Eucalyptus cunninghamii (Myrtaceae) in the Blue Mountains of New South Wales – an Unexpected Connection between Botany and Geology

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A three-year field study of the rare *Eucalyptus cunninghamii* Sweet (Myrtaceae), the Cliff Mallee Ash, uncovered a hitherto unrecognised connection between this taxon and its substrate. *E cunninghamii* has long been known to grow on cliff edges around two valleys of the upper Blue Mountains, the Grose and the Jamison, but details of that habitat were unexplored. We show that its preferred habitat in the upper Blue Mountains is on or just downslope of a clay layer, most often the Wentworth Falls Claystone Member (WFC), and that *E cunninghamii* is not found elsewhere (except for an anomalous outlier near Mittagong) because the WFC is not expressed stratigraphically except around the clifflines of the two valleys. This and other environmental features delimit the distribution of *E cunninghamii* to a very precise geospatial range which may cause problems in times of climate change.

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KEYWORDS: Blue Mountains, botany, claystone, cunninghamii, Eucalyptus, geology, Wentworth Falls.

INTRODUCTION

Eucalyptus cunninghamii (Euclid 2019, Fairley 2004, Fairley and Moore 2000, Brooker and Kleinig 2006, Carolin and Tindale 1994) is one if six mallees in the eight “green ashes” of the Greater Blue Mountains World Heritage Area (Hager and Benson 2010). The others are *E apiculata, E laophila, E dendromorpha, E burgessiana,* and *E stricta.* They form a complicated genetic series, currently under investigation (Rutherford et al. 2016, Rutherford 2017, Rutherford 2019). Our field study complements this genetic research, and attempts to find markers to support known genetic differences within *Eucalyptus cunninghamii*. Along the way we discovered a hitherto unrecognised connection between this taxon and its substrate.

Its status is 2RCA (i.e. rare but probably adequately conserved) under the ROTAP Rare Plants classification of Briggs & Leigh (1996). At November 2019 there were 109 records in the National Herbarium in the Royal Botanic Garden and Domain Trust in Sydney, records which identified 12 occurrences overall, 11 in the upper Blue Mountains and one outlier at Wanganderry Walls near Mittagong (PlantNET 2019, AVH 2019). Our study increased the total number of occurrences of *Eucalyptus cunninghamii* to 38 without an increase in its range. However, because the outlier at Wanganderry Walls is now considered (S. Rutherford, pers. comm. 2019) genetically different, it was not included in our study of the connection between botany and geology. Thus our study examined 37 occurrences in the upper Blue Mountains

METHODS

We visited the 11 known occurrences in the upper Blue Mountains and collected data at each one, including GPS latitude and longitude, altitude, aspect, slope and Area of Occupation (AOO). We assigned a name and two-letter code for each occurrence, and converted latitude and longitude to more easily handled Grid References. Patterns emerging from this initial phase enabled us to find and record 26 more occurrences in the upper Blue Mountains (Table 1). Map references in the upper Blue Mountains are on one of three 1:25,000 Topographic and Orthophoto, Third Edition, GDA Maps: Jamison 8930-2N, Katoomba 8930-1S, and Mt Wilson 8930-1N. Measured map references and measured latitude and longitude were cross-checked using Redfearn's formulae (Geoscience Australia).

We collected samples of leaves and soils from a downhill transect at one site (Kedumba Walls). These samples, together with some from nearby clays and clayrocks, were air-dried for five days and then oven-dried for 72 hours at 80^{o}C. They were packaged as 10g samples in paper envelopes. Analyses were carried out by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICPAES) in Isotope Tracing in Natural Systems (ITNS) at the Australian Nuclear Science and Technology Organisation (ANSTO), Lucas Heights, Sydney. Elements analysed were Al, Ba, Fe, Sr, Ca, Cu, K, Mg, Mn, Na, P, S and Zn. The analyses did not include hydrogen, carbon, oxygen, nitrogen or silicon.

RESULTS AND DISCUSSION

The 37 occurrences of the upper Blue Mountains (Figure 1) fall neatly into two groups, the Jamison Valley Group in the south (21) and the Grose Valley Group in the north (16), separated by at least 8 km of urban development along the spine of the upper Blue Mountains. These two groups are further divided for reasons of biogeographic isolation.

In the Grose Valley there are three upland biogeographic isolations of *Eucalyptus cunninghamii*, Grose North, Pulpit Rock and Grose South. The Grose River Valley, 2 km wide and over 600 m deep between Mount Banks and Mount Hay, is the physical barrier for biological contact between Grose North and Grose South. A second biogeographic barrier, Govetts Creek, isolates Pulpit Rock from all other occurrences of *Eucalyptus cunninghamii* in the Grose Valley (Figure 1 and Tables 1 and 2).

In the Jamison Valley there are two biogeographic isolations of *Eucalyptus cunninghamii*, Jamison West and Jamison South. Their nearest occurrences are separated by 3 km of rugged terrain between Sublime Point (Leura) and Lincolns Rock/Little Switzerland (Kings Tableland), where the Jamison Creek (at 300 m altitude) is over 500 m below the average upland terrain. In this area no occurrences of *E cunninghamii* were found on the cliffs and surrounds at Inspiration Point, Moya Point and Cathedral Point. This separation represents a barrier to biological contact. Occurrences in Jamison West lie on an E–W line between Sublime Point and Giant Stairs (Katoomba), whereas occurrences in Jamison South lie on a N–S line between Undercliff Track and Kedumba Gate (Kings Tableland).

These six populations of *Eucalyptus cunninghamii*, three in the Grose Valley, two in the Jamison Valley and the outlier at Wanganderry Walls, represent biogeographic isolations. Table 2 summarises their average geospatial data. Note that grand averages are weighted for population sizes.

When we examined the data within each population of the upper Blue Mountains we discovered a close correlation between Easting and Altitude (Table 1). This feature is most easily shown graphically (Figures 2a–d). Twenty four of the 37 occurrences lie on trend lines with an east–west slope of just less than one degree.

In Grose North six of the nine occurrences labelled the 940 sub-Group (Figures 1 and 2a) occupy a narrow range of 935–945 m above the other three: one at Walls Cliff 2 (the base of Pierces Pass) is anomalously low at 665 m. In Grose South all seven occurrences lie on a well-defined trend (Figures 1 and 2b). In Jamison West seven of the ten occurrences lie on a smooth E–W trend, but three others (GF, GL1 and SP4) occur at significantly higher altitudes (Figures 1 and 2c). In Jamison South eight occurrences lie on a smooth N–S trend but three others (CR, KR and KG) occur at significantly lower altitudes: these three occurrences intersect with the Bodington Monocline (Holland 1974) which causes a change in slope (Figures 1 and 2d). Of the 37 occurrences in the upper Blue Mountains, twenty-four that lie on trend lines in Figure 2 are shown as blue diamonds; those that do not are shown as 12 red squares or one green triangle.

Because the scales of the abscissas in Figures 2a–d are 100 times that of the ordinate, the true environmental slopes are ~1 degree. Also, to accentuate these very shallow slopes, vertical origins have been highly suppressed. Thus in Figure 2b the west-to-east fall is roughly 115 metres over a distance of 7 km, in Figure 2c the fall is roughly 50 m over 2.3 km, and in Figure 2d the fall is roughly 23 m over 5 km.

We sought, and found, a reason for this regularity between easting and altitude, which indicates a largely planar distribution of *Eucalyptus cunninghamii* if, for the moment, we ignore the 13 off-trend occurrences.

