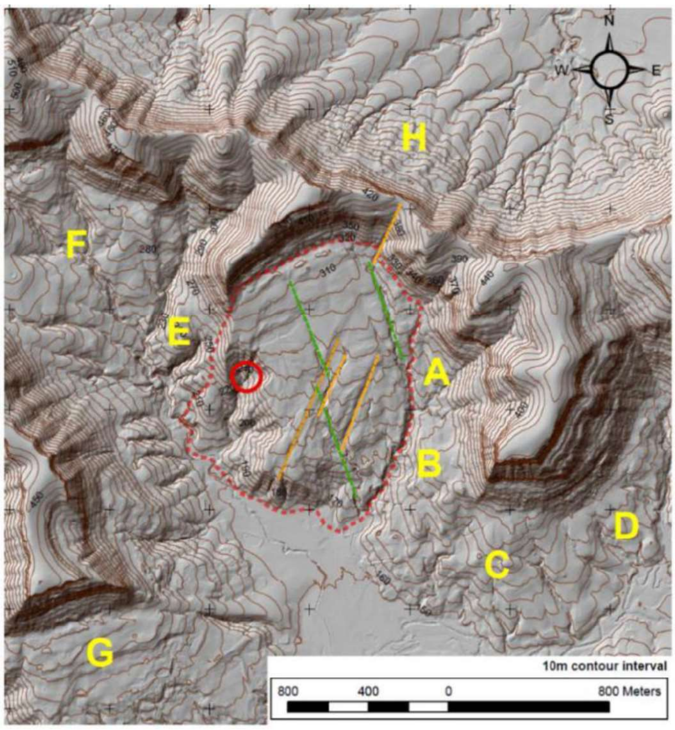

Figure 2. Topography of the study area

3.1 *Mass movement by collapse into a valley*

The outlined central landslide feature in Figure 2 shows a broad, long fan of slide debris that has run out in a southerly direction leaving a circular amphitheatre structure, rimmed by steep ridges with side slopes up to 45 degrees. The ridges are around 200m high on the western side (Fig. 3), but increase to around 400m high heading east. The ridge slopes

Figure 3. Overview of the slide from the western end of the upper ridge.

above the landslide display extensive sandstone out-crop in the form of short cliffs, narrow ledges and ter-races. Soil cover on the slope is thin, where it exists, and it comprises gravelly clayey sand.

The slide is ~700m wide along the head scarp area, and ~900m wide mid-way down its 1350m length. The thickness of the colluvium is estimated to be ~50m thick in the incised gully highlighted by the red circle in the middle left hand side of Figure 2, but may be much thicker within the accumulation zone closer to the toe. Using these dimensions, a slide volume of ~ 32 million m^3 has been calculated.

The upper portion of the slide fan has a smooth and even surface, with mature vegetation and little or no rock expression on the surface. An upright eucalyptus tree, well in excess of 100 years old, is growing in the upper central portion of the fan, at an RL of ~285m. As is evident from Figure 2, the slide mass shows two sets of lineaments, which extend for many hundreds of metres. Set 1, trending slightly west of south (~210^o, orange dashed lines) are evident as steps in the land, between 3 and 5m high, and moderately sloping at 25-35^o (see Figure 4). Set 2 trending slightly east of south (~150^o, green dashed lines) are evident as steep-sided, incised gullies, 3-5m deep (see Figure 5). Typical colluvial debris, including coarse rocky debris is widespread in the sides and base of these features.

3.2 *Mass movement by collapse around a ridge*

The eastern side of Figure 2 shows an apron of hum-mocky ground, blocks labelled as A, B, C and D ex-tending radially away from a narrow, steep-sided, southerly-trending ridge. Unlike the slide fan which extends from the valley to the west, the easterly slide debris has an irregular surface, suggestive of a for-mation by multiple events, with successive events producing a discrete lobe. The coalescence of these lobes, extending radially outward from the regressing ridge, has produced a different landform to the valley to the west.

4 ASSOCIATED ROCKFALL PHENOMENA

The massive landsliding which occurred produced steep slopes in the Narrabeen sandstones to the north,

Figure 4. Set 1 lineaments in the slide fan, evident as a step down in the ground surface (left to right).