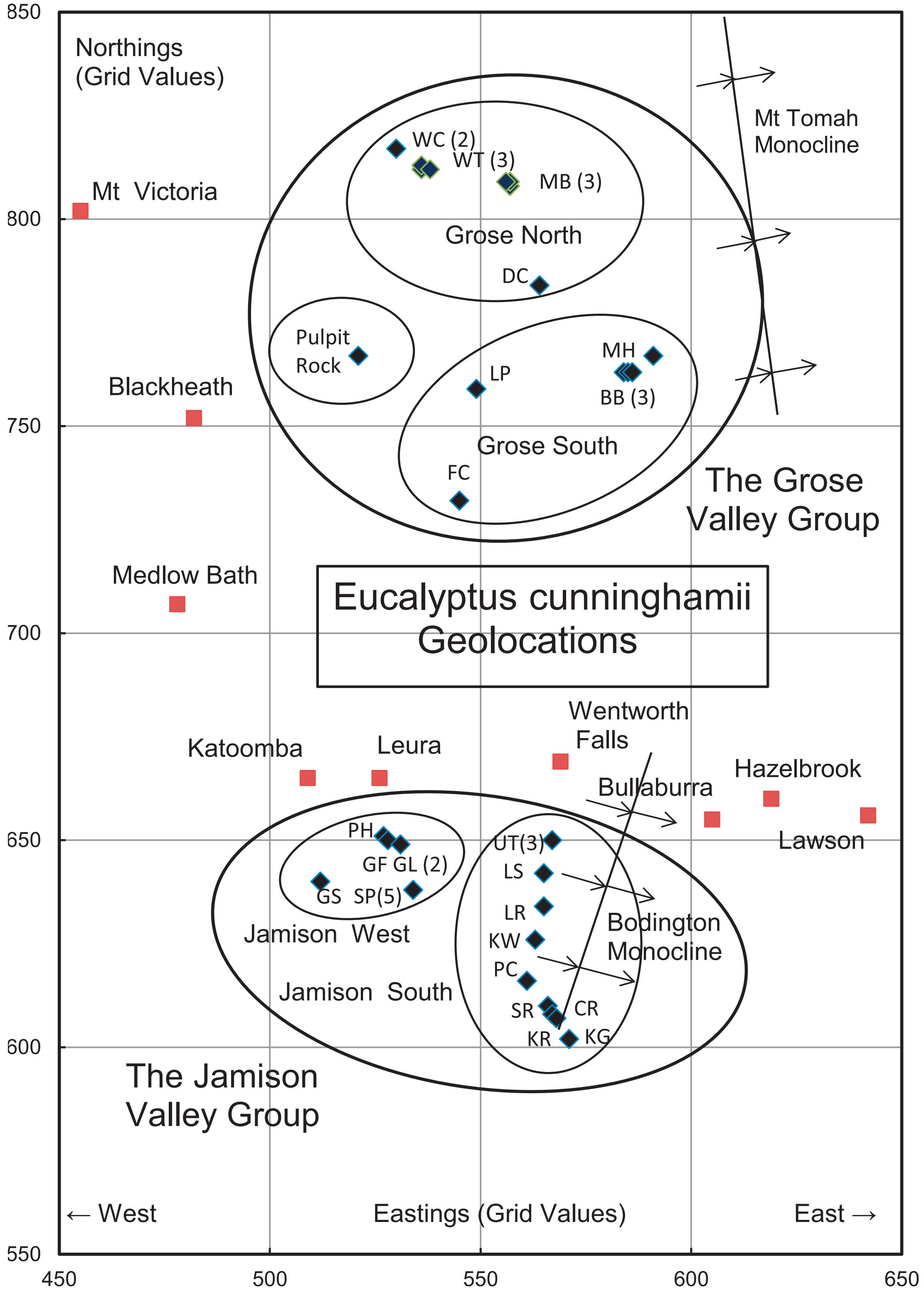

Figure 1. ***Eucalyptus cunninghamii*** **Geolocations, showing 37 occurrences in five populations in the upper Blue Mountains. See Table 1 for details. Eastings and Northings are Grid Values. Red squares are railway stations.**

Table 1. *E cunninghamii*, geospatial attributes, Grose Valley and Jamison Valley.

Occurrence (* New occurrences)	Code	Map References Easting	Map References Northing	Latitude	Longitude	Altitude (m)
E cunninghamii: Geospatial Attributes: Grose North						
Walls Cliff 1	WC1	530	817	-33º 34′ 33″ S	150º 20′ 18″ E	885
*Walls Cliff 2	WC2	529	818	-33º 34′ 31.3″ S	150º 20′ 16.4″ E	665
*Wongarra 1	W1	536	812	-33º 34′ 46.6″ S	150º 20′ 41.2″ E	935
Wongarra 2	W2	536	813	-33º 34′ 48.1″ S	150º 20′ 41.5″ E	945
*Wongarra 3	W3	538	812	-33º 34′ 50.8″ S	150º 20′ 49.2″ E	940
Mount Banks 1	MB1	558	808	-33º 35′ 04″ S	150º 22′ 04″ E	940
*Mount Banks 2	MB2	557	809	-33º 35′ 1.8″ S	150º 22′ 1.7″ E	940
*Mount Banks 3	MB3	556	809	-33º 35′ 1.0″ S	150º 22′ 00″ E	945
*David Crevasse	DC	564	784	-33º 36′ 23.1″ S	150º 22′ 27.6″ E	845
E cunninghamii: Geospatial Attributes: Grose South (inc PR)						
Pulpit Rock	PR	521	767	-33º 37′ 15″ S	150º 19′ 40″ E	925
Fortress Cliff	FC	545	732	-33º 39′ 10″ S	150º 21′ 10″ E	860
*Lockley Pylon	LP	549	759	-33º 37′ 41.4″ S	150º 21′ 27.5″ E	870
*Butterbox West	BW	583	764	-33º 37′ 32.6″ S	150º 23′ 44″ E	809
Butterbox South	BS	584	763	-33º 37′ 29″ S	150º 23′ 44″ E	810
*Butterbox East	BE	585	762	-33º 37′ 33″ S	150º 23′ 40″ E	810
*Mt Hay SW	MH	591	767	-33º 37′ 20.3″ S	150º 24′ 13.0″ E	820
E cunninghamii : Geospatial Attributes: Jamison West						
Giant Stairs	GS	512	640	-33º 44′ 4″ S	150º 18′ 54″ E	925
*Prince Henry C/W	PH	527	651	-33º 43′ 32.3″ S	150º 19′ 34.1″ E	900
*Gordon Falls L/O	GF	528	650	-33º 43′ 35.8″ S	150º 19′ 57″ E	912
*Golf Links 1	GL1	531	649	-33º 43′ 38.2″ S	150º 20′ 8.2″ E	912
*Golf Links 2	GL2	531	649	-33º 43′ 38.9″ S	150º 20′ 7.7″ E	890
Sublime Point 1	SP1	534	638	-33º 44′ 14″ S	150º 20′ 18″ E	875
*Sublime Point 2	SP2	534	639	-33º 44′ 10.2″ S	150º 20′ 17.5″ E	883
*Sublime Point 3	SP3	534	640	-33º 44′ 8.1″ S	150º 20′ 15.8″ E	890
*Sublime Point 4	SP4	534	640	-33º 44′ 8.4″ S	150º 20′ 16.6″ E	910
*Sublime Point 5	SP5	533	648	-33º 43′ 42.8″ S	150º 20′ 13.2″ E	877
E cunninghamii : Geospatial Attributes: Jamison South						
*Undercliff Track 1	UT1	567	650	-33º 43′ 37″ S	150º 22′ 26.7″ E	830
*Undercliff Track 2	UT2	562	650	-33º 43′ 37.1″ S	150º 22′ 8.8″ E	815
Undercliff Track 3	UT3	557	653	-33º 43′ 27.9″ S	150º 21′ 49.0″ E	853
*Podgers Cliff	PC	562	618	-33º 45′ 20.1″ S	150º 22′ 4.3″ E	850
*Kedumba Walls	KW	563	626	-33º 44′ 55.4″ S	150º 22′ 10.5″ E	841
*Lincoln's Rock	LR	565	634	-33º 44′ 30.2″ S	150º 22′ 18″ E	845
Little Switzerland	LS	565	642	-33º 44′ 04″ S	150º 22′ 18″ E	835
*Sunset Rock	SR	566	610	-33º 45′ 47″ S	150º 22′ 19″ E	845
*Colraine Rock	CR	567	608	-33º 45′ 54.2″ S	150º 22′ 22.1″ E	814
Kedumba Road	KR	568	607	-33º 45′ 57″ S	150º 22′ 26″ E	805
Kedumba Gate	KG	571	602	-33º 46′ 14″ S	150º 22′ 38″ E	790