Figure 5. Set 2 lineaments in the slide fan, evident steeply incised gullies in the ground surface.

with the most massive beds remaining at the capping units of the ridge. Figure 6(a) shows an example of the uppermost cliff line, revealing the extensive rock-mass deterioration and the potential to generate vary large sandstone blocks. Figures 6(b) – (f) are exam-ples of the blocks which have fallen to the base of the ridge. Dimensions of the blocks range from 3 to 7m, with the largest having volumes as great as $280m^3$. The blocks range in shape, but are mostly equant (cu-bes (f), octahedra and balls (b, e)), rectangular prisms (d) and discs (c). Roundness ranged from round to an-gular.

The blocks were observed to have run out onto the fan to different distances of between 10 and 160m, beyond the toe of the slope. Fahrboschung angles of between 35^o and 27^o have been calculated. There was generally a correlation between shape and runout dis-tance, with rounder, more equant blocks tending to travel further. However, there were instances where disc-shaped blocks had also travel larger distances. There were also examples where the blocks had frag-mented where they came to rest. Figure 7 shows the base of the slope, with the positions of fallen rocks recorded. The mapped boulders are also all directly below the upper 40m high cliff line (RL 435 – 475m AHD).

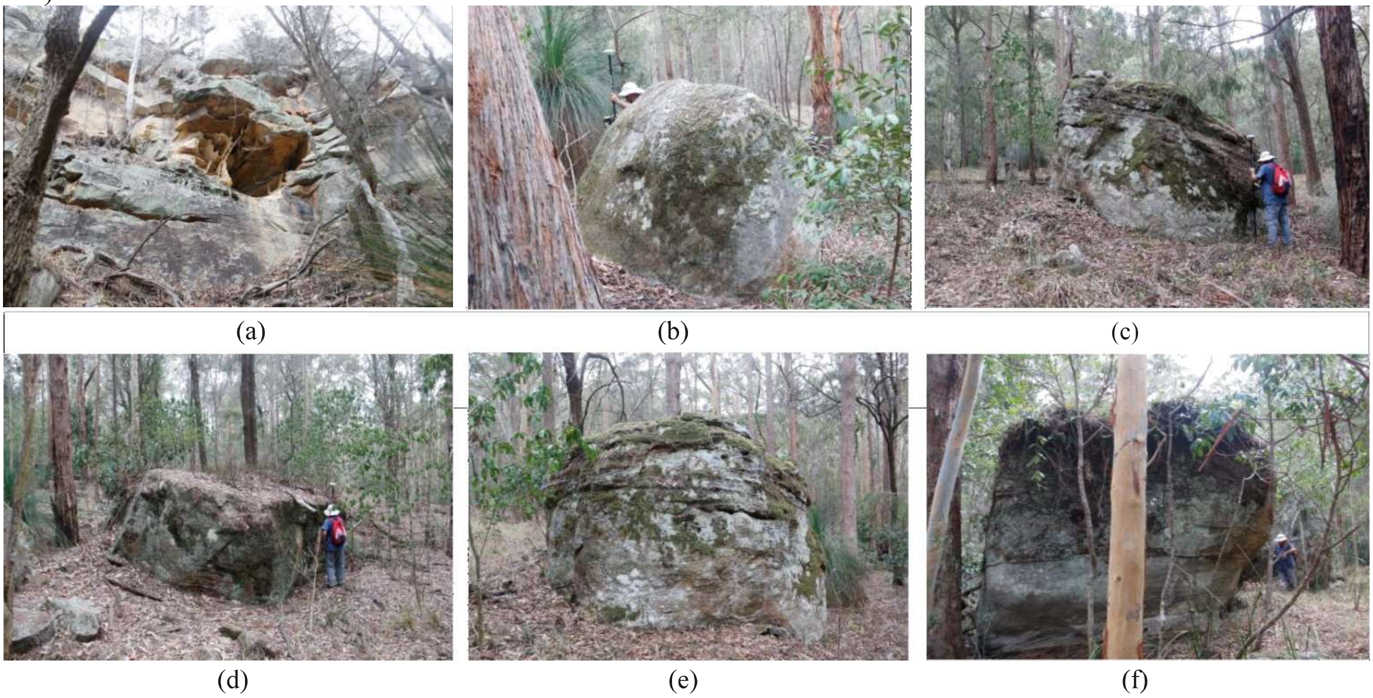

Figure 6 a) typical outcrop on the top of the ridge above the slide, with the potential to produce large blocks; b)-f) examples of some of the large blocks mapped at the base of the ridge slope.

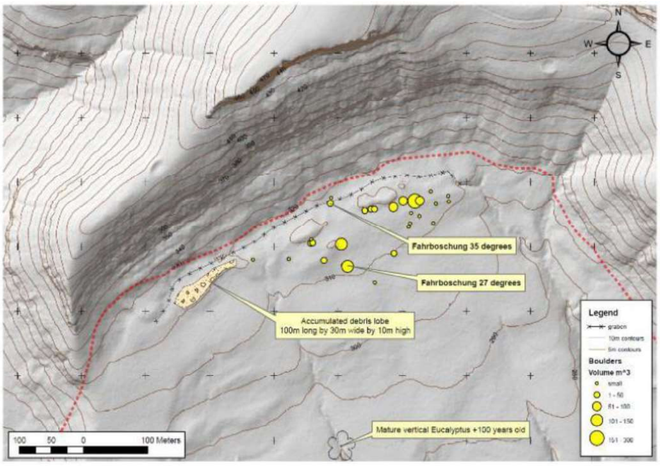

Figure 7 Positions of runout boulders on the landslide fan, relative to the toe of the slope.

5 RECENT SURFACE SLUMPING

A third manifestation of slope instability is present in the form of shallow surface slumping on the steep slopes of the northern ridges. The runout from these has created an interesting morphological feature in the region immediately beyond the toe of the slope, in the form of parallel hummocks and swales. In many cases, these appear as basins or depressions, and there is evidence that they may even impound water intermittently. The swale may be an extensional graben structure forming between the steeper bedrock slope and the main colluvial mass and as it continues to slide southward.

Figure 8 shows the morphology of these features, which appear as a line of mounds, at a distance of around 30m from the toe. Note that on the ridge slope above the crest of each discrete mound, there appears to be a small terrace that may be the source of the smaller slide flows.

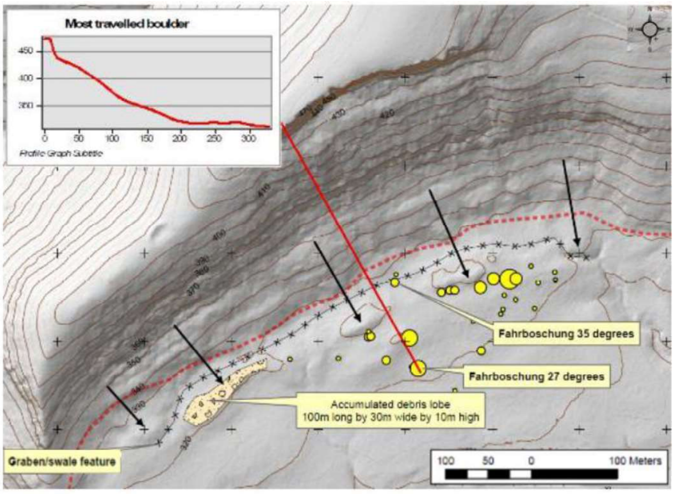

Figure 8. Hummocks and swale/graben at the toe of the ridge slope caused by shallow surface slumping. The arrows indi-cate the corresponding sites on the slope where the slumps appear to have originated.

Figure 9 shows an example of a swale/graben at the toe of the ridge slope, with mudcracks observed in the base. Water level marks on the large rocks clearly demonstrates these features hold water up to 1.5m or so deep at times.

6 GEOLOGICAL FACTORS CONTROLLING INSTABILITY

Figure 10 shows the siltstone bedrock exposure at the base of the slide, (red circle in Figure 1) in a deeply incised gully. It comprises a moderately weathered and intensely shattered siltstone material, pale brown, with a fissile nature and fine mica delineating bedding surfaces.

Figure 10. Intensely shattered siltstones at the base of the slide.

It is consistent with the Mulbring siltstone, as found exposed in other parts of the region, however, it could also be a fine grained unit corresponding to the Clifton sub-group (e.g. Dooralong shale), which may be present at this location. Regardless of its precise geological affiliation, it represents a weak foundation for the contrasting strong bedded sandstones which overlie it, and a likely host for the sliding that has occurred.