Table 2. Summary of geospatial attributes of all six populations.

E cunninghamii – Geospatial Attributes Summary of All Six Populations				
Occurrence	Altitude (m)	Aspect (degrees)	Slope (degrees)	AOO (m^2)
Grose North	893	226	29	2560
Pulpit Rock	925	250	20	2000
Grose South	830	244	21	1890
Jamison West	897	214	36	1310
Jamison South	829	239	37	1560
Wanganderry Walls	744	250	25	100
Total				9420
Average	853	237	28	

Substrate

All occurrences of *E cunninghamii* in the upper Blue Mountains are associated with clay, either at the outcrop or closely downslope. One prominent clifftop clay layer, the Wentworth Falls Claystone Member (WFC) (Bembrick and Holland 1972) is regionally extensive and constitutes a marker horizon for a change in direction of sediment provenance (Figure 3).

The WFC was laid down in mid-Triassic times (240 mya) in a widespread fluvial-deltaic system of braided streams (Bembrick 2015, Gorjan 2019), essentially flat across the whole terrain, but not necessarily consistent in either thickness or content. Since the uplift of the Blue Mountains (at least 15 mya, and possibly even over 100 mya) the WFC forms a slightly inclined E-W plane with a slope of about 0.9 degree in the upper Blue Mountains. The most prominent and accessible expression of the WFC occurs along the Undercliff Track at Wentworth Falls (Figure 4).

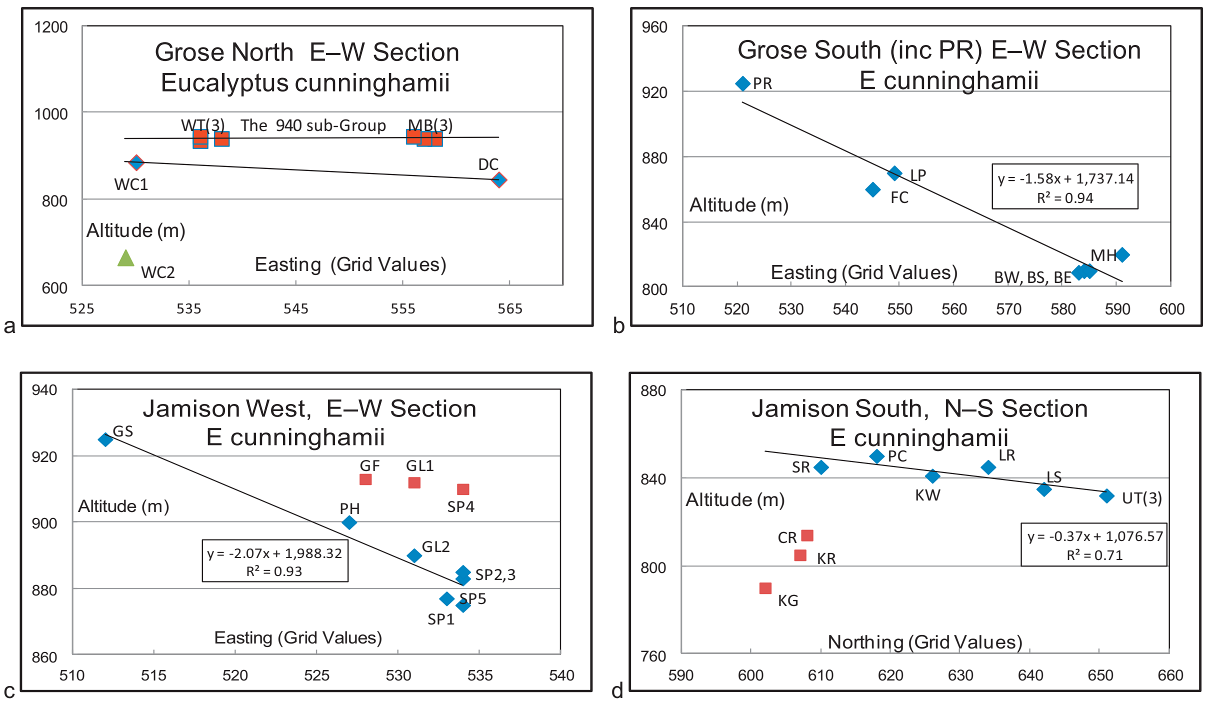

Figure 2. *Eucalyptus cunninghamii* in the upper Blue Mountains, correlations of altitudes with eastings (or northings) for four biogeographic isolations: a) Grose North, b) Grose South (including Pulpit Rock), c) Jamison West, d) Jamison South. Blue diamonds, occurrences on trend; red squares and one green triangle, anomalies (see Text).

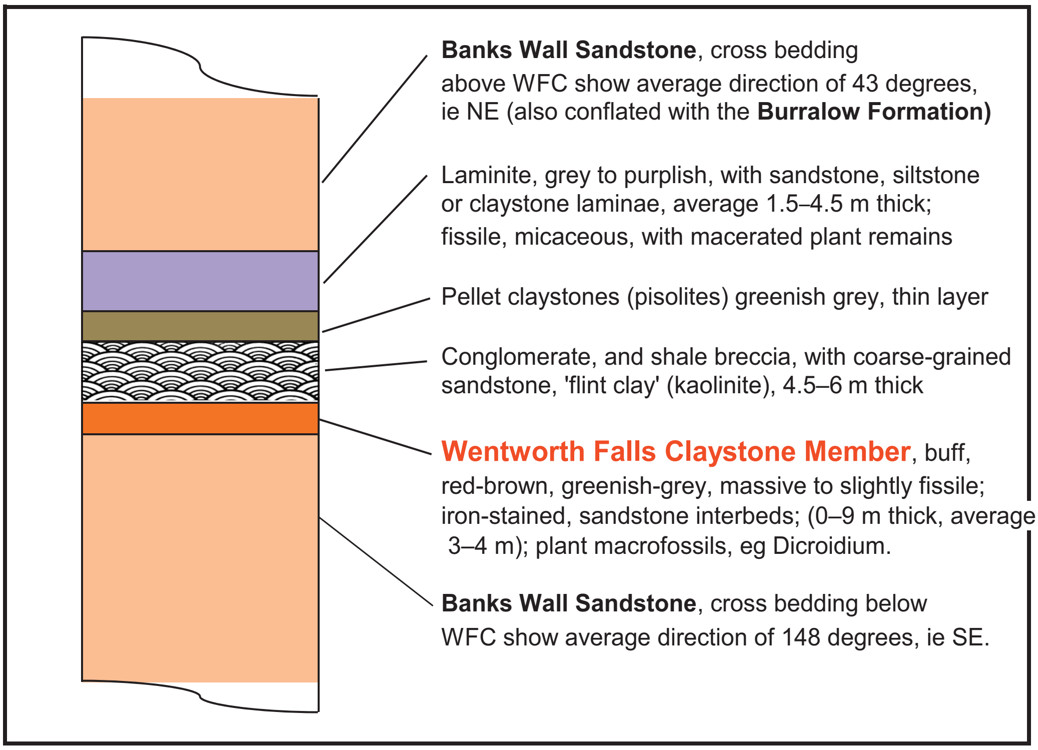

Figure 3. Sketch of the lithologies associated with the Wentworth Falls Claystone Member (WFC), of the Banks Wall Sandstone lying within the Narrabeen Group, based on Bembrick & Holland (1972).

Figure 4. Undercliff Track and WFC at Wentworth Falls.

Table 3. Wentworth Falls Claystone Member (WFC) in the Grose and Jamison valleys.

Wentworth Falls Claystone				
	Code	Northing	Easting	Altitude
		(Grid Values)		(m)
Grose Valley				
GWH Medlow Bath[4]	GWH	692	487	965
N of Neates Glen[1,4]	NNG	733	514	910
Mt Banks Summit	MBS	806	559	840
Mount Hay[2]	MHS	768	590	810
"F" WFKT[4]	"F"	646	577	820
Jamison Valley				
Kure Narrow Neck[4]	KNN	629	481	975
Narrow Neck Quarry[1,3]	NNQ	647	493	953
Sublime Point[1,4]	SP	631	534	875
"F" WFKT[4]	"F"	646	577	820
Sunset Rock	SR	610	566	845

We collected data from a number of journal articles from the 1970s which gave measurements of the location and altitude of the WFC over the Grose and Jamison valleys. These data derive from Bembrick and Holmes[1] (1978), Goldbery[2] (1972), Bembrick and Holland[3] (1972), and Goldbery[4] (1996) manipulated as required from imperial units to metric, and geographic locations from 1:63,360 maps (1935) to GDA94. They are summarised in Table 3.

We then inserted into Figures 2a–d the relevant data for the WFC from Table 3.and graphed the results in Figures 5a–d, where the WFC appears as black circles and black trendlines.

In each graph, slope and intercept of the WFC closely match those of the graphs for *Eucalyptus cunninghamii*. There is a high degree of correlation between these independent sets of data for the five populations in the upper Blue Mountains. The thirteen

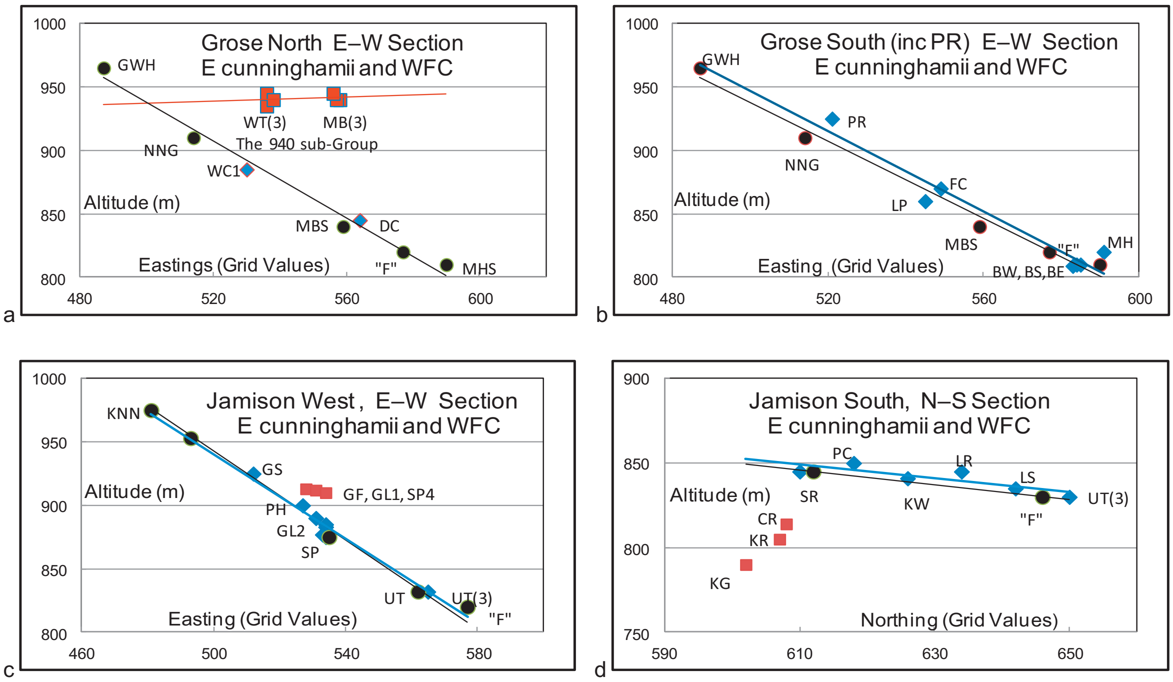

Figure 5. ***Eucalyptus cunninghamii* in the upper Blue Mountains, altitudes and eastings (or northings) compared with the Wentworth Falls Claystone Member: a) Grose North, b) Grose South (including Pulpit Rock), c) Jamison West, d) Jamison South. Blue diamonds, occurrences on trend; red squares, anomalies (see text); black circles, WFC.**

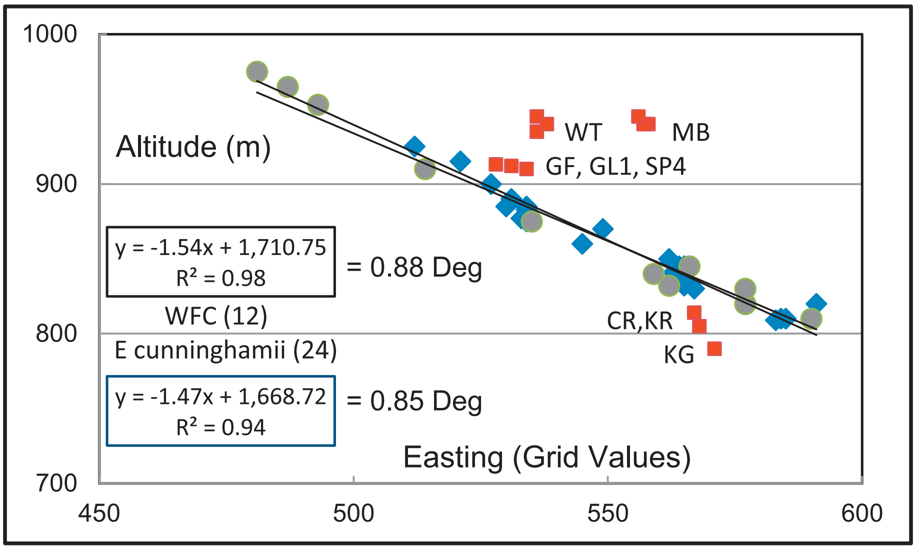

Figure 6. Correspondence of altitudes of 24 occurrences of *E cunninghamii* occurrences with 12 published altitudes of the Wentworth Falls Claystone Member (WFC). *E cunninghamii* data are shown as blue diamonds and blue trendline, WFC data as grey circles and grey trendline. Anomalous altitudes of *E cunninghamii* are shown in red (see text).

occurrences that do not lie on the trend lines depicted in Figures 5a–d are either associated with other claystones or, in the examples at Jamison South, with a change in slope arising from the Bodington Monocline.