Ironically, despite being strongly bedded, the sub-horizontal overlying Narrabeen sandstones have slightly undulose bedding surfaces and strongly developed cross bedding, making their attitude difficult

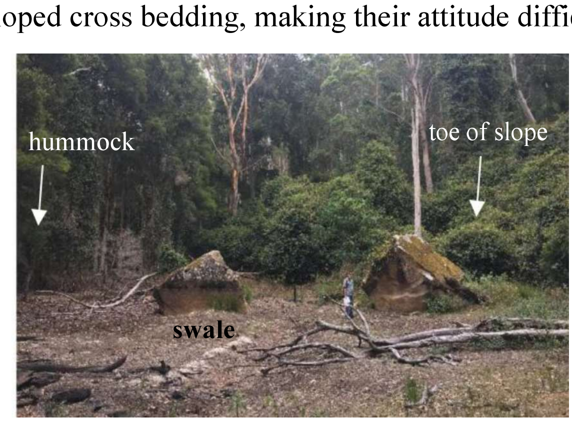

Figure 9. Swale or graben at the toe of the ridge slope with several of the many mapped boulders.

to measure reliably. This is complicated also by the proximity of the study site to the Lochinvar anticline,

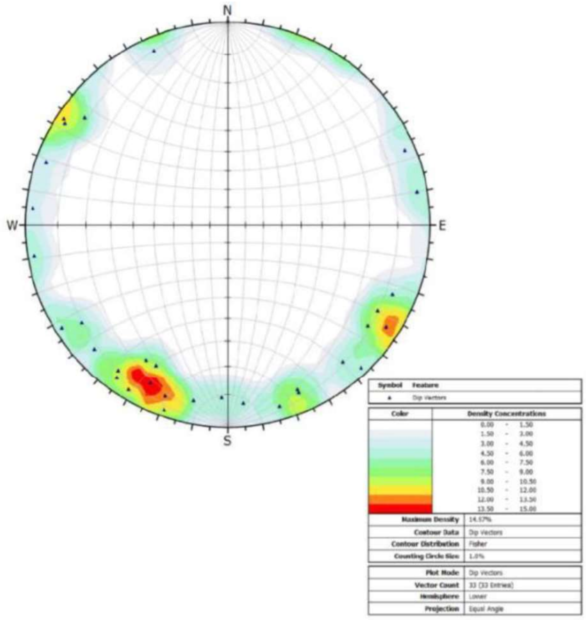

Figure 11 Bedding trends in the Narrabeen sandstones of the area, with a strong trend around 5^{o} to 205^{o}.

whose axis lies slightly to the west, but which plunges to the south at this location.

Figure 11 shows a stereo-net plot of 33 dip and dip direction values of the bedding surfaces that were measured within the outcropping sandstone units in the ridges above the slide. Despite some scatter, they show a peak concentration around 5^{o} towards 205^{o}. This general shallow south-southwesterly helps explain the prevalence of these landsldies on the south facing slopes of the ridges, and the relative absence of similar large scale sliding on the north faces, such as area H, in Figure 2.

7 SEQUENCE AND AGE OF EVENTS

There are no indications to suggest that any of the features of instability observed at this site are truly re-cent; that is, have occurred since European settlement of the region. Hence, there is no way to be certain of their precise age or specific timing.

The massive valley slide is certainly very old, although the feature is still clearly visible in the terrain. The smooth and regular surface of the debris fan is very mature, having developed its own stable soil pro-files that expresses little or none of the rock rubble or sandstone debris that would almost certainly have littered the surface immediately after the event. It has developed deeply incised drainage lines along both the eastern and western margins. Compared with other landforms around the Hunter Valley, an age of several hundred thousand years (several glacial cycles) is certainly possible.

Whilst it would seem reasonable to presume that the debris fans around the eastern ridge should be of similar age, they appear to be less mature, with a much rougher hummocky surface expression. Whereas the massive valley slide to the west might well be presumed to have occurred as a single cata-strophic event, the lobed fan of debris radiating out from around the base of the eastern ridge appears more likely to have occurred as a series of large rock-falls or discrete slides which have coalesced to produce the apron as we see it today. Despite this, there is no obvious evidence of recent large scale activity.

By contrast, the rockfall boulders and the ridge slope surface slumps would appear to be the result of more recent contemporary events. The rockfall events span a long period, potentially as far back as the time of the massive valley slide, but rockfall from the retreating ridgetop certainly continues to the present day. In general, the boulders on the surface of the massive slide are neither extensively broken down, nor are they significantly embedded into the massive slide surface. They do exhibit a wide range of surficial rounding, and whilst this could reflect a wide range of different ages since reaching the valley floor, it may also be a result of the extensive weathering taking place in situ at the top of the ridge, or the consequence of rolling more than 200m down the ridge slopes at what is likely to have been a very high speed.