As with text notes concerning Figures 2a–d, the origins of Figures 5a–d have been suppressed and the vertical scale is 100 times that of the horizontal. The graph slopes thus accentuate the very shallow real slopes of about 0.9 degree.

We combine the data in Figures 5a-d into one graph (Figure 6) which shows the overall correspondence between the majority (24) of 37 occurrences of *Eucalyptus cunninghamii* and the 12 published occurrences of the Wentworth Falls Claystone Member (WFC).

Anomalous Altitudes

Most, but not all, occurrences of *Eucalyptus cunninghamii* in the upper Blue Mountains are associated with the WFC. The most prominent of the others is the 940 sub-Group (Mount Banks 1, 2 and 3, Wongarra 1, 2 and 3). They occupy a horizontal zone in the north of Grose North at approximately 940 m. They correlate with the upper of two unnamed horizontal claystones (Pickett and Alder, 1997) at Mount Banks (Figure 7). We first measured altitudes in the Marginal Section ABC of Geological Series Sheet 8930-1 Katoomba 1:50,000 (Goldbery, 1996) to establish the altitude of the Mount York Claystone at 729 m at Mount Banks.

There are two unnamed clay layers at MountBanks (Pickett and Alder, 1997). We identified those two layers in one of our photographs of Mount Banks (Figure 7), and measured their altitudes using the known altitudes of the summit (Mt King George,

Figure 7. Claystone Layers at Mount Banks (see text for details).

1062 m) and the Mount York Claystone (729 m). The lower unnamed claystone lies at an altitude of 840 m, the upper clay layer lies at 940 m. The lower clay layer has been interpreted as possibly equivalent to the Wentworth Falls Claystone (Bembrick 2015), and we follow that interpretation here. Mount Banks occurrences (MB 1, 2, 3) of *Eucalyptus cunninghamii* lie on the upper claystone layer (Figure 7). Together with MB1, 2 and 3, the nearby occurrences of *E cunninghamii* at Wongarra 1, 2 and 3, constitute the six occurrences of the "940 sub-Group".

Another occurrence not associated with the WFC (and not shown in Figure 5a) is Walls Cliff 2, where *E cunninghamii* has propagated at 665 m from seed dropping down from Walls Cliff 1 at 885 m.

In Jamison West, because Golf Links 1 lies about 22 m above the trend line, we predicted (and found) Golf Links 2 on the trend line. Similarly, from our discovery of Sublime Point 4, 25 m above the trend line, we predicted (and found) Sublime Point 2 and 3 on the trendline. The occurrence at Gordon Falls, also above the trendline, is on a vertical cliff, and no occurrence on the trendline could be seen or accessed. It is possible that this upper claystone in Jamison West may be a remnant of the Docker Head Claystone (Loughnan et al. 1974, Martyn 2018).

Mount York Claystone

Our investigation of the easting and altitude of clay layers in the upper Blue Mountains also enabled us to graph known eastings and altitudes of both the WFC and the Mount York Claystone (MYC) (Figure 8). The MYC lies halfway up the familiar sandstone cliffs and separates the (lower) Burra-Moko Head Sandstone from the (upper) Banks Wall Sandstone. The MYC is also regionally extensive and planar, with an E–W slope of ~1.5 degrees. Though small, this difference in the slope of the two graphs for MYC and WFC means that the Banks Wall Sandstone that separates them thins down from east to west. At Jamison South on Kings Tableland the separation is over 100 m, but further west, as at the top of the Great Western Highway at Victoria Pass and at the quarry on the Mount York Road, the separation should be almost zero. However, at these locations the WFC has eroded away and no comparison is possible. A recent discussion of the relationship between the geology and the flora of much of the Sydney Basin can be found in Martyn (2018).

All the foregoing discussion refers to the upper Blue Mountains, which traditionally lie west of the Mount Tomah and Bodington monoclines (Figure 1). East of this line the slopes of both the MYC and the

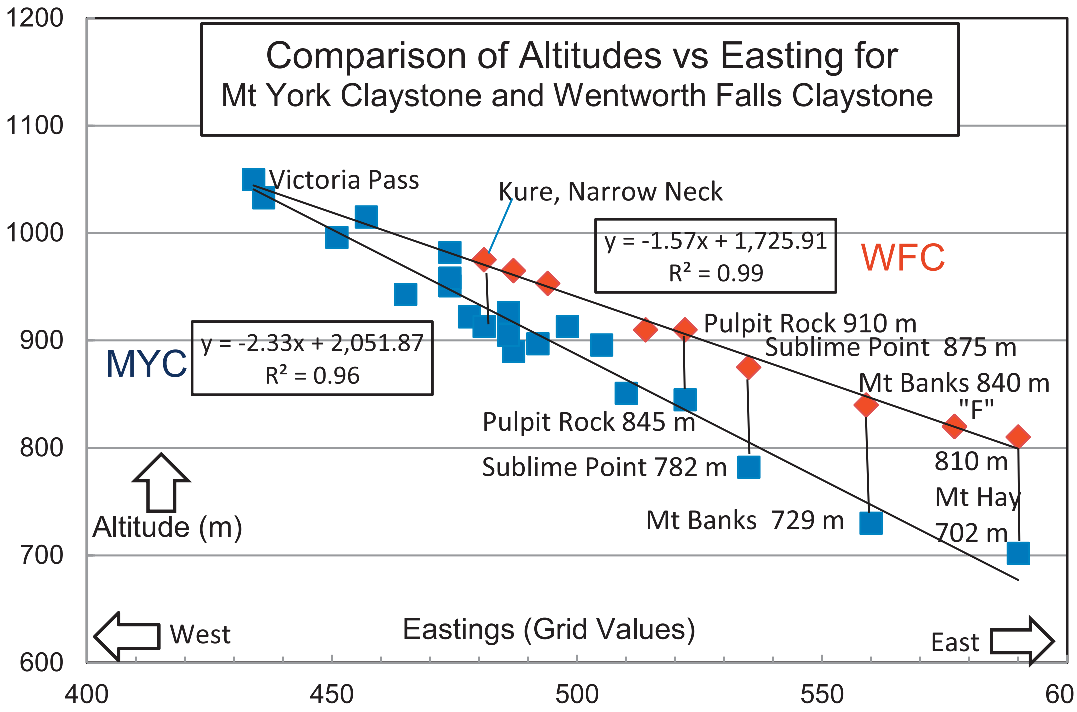

Figure 8. Comparison of altitudes vs easting for the Mount York Claystone and the Wentworth Falls Claystone Member in the upper Blue Mountains.

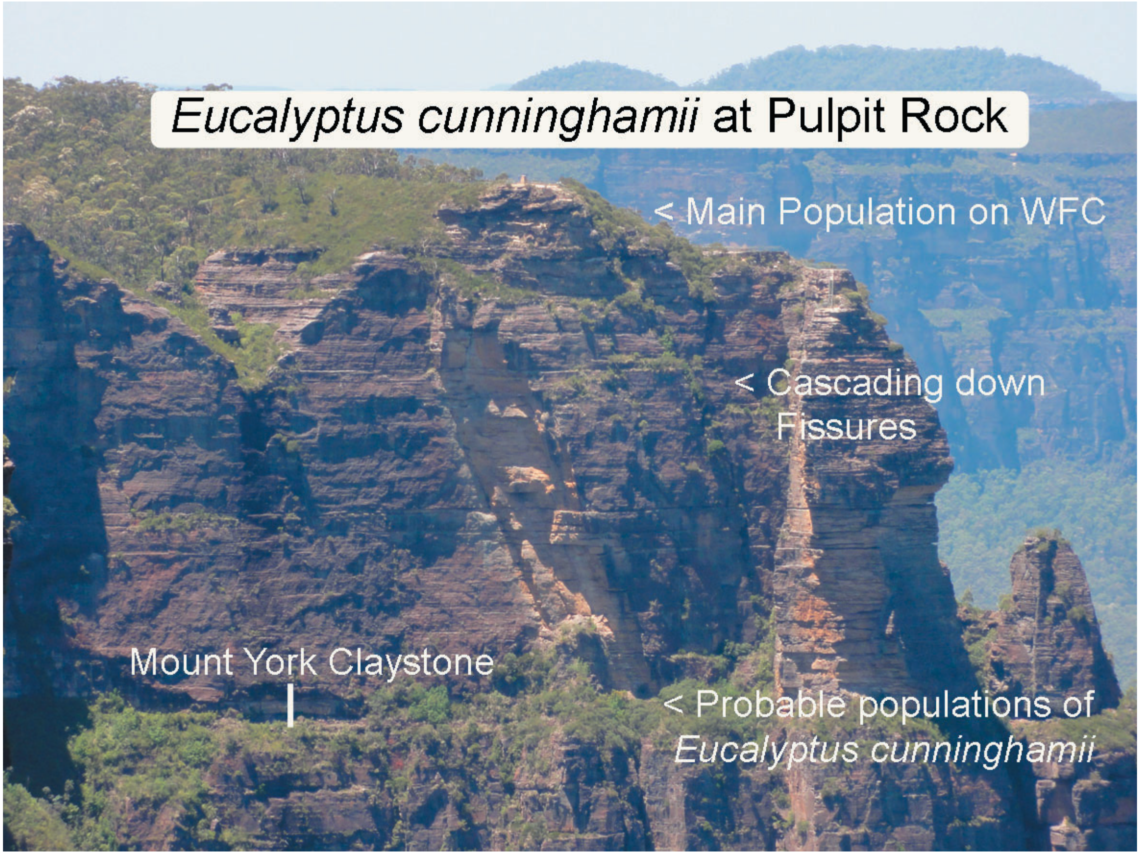

Figure 9. Cascading *Eucalyptus cunninghamii* at Pulpit Rock.

WFC increase to 2–2.5 degrees, with the consequence that neither exhibits a surface outcrop lower down the mountain (Bembrick 1980, Goldbery 1969/1996).

Pulpit Rock demonstrates that *Eucalyptus cunninghamii* cascades down fissures and cracks and inhabits the ledge associated with the Mount York Claystone (Figure 7), some 65 m below the average altitude, 910 m, for Pulpit Rock (Figures 9 and 10). If this interpretation is correct, *Eucalyptus cunninghamii* may be found on other outcrops of the Mount York Claystone, such as at National Pass at Wentworth Falls.

We sought reasons why 24 of our 37 upper Blue Mountains occurrences should show a strong association with the WFC. We chose an occurrence at Kedumba Walls (Jamison South) where it was possible, even on a steep slope (Figure 11), to make a downslope transect to include not only four specimens of *Eucalyptus cunninghamii*, but also the terrain above and below the occurrence (Figure 12). We analysed leaf and soil samples (Table 4).

It appears that the four elements Al, Ba, Fe and Sr are present in soils in far larger quantities than are required for sustained growth of *E cunninghamii*, whereas another eight elements Ca, Cu, K, Mg, Mn, Na, P and S are present in such low proportions as requires concentration in the leaves and other structures of *E cunninghamii* for proper plant development. This results in above-ground storage of vital nutrients (Keith 2004). The remaining element, Zinc, is present in both soils and leaves in about the same concentrations. This analysis does not include hydrogen, carbon, nitrogen or oxygen.

We sought correlations of elemental presence between soils and leaves downslope at Kedumba Walls. There is a positive correlation factor of 0.995 for barium and 0.898 for strontium. Of the remaining elements only sodium (-0.80) was significant. Thus for Ba and Sr at this site their uptake in leaves is proportional to their concentration in soil.

Our expectation that soil analysis at 0 m (above the clay layer) and at 20 m downslope (where there are no *Eucalyptus cunninghamii*) would exhibit differences from the remainder was not realised. The analysis does not therefore pinpoint the reason why the presence of *E cunninghamii* at a particular

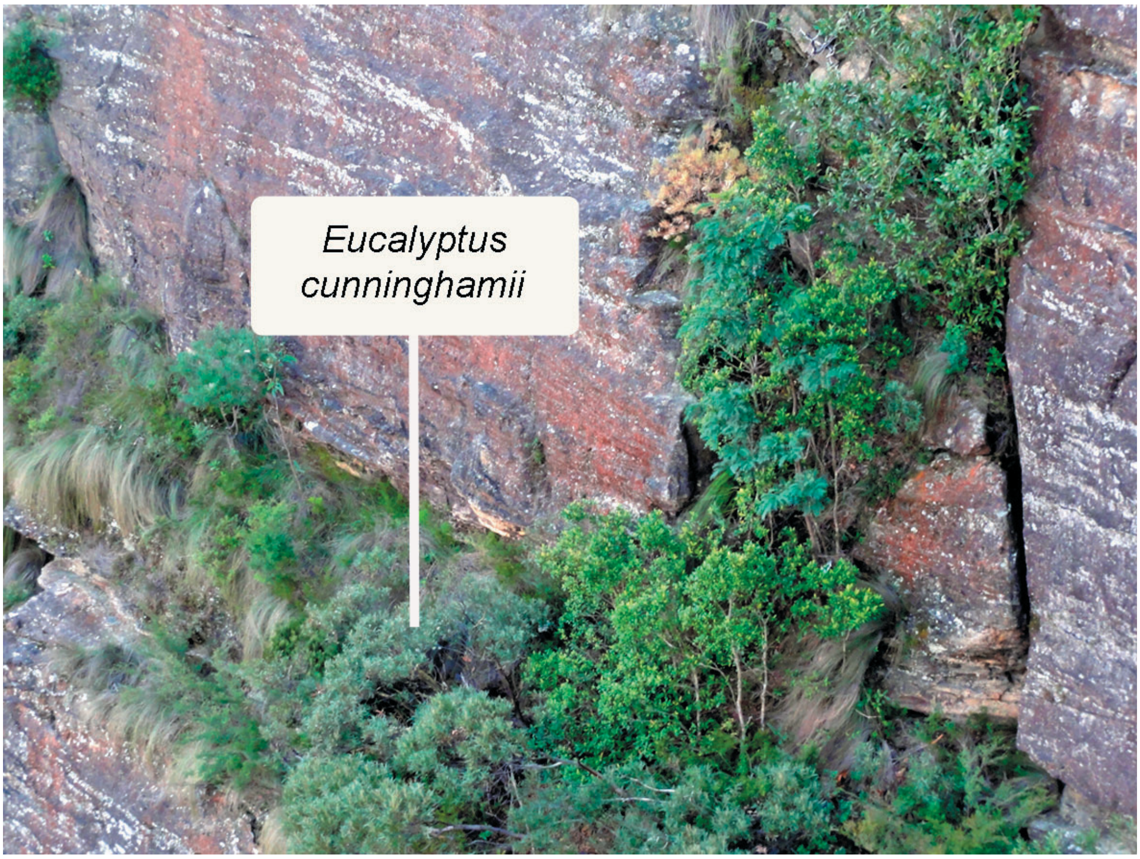

Figure 10. *Eucalyptus cunninghamii* on the MYC.