The smaller slides and flows from the steep ridge slopes, and those around the steeper toe of the main slide would appear to be the most recent landslide events, other than perhaps the presence of the swale/graben. Certainly they manifest as undulations on what is otherwise a smooth and mature massive slide surface, but they are also observed to partially engulf and bury several of the rockfall boulders, with evidence that they have done so from the direction of the slopes adjacent to them

It is not so apparent why the debris from the surface slumps has travelled out from the toe of the slope to form hummocks which define swales between themselves and the slopes from which they derived. This could be explained by a mechanism whereby the smaller landslides developed.

Perhaps the most difficult to explain feature at this location are the lineaments which criss-cross the massive slide surface. They seem too geometrically consistent to be simple radial drainage lines. The linear persistence may suggest they may be stress or structure related, but a regional rock mass structure or structural control seems unlikely. From the gross morphology of the slide feature itself, it could be proposed that the body of sliding material, as it moved downward and funnelled out of the circular valley it created, might have experienced some sort of lateral compression and then relaxation which caused the formation of a conjugate set of compressional/extensional strains. Alternatively, with the development of the incised drainage channels along the eastern and western margins of the slide, it is possible the colluvial mass has relaxed laterally into these drainage lines after major erosive periods, initiating the development of these conjugate sets of linear stress relief strain features across the landslide mass. These conditions are however, purely speculation, and it remains difficult to explain how such strain features could have been preserved when all other surface irregularities have all but been lost.

8 CONCLUSIONS

The slope instability at this location is impressive in its magnitude and it represents an event that is as big as any that might occur anywhere in the Sydney basin. It appears to be one of a series of similar features extending over a distance of at least 12km along the northern side of the Watagans, in a similar geological setting. Certainly it is of a scale that is exceptional for the northern part which comprises the Watagan mountains.

It is very likely that the characteristics of instability observed at this site are the direct result of the unique situation where the massive rocks of the Tri-assic Narrabeen group have been directly and unconformably underlain by weak marine siltstones, adjacent to the axis of a major anticlinal structure. The Lochnivar anticline is a complex structure, with some uncertainty around the extent to which it pre-existed the Sydney basin as a topographic high, and the extent to which it was the result of post-depositional compressive folding. Regardless of this, some compressional deformation is likely to have structurally deformed the rocks adjacent to the fold axis, and provides a plausible cause for the intense shearing observed in the basal siltstones of the slide. Perhaps this provided the necessary condition to host the massive collapse of the steep sides of a deeply incising valley.

The massive landslide does represents an ancient and extreme event in a relatively remote area with a unique geological setting. However, our ongoing investigations are showing that there are other similar features in the surrounding areas. Whilst the significance to infrastructure may be limited due to the location, its significance for everyday geotechnical practice and regional development will be significant as these features are added to the NSW Landslide Inventory managed by the second author of this paper. This will in turn highlight this area and this geological sequence has having an increased landslide susceptibility.

REFERENCES

Bembrick C.S. 1980. Geology of the Blue Mountains, Western Sydney Basin. In *A Guide to the Sydney Basin*. (C. Herbert and R Helby eds). Geol. Surv. NSW. Bulletin 26. D. West. Government Printer. 134-161.

Cunningham, D.M. 1988. A rockfall avalanche in a sandstone landscape, Nattai North NSW. *Australian Geographer* 19 (2): 221-229.
Flentje, P., Palamakumbure, D. and Thompson, J., 2015. Assessing rockfall along the Illawarra escarpment. In *Engineer-ing Geology for Society and Territory-Volume 2* (pp. 2031-2036). Springer, Cham.
Uren, R. 1980. Notes on the Clifton Subgroup, Northeastern Sydney Basin. In *A Guide to the Sydney Basin*. (C. Herbert and R Helby eds). Geol. Surv. NSW. Bulletin 26. D. West. Government Printer. 162-169.
Ward C.R., 1980 Notes on the Bulgo Sandstone and the Bald Hill Claystone. In *A Guide to the Sydney Basin*. (C. Herbert and R Helby eds). Geol. Surv. NSW. Bulletin 26. D. West. Government Printer. 178-187.