occurrence should correlate with any particular element in the substrate. The alternative interpretation that the WFC acts as an aquitard, and discharges water at the outcrop to help sustain *E cunninghamii*, was not measured in our study. We lacked resources a) to measure environmental factors such as soil moisture averaged over a year, or b) to determine whether a specific mycorrhizal fungus was present. We also lacked resources to measure similar attributes at other occurrences.

We therefore conducted a similar analysis on leaf and soil samples of *Eucalyptus stricta* from three separate locations in the upper Blue Mountains: Willoughby Road, south Leura; Flat Top carpark on the Mt Hay Road; and the carpark at the northern end of the Mt Hay Road. These three sites are specific for *E stricta* and remote from any other occurrences of *E cunninghamii* (Table 5).

When comparing the data of Tables 4 and 5, the overall pattern is the same in both. Al, Ba, Fe and Sr are all diluted in leaves from their environmental concentrations in soils. Eight other elements, Ca, Cu, K, Mg, Mn, Na, P and S, are all concentrated in the plant above the levels found in their soils. The average 'Dilution percentage' in *Eucalyptus cunninghamii* is 3%, in *E stricta* it is 7%. The average 'Concentration factor' in *E cunninghamii* is 14%, whereas in *E stricta* it is 20%. We found no other significant differences.

Our analyses neglect the probability that elements may not always be biologically available: soluble ferrous iron which oxidises to insoluble ferric iron (Washington and Wray 2011) is an example that produces contorted deposits at some occurrences (Figure 13).

General

Our 37 occurrences do not necessarily represent totality. There may be more *Eucalyptus cunninghamii* in some relatively inaccessible locations, as at Mount Solitary in the Jamison Valley, and along Kedumba Walls (Jamison South) from Rocket Point south to Sunset Rock. In the Grose Valley there are some relatively inaccessible locations between Bell and Mount Banks, and along the SW flanks of Fortress Ridge and Lycon Plateau, where *E cunninghamii* may be discovered.

Figure 11. ***Eucalyptus cunninghamii*** **at Kedumba Walls.**

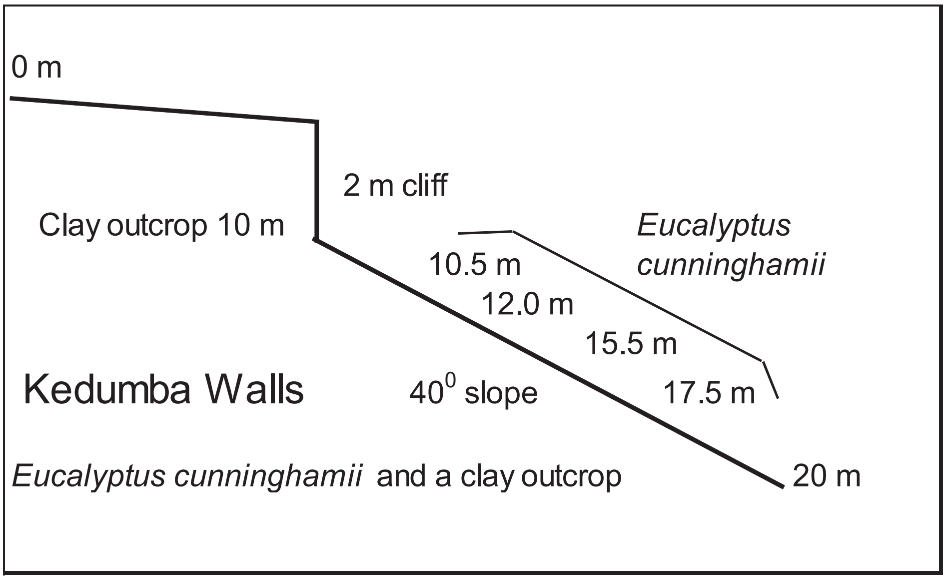

Figure 12. Sketch of terrain at Kedumba Walls.

Table 4. Leaf and soil analyses, Kedumba Walls (see Figure 12)

Elemental analysis at Kedumba Walls (mg/Kg)													
Element / Item	Al (3)	Ba (2)	Ca (2)	Cu (TM)	Fe (TM)	K (1)	Mg (2)	Mn (TM)	Na (1)	P (5)	S (6)	Sr (2)	Zn (TM)
Soil: 0 m	4230	16.5	39	<0.6	6110	454	129	6.1	89	71	119	24	4.8
Soil 10.5 m	3900	15.7	34	<0.7	7200	354	108	16	34	69	107	20.2	5.2
Soil: 12 m	5710	22.5	29	<0.7	6750	596	109	8.1	108	81	101	32.4	3.8
Soil: 15.5 m	9370	84.6	36	<0.7	8600	1030	165	8.1	93	163	101	73	4.4
Soil: 17.5 m	6750	41.3	43	<0.7	6660	703	139	9.1	61	110	89	42.1	4.1
Soil: 20 m	8000	42.1	43	1.1	6340	1020	225	12.5	131	127	196	47.1	7.2
Clay: 10 m	8050	32.1	51	<0.7	12300	818	160	45.8	91	123	116	44.8	6.6
Leaf: 10.5 m	60	0.5	762	3.3	40	4320	1290	260	3130	328	1040	1.5	5.3
Leaf: 12.0 m	44	0.6	946	1.8	30	3520	912	192	2440	375	941	4.4	5.3
Leaf: 15.5 m	53	1.1	1120	2	27	3570	941	265	2670	287	862	6.1	5.1
Leaf: 17.5 m	66	0.7	865	3.5	40	5270	913	163	2530	436	1040	4.3	5.7
Elements which are relatively abundant in soils, but required only in small concentrations in E cunninghamii													
Dilution factor (%)	0.9	1.8			0.5							9.7	
Elements which are relatively scarce in soils, but concentrated in the metabolism of E cunninghamii													
Concentration factor			26	3.8		6.2	7.8	21.3	36.4	3.4	9.8		
This table of analyses does not include Hydrogen, Carbon, Nitrogen and Oxygen													
Correlations (of four leaf samples with four soil samples for each element)	-0.109	0.9954	-0.093		-0.625	-0.26	-0.49	0.4482	-0.801	-0.379	-0.213	0.8978	-0.253

Table 5. Elemental analysis of soils and *Eucalyptus stricta*

Elemental analysis of soils and *Eucalyptus stricta* (mg/Kg)													
Element / Item	Al (3)	Ba (2)	Ca (2)	Cu (TM)	Fe (TM)	K (1)	Mg (2)	Mn (TM)	Na (1)	P (5)	S (6)	Sr (2)	Zn (TM)
Leaves: *Eucalyptus stricta*													
Willoughby Road	88	3.1	3210	2.4	37.4	1650	1200	353	1710	320	851	7	4.6
Flat Top Carpark	45	4.1	4330	6.8	39	3450	1170	292	2370	362	803	11.3	6.5
Mt Hay Carpark	56	4.7	2970	3.4	32	3250	1440	148	2630	509	809	17.9	6.4
Soils: *Eucalyptus stricta*													
Willoughby Road	5740	26.6	79	0.7	10200	358	114	10.1	55.8	109	132	28	5.1
Flat Top Carpark	6270	24.6	167	1	5710	316	122	9.2	34	56	89	16.5	6.7
Mt Hay Carpark	2250	8.4	104	1	1690	206	76.2	4.1	22	45	55	7.8	2.3
Elements which are relatively abundant in soils, but required only in small concentrations in *E stricta*													
Dilution factor %	1.3	20			6.2							1.4	
Elements which are relatively scarce in soils, but concentrated in the metabolism of *E stricta*													
Conc. factor x			30	4.7		9.5	12.2	33.9	60	5.7	8.9		
This table does not include Hydrogen, Carbon, Nitrogen or Oxygen													

Figure 13. Contorted ironstone in claystone.

CONCLUSION

Eucalyptus cunninghamii in the upper Blue Mountains exhibits a marked preference for outcrops of claystone for its habitat. The most prominent of these claystones is the relatively thin, planar and regionally extensive Wentworth Falls Claystone Member (WFC) that outcrops across the upper Blue Mountains of NSW. Geologic accidents of topography and stratigraphy indicate that outcrops of the WFC occur only around the clifftop rims of the Jamison and Grose valleys. *E cunninghamii* in the upper Blue Mountains is therefore constrained to a narrow range of altitudes (approximately 800–920 m), but with occasional deviations to 940 m on other smaller and less extensive claystones. The random outcrops of the Wentworth Falls Claystone Member limit the Extent of Occurrence (EOO) of *E cunninghamii* to less than 200 $km^{2,}$ and its Area of Occupation (AOO) to less than one hectare (Coleby, pers comm., 2019). The implications of climate change for *E cunninghamii* are therefore severe, unless it is capable of adapting. One of the options discussed by Booth (2017), to move, seems improbable, and the third option, to go extinct, is unacceptable.

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REFERENCES

Australia's Virtual Herbarium (AVH) (2019), Atlas of Living Australia (ALA) (2019), http://avh.ala.org.au

Bembrick, C, (2015) The Geology of the Blue Mountains, with reference to Cox's Road, http://coxsroaddreaming.org.au/wp-content/uploads/Geol-Blue-Mtns_CSB_edited.pdf

Bembrick, C, (1980). Geology of the Blue Mountains, Western Sydney Basin. In Herbert, C, and Helby, R, (eds), A guide to the Sydney Basin, *Geological Survey of New South Wales,* Bulletin **26**, pp 134-161.*DIGS Publication collection: Catalogue No. 778

Bembrick, C.S., and G.G. Holmes, (1978), Comments on the Geology of the Katoomba 1:50 k Geological Sheet 8930–1, Geological Survey Report GS 1978/296*, Geological Survey of New South Wales, Department of Mines*.

Bembrick, C.S., and W.N. Holland, (1972), Stratigraphy and Structure of the Grose Sandstone in the Blue Mountains, in *Quarterly Notes 7, pp 11-18, Geological Survey of NSW,* 1 April 1972, NSW Department of Mines. *DIGS Report collection: ID = R00040839.

Booth, T.H., (2017), Going nowhere fast: a review of seed dispersal in eucalypts, *Australian Journal of Botany*, **65**, pp 401–410, Turner Review No. 20, ttps://doi.org/10.1071/BT17019

Briggs, J.D. and J.H. Leigh, (1996). Rare or threatened Australian plants, Revised Edition, *CSIRO Publishing, Australia*. ISBN: 9780 6431 05966

Brooker, M.I.H., and D.A. Kleinig, (2006) Field Guide to Eucalypts. Volume 1. South-eastern Australia. 3rd Edition, *Bloomings Books, Melbourne*. ISBN 1 876473 52 5 (Vol 1)

Carolin, R.C., and M.D. Tindale, (1994), Flora of the Sydney Region, *Reed, Sydney*. ISBN 0730 104001

Euclid (2018), http://keyserver.lucidcentral.org:8080/euclid/data/02050e02-0108-490e-89000e0601070d00/media/Html/Eucalyptus_cunninghamii.htm

Fairley, A., (2004), Seldom Seen, Rare Plants of Greater Sydney, *Reed New Holland, Sydney*, ISBN 1 876334 99 1

Fairley, A., and P. Moore, (2000) Native plants of the Sydney District, an identification guide. Second Edition, *Kangaroo Press, Roseville NSW*. ISBN 0 7318 1031 7

Geoscience Australia, (2019) Redfearn's Formulae, http://www.ga.gov.au/geodesy/datums/redfearn_geo_to_grid.jsp and http://www.ga.gov.au/geodesy/datums/redfearn_grid_to_geo.jsp

Goldbery, R., (1972), Geology of the Western Blue Mountains, Bulletin 20, *Geological Survey of New South Wales, Department of Mines, Sydney.*

Goldbery, R., (1996), Australia 1:50,000 Katoomba Geological Series Sheet 8930-1, *Geological Survey of New South Wales, Department of Mineral Resources.*

Gorjan, P., (2019) Geology of the Blue Mountains: A Tourist's Guide, *Yarnspinners Press Collective, PO Box 9, Wentworth Falls NSW 2782.* ISBN 978-0-6481342-2-0.

Holland, W.N., (1974), Origin and development of hanging valleys in the Blue Mountains, New South Wales. PhD Thesis, University of Sydney.

Hager, T. and D. Benson, (2010), Eucalypts of the Greater Blue Mountains World Heritage Area, *Cunninghamia* **11(4):** 2010. ISSN 0727 9620

Loughnan, F.C., R. Goldbery, and W.N. Holland, (1974) Kaolinite clayrocks in the Triassic Banks Wall sandstone of the western Blue Mountains, New South Wales, *Journal of the Geological Society of Australia*, **21:4**, 393-402.

Martyn, J., (2018), Rocks and Trees: A Photographic Journey through the rich and varied geology, scenery and flora of the Sydney Region, *STEP, Sydney*, ISBN 978 0 9578390 4 5

Pickett, J.W., and J.D. Alder, (1997), Layers of time: the Blue Mountains and their Geology, *New South Wales Department of Mineral Resources, Sydney* 34pp. ISBN 0 7313 0274 5

PlantNET (2019), http://plantnet.rbgsyd.nsw.gov.au/search/simple.htm.

Rutherford, S., Wilson, P.G., Rossetto, M., Bonser, S.P., (2016) Phylogenomics of the green ash eucalypts (Myrtaceae) – a tale of reticulate evolution and misidentification. *Australian Systematic Botany* 28: pp. 326–354.

Rutherford, S., (2017) Adaptive variation versus vicariance: what drives speciation in Eucalyptus? PhD thesis, University of New South Wales.

Rutherford, S., (2019) Insights into speciation and species delimitation of closely related eucalypts using an interdisciplinary approach, *Australian Systematic Botany* SB18042 (in press).

Washington, H., and R. Wray, (2011), The Geoheritage and Geomorphology of the Sandstone Pagodas of the Northwestern Blue Mountains Region (NSW), *Proceedings of the Linnean Society of New South Wales* **132**, pp 131-143.